Evaluation of Various Treatment Methods for Enhancing the Properties of Recycled Concrete Aggregate for Hot Mix Asphalt

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Sustainability and awareness of the environment are becoming increasingly important for transportation agencies worldwide. Sustainable development has significance for obvious and relevant reasons in all areas of civil transportation infrastructure. In the asphalt industry, a large number of innovative materials and technologies are explored in order to evaluate their suitability in the design, construction and maintenance of pavements. Attaining a sustainable solution has become a critical and urgent priority in the asphalt industry to solve various problems including lowering the consumption of virgin materials, decreasing waste materials in landfills and reducing environmental problems.

For the above-mentioned reasons, the utilization of Recycled Concrete Aggregate (RCA) is increasingly becoming a highly interesting issue in Canada, and worldwide. The use of RCA has been successfully applied in base aggregates and Portland Cement Concrete (PCC) aggregates. However, there have been very limited investigations for the usage of RCA in asphalt pavement mixtures due to its inferior properties such as higher water absorption and low density, but the main challenge is that RCA is a highly porous material. These characteristics have become strong restrictions for its usage in wide applications.

The overall objective of this study is to evaluate the application of Coarse Recycled Concrete Aggregate (CRCA) as an alternative for coarse natural aggregate in asphalt mixtures within Ontario specifications. To achieve this, the research' objective is divided into five major goals. The first goal is to enhance the physical and mechanical properties of different CRCA types by combining different types of treatment methods. The second main objective is the assessment of surface microstructure of different CRCA types. The effects of different treatment types on the morphological and mineralogical properties of the CRCA surface such as surface texture, roughness, surface morphology and chemical composition are examined. The influence of different treatment types on the interfacial transition zone (ITZ) is also extensively studied. Volumetric properties of hot mix asphalt (HMA) are necessary requirements to ensure good performance for asphalt mixtures. Therefore, the third major objective is the evaluation of volumetric properties of asphalt mixtures that include

CRCA addition. The fourth main objective is the assessment of the application of treated and untreated CRCA of two different types in typical Ontario HMA mixtures, whereas the fifth main objective is to investigate a simple cost and statistical analysis for different mixtures that include various untreated and treated CRCA.

Different types of treatments were performed under various conditions to evaluate each type of treatment separately, then the combinations of various treatments were tested. In order to achieve the objective, pre-soaking and heat treatment followed by different types of short mechanical treatment were conducted to evaluate the physical and mechanical properties of CRCA before and after the treatment method combination. Heat treatments were conducted at the following temperatures: 250 ºC, 350 ºC, 500 ºC and 750 ºC. The pre-soaking method involved the use of strong acid HCl and weak acid $C_2H_4O_2$, whereas short mechanical treatment included the utilization of a Micro-Deval device with two different testing techniques with/without steel balls. To evaluate the surface characterization of the CRCA surface of both treated and untreated CRCA, various advanced techniques were performed: Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Microanalyzer (EDAX), X-Ray Diffraction Analysis (XRD). The performance of typical Ontario asphalt mixtures for usage in a Superpave (SP) SP19 with various percentages of CRCA (0%, 15%, 30%, and 60%) was evaluated using many laboratory tests such as indirect tensile test (ITS), dynamic modulus test, rutting and thermal stress restrained specimen test (TSRST) test.

Compared to Natural Aggregate (NA), the obtained results indicated that RCA has inferior physical and mechanical properties. RCA has a lower Bulk Relative Density (BRD), higher water absorption, and higher porosity than NA. With respect to the mechanical properties, RCA has a higher abrasion loss and Aggregate Crushing Value (ACV) than NA. In these properties, a significant difference is observed between different CRCA types. The amount of adhered mortar and the original source of RCA have a considerable effect on these properties. The use of heat treatment method is highly successful in improving various physical and mechanical properties. For different CRCA types, the heat treatment has the maximum influence at 350 °C, which results in lower absorption with an approximate decrease of 9.5% and 11.23% for CRCA#1 and CRCA#2, respectively and decreased porosity with an approximate reduction of 8% and 10.3% for CRCA#1 and CRCA#2, respectively. However, it is recommended to use this method at temperatures between 300 °C and 350 °C because of the noticeable negative effects of higher temperatures on the CRCA properties. The acid treatment at low concentration is an effective technique to enhance the quality of CRCA depending on the acid type due to corrosive influence on the attached mortar. Nevertheless, it is concluded that using weak acid is more efficient than the strong acid to decrease the influence of acid attacks on the CRCA surface as demonstrated by the characterization images.

In terms of water absorption, the combination of heat treatment at 300 °C and short mechanical treatment leads to a reduction of 30% and 23.0% for CRCA#1 and CRCA#2 respectively, whereas, the application of the pre-soaking with the weak acid solution and short mechanical method results in a reduction of 22.5% and 37% for CRCA#1 and CRCA#2, respectively. With respect to the porosity, a significant reduction, approximately 26%, and 20.9%, is recorded for CRCA#1 and CRCA#2 respectively after applying the combination of heat treatment at 300 °C and short mechanical treatment, whereas the combination of pre-soaking in acetic acid method and the same mechanical treatment leads to a substantial decrease with an approximate reduction of 19.4% and 33.5% for CRCA#1 and CRCA#2 respectively.

The observations of SEM and EDAX tests indicated that the surface morphology of untreated CRCA is a rough and heterogeneous surface and a highly porous structure, whereas the surface of treated CRCA is more homogeneous and exhibits less adhered mortar depending on treatment type. A significant enhancement of CRCA microstructure was obtained under influence various treatment types. However, improved microstructure mainly includes increased density, increased surface homogeneity, reduced pore size, reduced Ca/Si ratio, and improved properties of ITZ microcracks including width and length of microcracks. There was a significant negative impact of heat treatment within a temperature range of (350-500 °C) due to a considerable increase of pore size compared with untreated CRCA.

The obtained results indicated that the optimum asphalt content (OAC), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) decrease as the filler content is increased. For control mix, the addition of filler with 2.5% percentage is very successful due to satisfying all Ministry of Transportation Ontario (MTO) requirements for volumetric properties of HMA. The NA replacement by CRCA leads to increasing the OAC for the mixtures, whereas the VMA and VFA are decreased. Compared to the mixture with 30% untreated CRCA, a small improvement and a slight increase in VMA and VFA properties, respectively, were seen for mixtures with 30% treated CRCA with different treatment techniques. The CRCA addition with different proportions is very successful for both untreated and treated CRCA due to achieving all MTO requirements for volumetric properties of HMA. However, CRCA treated with various treatment methods appears to be more successful than untreated CRCA application.

The addition of different types of untreated CRCA in various proportions produces higher rutting resistance and higher stiffness modulus than the control mix. The CRCA type has an effect on the rutting characteristics of asphalt mixtures. The application of treated CRCA with heat treatment and short mechanical treatment leads to an increase in the rutting resistance, a decrease in the total rut depth, a slight increase in the stiffness modulus, and an increase in the rutting factor of asphalt mixtures depending on the type of CRCA. The application of treated CRCA with the pre-soaking method and short mechanical treatment results in an increase in the stiffness and rutting factor of mixtures, depending on the type of CRCA.

The findings demonstrated that the mixtures that included untreated CRCA have much higher ITS values than the control mix, registering a significant increase of 68%, 70%, 85.6% and 86.7%, for the mixtures that included 30% untreated CRCA#1 and CRCA#2 in both unconditioned and conditioned samples, respectively. This is followed by the ITS values of the mixtures that included 60% untreated CRCA#1 and CRCA#2 for both unconditioned and conditioned samples with an increase of 41.4%, 49.0%, 71.5%, and 56.8%, respectively. Additionally, a reasonable improvement in the ITS values in both conditioned and unconditioned samples were recorded for the mixtures that included 30% treated CRCA with different treatment techniques compared to the mixture that included 30% untreated CRCA. Furthermore, all tensile strength ratio (TSR) values for mixtures that included untreated CRCA with different types and percentages are higher than the minimum required value of MTO specifications. This indicates a successful application for CRCA in these mixtures. The use of the combination technique of pre-soaking method with weak acid followed by a short mechanical treatment method was a highly successful method for enhancing moisture resistance of asphalt mixtures as compared to other combination methods.

From TSRST test, the findings indicated that the fracture temperature is reduced due to the CRCA addition compared to the control mix. However, there is no significant influence for the RCA type on the thermal cracks at low temperatures. Additionally, the fracture stress of the mixtures that included different untreated CRCA types with various proportions is generally higher than the fracture stress of the control mix

Furthermore, the application of the combination of various treatments leads to a significant reduction in the fracture temperature, indicating a successful application of treated CRCA in HMA mixtures in cold regions. However, the combination of heat at 300 °C and short mechanical treatment has a considerable impact on the fracture temperature of asphalt mixtures as compared to other combination techniques.

The results of ANOVA statistical analysis showed that the type of CRCA had a significant effect on the stiffness and rutting, ITS, and the fracture temperature of asphalt mixtures. Additionally, the type of treatment method had a considerable effect on the stiffness, rutting, and fracture temperature of HMA mixtures. In contrast, both the type of treatment method and the type of CRCA have an insignificant effect on the fracture stress of asphalt mixtures. The results of cost analysis revealed that both heat and pre-soaking treatment is quite reasonable, referring to many economic benefits and indicating that these treatment methods could be applicable. In conclusion, the results of this study indicate that the application of different CRCA types in various forms: treated and untreated is very successful and can contribute greatly towards more RCA applications in the asphalt pavements.

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Dedication

This thesis is dedicated to:

My husband and children, for them all the thanks and warm love in the world.

My parents, I owe them my life and my success.

My sisters and brothers with all thanks.

The beloved homeland "Iraq".

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LIST OF ABBREVIATIONS

AASHTO	American association of state highway and transportation officials
AC	Asphalt concrete
ACV	Aggregate crushing value
AFm	Monosulfate
AFt	Sulfoaluminate hydrate (ettringite)
Al/Ca	Aluminum to calcium ratio
ANOVA	Analysis of variance
ARO	Aggregate recycling Ontario
ASTM	American standards and test methods
BRD	Bulk relative density
BS	British standard
C&D	Construction and demolition
$C_2H_4O_2$	Acetic acid
C3AH6	Hydrogarnet
Ca	Calcium
Ca/Si	Calcium to silicon ratio
CAH	Tricalcium aluminate hydrate
CaO	Calcium oxide
CH	Calcium hydroxide
CO_2	Carbon dioxide
COV	Coefficient of variation
CPATT	Centre for pavement and transportation technology
CRCA	Coarse recycled concrete aggregate
CSA	Canadian standards agency
CSCE	Canadian society for civil engineering
CSH	Calcium silicate hydrate

CTAA	Canadian technical asphalt association
D	Sample diameter
Dp	Dust to binder ratio
EDAX	Energy dispersive X-ray microanalyzer
EEA	European environment agency
FRCA	Fine recycled concrete aggregate
Gmb	Bulk specific gravity
Gmm	Theoretical specific gravity
$\mathbf{H_2SO_4}$	Sulphuric acid
$\mathbf{H_3PO_4}$	Phosphoric acid
HCl	Hydrochloric acid
HMA	Hot mix asphalt
HPC	High performance concrete
HWRT	Hamburg wheel rut test
ITS	Indirect tensile test
ITZ	Interfacial transition zone
LA	Los Angeles
LVDT	Linear variable differential transducer
MNRO	Ministry of natural resources Ontario
MSW	Municipal solid waste
MTO	Ministry of transportation of Ontario
NA	Natural aggregate
NCA	Natural coarse aggregate
$\mathbf{N_{des}}$	Design gyration level
NFA	Natural fine aggregate
$\mathbf{N_{max}}$	Maximum gyration level
NMS	Nominal maximum size
NSC	Normal strength concrete

OAC	Optimum asphalt content
^{o}C	Celsius degree
PC	Portland cement
RA	Recycled aggregate
RBM	Reclaimed building materials
RCA	Recycled concrete aggregate
SCC	Self-compacting concrete
SEM	Scanning electron microscopy
SGC	Superpave gyratory compactor
SG_{SSD}	Specific gravity of saturated surface dry
Si	Silicon
SS	Sum of squares
SSD	Saturated surface dry
t	Sample thickness
TAC	Transportation association of Canada
TGA	Thermal gravimetric analysis
TRB	Transportation research board
TSR	Tensile strength ratio
TSRST	Thermal stress restrained specimen test
UNSD	United Nations statistics division
Va	Air voids
Vb	Asphalt binder volume
VEAC	Volume effective asphalt binder
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregates
Vs	Aggregates volume
VTM	Voids in total mix
Vv	Void volume

WATL	Waterloo advanced technology laboratory
WCED	World commission on environment and development
WMA	Warm mix asphalt
W_{OD}	Weight of oven dry
W_{SSD}	Weight of saturated surface dry
XRD	X-ray diffraction analysis

UNITS

g	Gram
hr	Hour
Hz	Frequency
kg	Kilogram
kN	Kilonewton
kPa	Kilopascal
kV	Kilovolt
M	Molar concentration
mA	Milliampere
min	Minute
mm	Millimeter
N	Newton
s	Second
MPa	Megapascal
µm	Micrometre

CHAPTER 1
INTRODUCTION

In this chapter, the main parts have been published in two journals: Construction and Building Materials (Al-Bayati et al., 2016) and Resources, Conservation & Recycling Journal (Al-Bayati et al., 2016).

1.1 Background

For the construction of road pavements throughout the world, one of the essential materials required is asphalt mixture (Liu et al., 2017). Asphalt mixture can be categorized as a complex mixture that consists of three main phases: aggregate, binder, and air voids. Additionally, various additives including fibers and polymers are generally utilized for enhancing its performance (Poulikakos et al. 2017). However, asphalt mixture is mainly composed of approximately 95% aggregate and 5% asphalt binder materials. In asphalt pavement, the aggregate particles represent a structural framework (skeleton) for the mixture, whereas, the asphalt binder works like a sticky substance. It was estimated that one kilometre of road approximately 150 mm thick and 10 m wide needs roughly 3750 tonnes of hot mix asphalt (HMA) mixture, whereas another study showed that a kilometre of pavement construction required 12,500 tonnes of natural aggregate (NA) (Zoorob and Suparma, 2000; Ektas and Karacasu, 2012).

In terms of natural resources, NAs are quickly becoming exhausted worldwide due to an overwhelming demand for raw materials. It is estimated that the consumption of the construction industry worldwide for raw materials is approximately 3000×10^6 tonnes per year. This represents twice the required quantity for any other industry (Pacheco-Torgal & Labrincha, 2013). In the province of Ontario, Canada, the average consumption of aggregate reached approximately 179 million tonnes per year in Ontario during the period of 2000-

2009, while this average is projected to amount to approximately 191 million tonnes between 2020 and 2029 according to the ministry of natural resources Ontario (MNRO, 2010). Therefore, this would lead to a critical shortage of NAs in Ontario and similarly in other Canadian provinces and in other countries worldwide. Additionally, the manufacturing process of concrete and its main constituent, Portland cement (PC), releases massive amounts of various pollutants including carbon dioxide, sulfur compounds and nitrogen compounds that are responsible for serious environmental pollution (Mukharjee & Barai, 2014). For instance, the manufacture of one ton of PC leads to the release of nearly one ton of carbon dioxide into the environment depending on the type of production process (Demie et al., 2013).

Simultaneously, tremendous amounts of construction and demolition (C&D) waste are generated from various human activities including but not limited to construction, renovation and the demolition of aged buildings and civil engineering structures. Recently, the amount of C&D waste generated annually has been estimated at 1,183 million tonnes worldwide (Purushothaman et al., 2014).

The solid waste material consists of a significant proportion of construction debris, which is the result of C&D works. Among different types of C&D wastes, concrete is the most significant component, which makes up a considerable proportion of the total C&D wastes as shown in Table 1-1. The management of these huge waste quantities is becoming a serious challenge especially for large urbanized areas because of the continuous increase in waste quantities, shortage of dumping sites, and cost increases in transportation and disposal.

Due to the above factors, the accumulation of these large quantities is related to serious environmental concerns such as pollution and environmental deterioration (Rafi et al., 2011). Moreover, with the existence of a global critical shortage of NA sources (Ismail and Ramli, 2013; Güneyisi et al., 2014), concrete waste disposal in landfill sites is not a feasible and sustainable solution (Hossain et al., 2016).

To solve various problems including lowering the consumption of virgin materials, decreasing waste materials in landfills (Hossain et al. 2016; Jin et al., 2017) and reducing environmental problems, the utilization of recyclable waste materials, especially recycled concrete, as a sustainable solution has become highly required and an urgent priority in the asphalt industry.

Table 1-1: Composition of Construction Waste in South-East New Territories Landfills (Arabani et al., 2012).

Waste type	Construction site (%)	Demolition site (%)	General civil work (%)	Renovation work (%)
Metal	4	5	10	5
Wood	5	7	0	5
plastic	2	3	0	5
Paper	2	2	0	1
Concrete	**75**	**70**	**40**	**70**
Rock/Rubble	2	1	5	0
Sand/Soil	5	0	40	0
Glass/Tile	3	2	0	10
Others	2	10	5	4
Total	100	100	100	100

1.2 Problem Statement of the Research

Construction waste materials are increasing due to the rising demand for new highways, commercial buildings, housing developments, and infrastructure projects. Unless recycled properly, these large amounts of waste end up in landfills every year, and natural resources are being depleted rapidly because of a tremendous demand for raw materials (Bolden, 2013). Nowadays, recycled concrete aggregate (RCA) obtained from C&D waste has become a valuable resource as an alternative solution to NAs (da Conceição Leite et al., 2011). Due to the lack of NA resources, the use of recycled concrete in different civil construction works has become widespread in Europe and countries such as Singapore, Japan, and Australia for more than 20 years (Paranavithana & Mohajerani, 2006).

RCA is a composite material, wherein NAs (65-70%) are coated by an adhered mortar layer (30-35%) and can be produced from the crushing of the hunks of concrete into smaller pieces (Paranavithana and Mohajerani, 2006; Kong et al., 2010; Ismail and Ramli, 2013). The type of crushing method can have an influence on the shape and texture of the produced RCA

(Güneyisi et al., 2014). The particle size, the strength of the original concrete and the crushing process have an impact on the percentage of adhered mortar in RCA (Akbarnezhad et al., 2011; Spaeth and Tegguer, 2013). The quality and the amount of adhered mortar are also major factors, which may have an effect on the physical properties of RCA (Spaeth and Tegguer, 2013). In addition, tiny cracks that appear during the crushing process, and weak adhesion between mortar and aggregate are the other important factors (Lee et al., 2012; Tam et al., 2007). These factors, therefore, play an important role in making RCA a poor-quality substitute compared to NA (Lee et al., 2012; Pérez et al., 2012).

The properties of RCA are different from those of NA due to the existence of an adhered mortar layer on the surface of the RCA (Behring, 2013). RCA is generally rough, porous, flat and irregular, but in particular, it is characterized by a lower bulk and specific gravity, and a significantly higher water absorption, which results in inferior mechanical properties (Malešev et al., 2010; Lee et al., 2012; Pepe et al., 2014). The higher porosity characterizing the adhered mortar layer is the main reason behind this behavior (Pepe et al., 2014).

As a result, the general major reason for poor quality for RCA appears to be due to the adhered mortar layer, which is more porous and less dense than crushed stone (Tam et al., 2007; Gul, 2008; Lee et al., 2012; Pérez et al., 2012), while the porosity of RCA is the main specific reason. These characteristics have become restrictions for using RCA in some applications.

1.3 Research Approach

The application of RCA is more than just the use of a low-quality material in asphalt mixtures. To obtain a successful application, various aspects must be taken into account. Some of these issues are related to RCA itself and others are connected to asphalt mixtures. Figure 1.1 shows the conceptual framework of the possible related aspects of RCA-asphalt mixtures. The main approach of this research was concentrated on testing and comparing the performance effects of typical Ontario HMA mixtures containing different percentages of RCA from different sources. The fundamental principle behind the use of RCA in asphalt mixtures was that increasing the quality of RCA can significantly improve the performance of HMA so that it can withstand the combined stress of traffic and the environment. The main approach of the study is divided into many sub-approaches. Different approaches have been followed to make this research more practical. Brief explanations for each approach are described as follows.

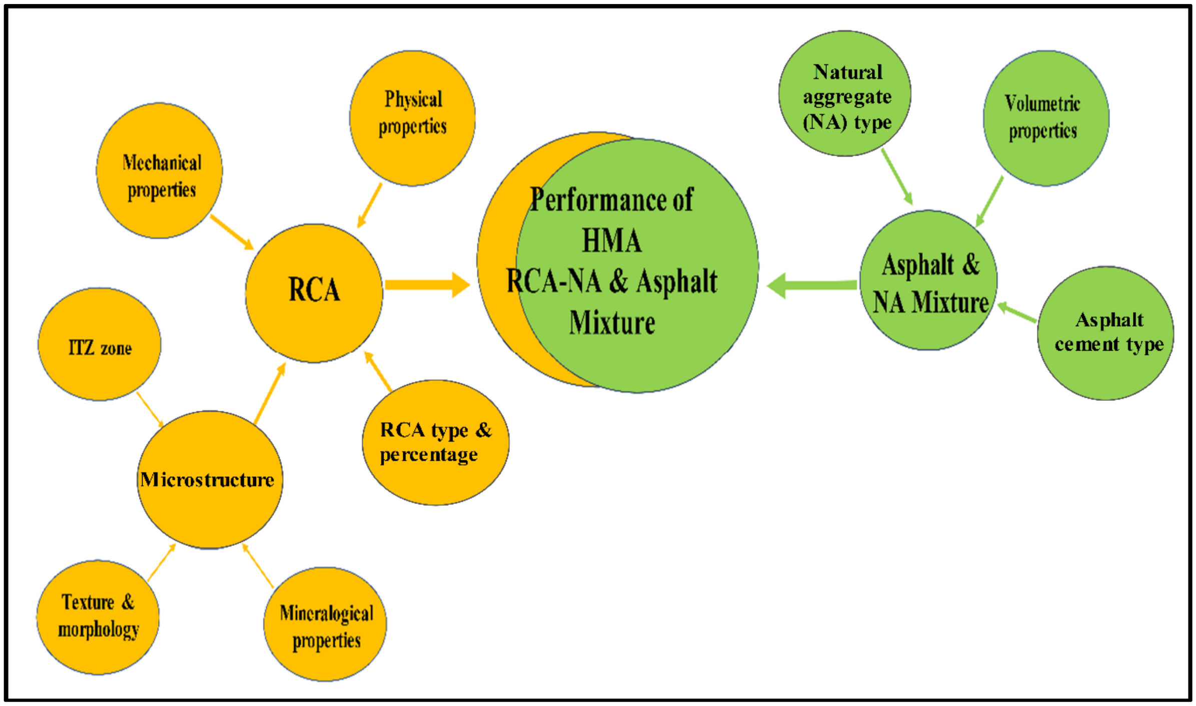


Figure 1.1: Schematic diagram for various aspects of RCA-asphalt mixtures.

It is generally accepted from the literature that the amount of adhered mortar in coarse recycled concrete aggregate (CRCA) is lower than in fine recycled concrete aggregate (FRCA) (De Juan & Gutiérrez, 2009; Akbarnezhad et al., 2013). This means that CRCA is of higher quality than a fine fraction of recycled aggregate, and in this way, it seems reasonable to work towards increasing the quality of a material that has a relatively high quality, rather than attempt to work with a poor-quality material. For this reason, the present research is mainly focused on the CRCA fraction. Hence, this route was considered as the first sub-approach of the research.

It is obvious that the performance of HMA made with RCA is going to be affected by the properties of RCA which are different, more precisely, inferior, compared to those of NAs. Additionally, performance is also affected by the RCA content that can range between 0% and 100%. Therefore, the second sub approach concentrates on performing various types of treatments under different conditions to improve the physical and mechanical properties of CRCA. Various treatment methods were conducted under different conditions to evaluate each type separately, then the combinations of different treatments were tested. In order to achieve the objective, pre-soaking method, heat treatment followed by different types of short mechanical treatment were performed to evaluate the physical and mechanical properties of CRCA before and after the treatment method combination.

It is well known from the literature that concrete is a highly complicated structure at the microstructural level, consisting of three regions, namely aggregate, cement paste and an interfacial transition zone (ITZ) (Kong et al., 2010), which is classified as the weakest region among the other concrete components (Otsuki et al., 2003). Therefore, microstructure enhancement of the RCA surface or ITZ zone can contribute to improved physical and mechanical properties of RCA. Thus, the third sub-approach examines the effect of the above-mentioned treatments on the ITZ zone and morphological and mineralogical characteristics of the CRCA surface such as texture and roughness for surface morphology and chemical composition of the surface, and calcium to silicon (Ca/Si) ratio for surface mineralogy. In order to achieve surface characterization, the CRCA surface of both of the treated and untreated CRCA, different advanced techniques were used such as Scanning Electron Microscopy (SEM), X-Ray Diffraction Analysis (XRD) and Energy Dispersive X-ray Microanalyzer (EDAX) to evaluate surface characterization.

It is known that asphalt mixture design requires highly accurate amounts of both aggregate and asphalt to obtain certain requirements of volumetric and mechanical properties (Anderson & Bahia, 1997). Therefore, the volumetric properties are considered a key factor for achieving optimum performance of the asphalt mixtures. The fourth sub-approach investigates the influence of filler with different proportions to obtain the optimum percentage that can achieve successful volumetric properties for a mixture that includes only NA, within the acceptable requirements of Ministry of Transportation of Ontario (MTO) specifications. This mix represents a reference mixture which was compared with different mixtures that included both untreated and treated CRCA.

Before adding treated CRCA into asphalt mixtures, a criterion was been developed to select the best treatment method and its condition and/or its property among various treatment method types and different conditions and was combined with a mechanical method to assess the main characteristics of CRCA. Then, the treated CRCA with the combination of the best treatment method and a mechanical treatment was added to gain successful volumetric properties for asphalt mixtures. This is the fifth sub-approach of research.

After obtaining successful volumetric properties for asphalt mixtures that included different percentages of both treated and untreated CRCA, performance tests were carried out to evaluate the mechanical properties of HMA that included different types and percentages of both treated and untreated CRCA. The performance of asphalt mixtures with different percentages of CRCA was tested by many laboratory tests such as indirect tensile test (ITS), dynamic modulus test, thermal stress restrained specimen test (TSRST), and rutting test to evaluate the performance of these mixtures. As water absorption is a main problematic issue for RCA, the sub approach was also focused on the impact of the moisture damage phenomenon on the asphalt mixtures that included both treated and untreated CRCA. This pathway is considered to be the sixth sub-approach.

1.4 Research Hypotheses

The hypotheses of this research are as follows:

- There is a considerable difference between NA and untreated CRCA in terms of physical and mechanical properties.
- The use of heat treatment method is successful in improving physical properties such as water absorption and density due to removed water molecules from hydrated compounds.

This results in forming new compounds, which enhance weak areas and improve physical properties.

- The acid treatment at low concentration is an effective technique to enhance the quality of CRCA depending on the acid type due to corrosive influence on the adhered mortar, which is dissolved into acid solution and leads to successful removal of the mortar layer.
- The use of mechanical methods after both heat and chemical treatment definitely help to increase the amount of adhered mortar removal due to collision and high friction especially with the presence of steel balls in the Micro-Deval device. Therefore, the combination of various treatment types seems to be more effective than using each method separately.
- The SEM, EDAX and XRD techniques are capable of accurately identifying the morphological and mineralogical properties of CRCA such as surface texture, roughness, and chemical composition. This information is extremely helpful for understanding different factors that relate to the microstructure of surfaces and affect or enhance the physical properties of CRCA. Therefore, advanced techniques are very beneficial for studying the CRCA surface.
- The optimum asphalt content and bitumen absorption for asphalt mixture with CRCA are increased with rising CRCA content in the mixture.
- The utilization of CRCA in HMA mixtures has produced stiffer mixtures, resulting in increased resistance of mixtures to permanent deformation.
- The moisture susceptibility of asphalt mixtures with CRCA is a highly complicated issue due to diverse factors such as natural aggregate type and CRCA. Therefore, the behavior of moisture susceptibility is unpredictable for these types of mixtures.
- Mechanical properties of HMA mixtures such as permanent deformation, thermal cracks, tensile strength and stiffness for asphalt mixtures with treated CRCA seem to be promising due to the influence of combinations of different treatment types on CRCA properties.

1.5 Research Objectives

The overall objective of this research is to evaluate the use of CRCA as an alternative for natural coarse aggregates in HMA within Ontario specifications. The research consists of five major objectives that include many sub-objectives as in the following:

❖ The first major objective is the evaluation of enhancing physical, mechanical properties, and surface microstructure of two different CRCA types.

- Evaluate the effect of various treatment types under different conditions separately regarding the physical and mechanical properties of different types of CRCA. Heat treatments were conducted at various temperatures: (250 ºC, 350 ºC, 500 ºC, and 750 ºC). The pre-soaking method involved the use of strong acid hydrochloric acid (HCl) and weak acid acetic acid ($C_2H_4O_2$) at low concentration whereas short mechanical treatment included the utilization of a Micro-Deval device to achieve treatment with/without steel balls.
- Investigate the ability of the combination of different types of treatment methods to enhance the physical properties of different types of CRCA such as water absorption and specific gravity and others. The heat treatment and pre-soaking method followed by short mechanical treatment included the utilization of a Micro-Deval device to achieve two different treatment types with/without steel balls are used to evaluate the combination of various treatment types.
- Examine the effects of different treatment types on the morphological and mineralogical properties of the CRCA surface such as surface texture, roughness, and chemical composition using various advanced techniques such SEM, XRD, and EDAX. Surface characterization is conducted for both treated and untreated CRCA.
- Examine the effect of different treatment types on the ITZ zone using the above-mentioned techniques.

❖ The second major objective is the evaluation of volumetric properties of asphalt mixtures.

- Examine the effect of filler with different proportions on the volumetric properties of HMA to obtain the optimal percentage for a mixture with a 0% CRCA that successfully meets the requirements of MTO specifications. This represents a reference mixture for comparison with different mixes that include various CRCA types with different proportions.

- Investigate the influence of CRCA on the volumetric properties of asphalt mixtures.

❖ The third main objective is the assessment of the application of treated and untreated CRCA for two different types in typical Ontario HMA mixtures.

- Examine the performance of HMA mixtures that included various CRCA types with different proportions. Different CRCA percentages are added to asphalt mixtures. The performance of asphalt mixtures is evaluated by various laboratory tests such as the indirect tensile test, dynamic modulus test, thermal stress restrained specimen test and rutting test.
- Explore the impact of CRCA on moisture damage in asphalt mixtures that include various CRCA types with different proportions.

❖ The fourth main objective is to investigate a simple cost and statistical analysis for different mixtures that includes various untreated and treated CRCA.

1.6 Significance of Research

Until now, little research has been done on the use of RCA waste in HMA, even though it is probably more appropriate as an aggregate in asphalt paving (Aljassar et al., 2005; Wong et al., 2007; Chen et al., 2011; Pérez et al., 2012; Lee et al., 2012). This is because of the clear difference between RCA and the NA which is the presence of adhered mortar on the surface of the original NAs after the crushing process of recycled concrete (Paranavithana and Mohajerani, 2006; Gul, 2008; Shen and Du, 2005). In Ontario, there are no effective studies or viable efforts for using RCA in asphalt mixtures. The Canadian construction industry until now still hesitates to use RCA as a replacement for NA in concrete due to two issues: there is no willingness from engineers and asphalt suppliers to assume a risk which is related with the quality of a material and there is a lack of technical and field data (Butler, 2012). Earlier, there was no support from the MTO for recycled aggregate in different applications due to the above-mentioned reasons. Then later, MTO stimulated the application of blending aggregates that consist of NA and recycled aggregate for only the base and sub-base of pavement construction (Huda, 2014). The application of RCA is very limited, with only a 3% utilization rate in Ontario (Huda, 2014).

From this research, various benefits are obtained that can be summarized as the following:

- Participation in the reduction of natural resource usage, precisely NA, for various construction industry works.
- The findings of the research lead to release the pressure on landfill sites towards more RCA applications that are generated from C&D waste.
- The obtained findings of the study provide a better understanding of RCA, and remove the hesitation related to RCA applications.
- The research findings can provide more understanding related to both physical and mechanical characteristics of RCA in terms of measurements and evaluation.
- The study can contribute to provide more knowledge related to different microstructure aspects such as surface morphology and surface mineralogy.
- The study can participate to encourage various sectors such as research centres and relevant companies towards more RCA applications especially asphalt mixtures.

1.7 Organization of Thesis

This thesis is organized according to the general guidelines of the Graduate Studies at the University of Waterloo. It is formatted into sixteen chapters. Chapter one introduces the study, problem statement of research, and research approach. It also includes the research hypotheses and objectives, significance of the research, and organization of the thesis. Chapter two reviews the literature related to the properties and current practices of recycled concrete aggregate. It also presents the treatment types that are currently used for enhancing properties of RCA with intention to identify existing research gaps and opportunities for innovation. Chapter three discusses the proposed research methodology and describes the laboratory testing protocols for both RCA and asphalt mixes that are used in this study. The influence of different treatment types separately on the physical and mechanical properties of CRCA is demonstrated in chapter 4, whereas the impact of the combination of various treatment types on enhancing the physical and mechanical properties of CRCA are explained in chapter 5. Chapter 6 demonstrates the effect of various treatments on the surface morphology, surface texture, and surface mineralogy of CRCA. The behaviour of different microstructure properties including pore size, matrix cracks, and matrix crack density under the effect of different treatments is discussed in chapter 7. Chapter 8 explains the impact of various treatments on ITZ microstructure in terms of ITZ microcracks. Both aggregate side and mortar surface of the ITZ zone are evaluated for ITZ improvement using Ca/Si ratio as an indicator for the mentioned improvement. Chapter 9 explains the obtained findings of the effect of various treatment techniques on ITZ improvement. Two different assessment types: general and specific evaluation are followed for ITZ improvement. While the general assessment is applied using surface morphology and Ca/Si as indicators for such improvement, the specific evaluation is followed using the main CSH compounds, namely: tobermorite and jennite, as an index for ITZ improvement. Chapter 10 demonstrates the influence of various filler percentages on the volumetric properties of asphalt mixtures to obtain the optimum filler proportion that successfully satisfies MTO requirements. Chapter 11 explains the impact of various CRCA types with different proportions on the volumetric properties of asphalt mixtures that meet the MTO specifications. Chapter 12 presents the impact of recycled concrete aggregate addition on the rutting and stiffness properties of asphalt mixtures such as permanent deformation and stiffness modulus. Chapter 13 displays the influence of recycled concrete aggregate addition on the moisture susceptibility of asphalt mixtures in terms of ITS and tensile strength ratio (TSR). Chapter 14 demonstrates the effect of recycled concrete aggregate addition on low temperature cracking in terms of fracture temperature and fracture stress. In all performance evaluation chapters, statistical aspects such as standard deviation and coefficient of variation are evaluated for various mixtures. In addition, one-way and two-way ANOVA analyses are carried out for various asphalt mixtures to investigate the impact of many factors on the various aspects of mixture evaluation indicators such as rutting, complex modulus, and TSR. In addition to these chapters, chapter 15 demonstrates an evaluation of cost analysis carried out for various asphalt mixtures that include untreated and treated CRCA with different treatments. Chapter 16 presents the major conclusions of this research that focused on the feasibility of the application of different types of untreated and treated CRCA with different treatments at various proportions in the conventional Ontario HMA mixtures. Additionally, the recommendations and future research are also provided in this part based on the obtained findings of this study.

1.8 List of Publications

1.8.1 Journal Papers

1. Al-Bayati, H. K. A., Das, P. K., Tighe, S. L., & Baaj, H. (2016 a). Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. *Construction and Building Materials*, *112*, 284-298.

2. Al-Bayati, H. K. A., Tighe, S. L., & Achebe, J. (2018). Influence of recycled concrete aggregate on volumetric properties of hot mix asphalt. *Resources, Conservation and Recycling*, *130*, 200-214.

3. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Effect of recycled concrete aggregate on rutting and stiffness characteristics of asphalt mixtures. *Journal of Materials in Civil Engineering.* The paper has accepted for publication.

4. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Evaluation of ITZ Improvement of Recycled Concrete Aggregate and its Influence on the Performance of Hot Mix Asphalt. *Journal of Materials in Civil Engineering*. Under review.

1.8.2 Conference Paper

1. AL-Bayati, H. K. A., & Tighe, S. L. (2016). Effect of different treatment methods on the interfacial transition zone microstructure to coarse recycled concrete aggregate. *Annual Conference of the Transportation Association of Canada Proceedings, Ontaro, Canada, September 25 – 28, 2016.*
   http://www.tac-atc.ca/sites/default/files/conf_papers/al-bayati-2.pdf

2. AL-Bayati, H. K. A., Tighe, S. L., & Baaj, H. (2016 b). Utilizing a different technique for improving micro and macro characteristics of coarse recycled concrete aggregate, *Annual Conference of the Transportation Association of Canada Proceedings (TAC), Ontaro, Canada, September 25 – 28, 2016.*
http://www.tac-atc.ca/sites/default/files/conf_papers/al-bayati_.pdf

3. Al-Bayati, H. K. A., & Tighe, S. L. (2018). Influence of Coarse Recycled Concrete Aggregates on the Dynamic Modulus of Asphalt Concrete Mixtures. In *TAC 2018: Innovation and Technology: Evolving Transportation-2018 Conference and Exhibition of the Transportation Association of* Canada (TAC), Saskatoon, Saskatchewan. Retrieved from
https://www.tac-atc.ca/sites/default/files/conf_papers/al-bayatih-influence_of_coarse.pdf

4. Al-Bayati, H. K. A., & Tighe, S. L. (2018). Investigation of treated CRCA in HMA mixtures through evaluating low temperature cracking. In *CSCE 2018: Building Tomorrow's Society-2018 Conference and Exhibition Canadian society for civil engineering (CSCE).*
5. Al-Bayati, H. K. A., & Tighe, S. L. (2018). Evaluating the effects of mineral filler on the volumetric properties of HMA mixtures based on Superpave mix design specifications. In *CSCE 2018: Building Tomorrow's Society-2018 Conference and Exhibition Canadian society for civil engineering (CSCE).*
6. Al-Bayati, H. K. A., & Tighe, S. L. (2018). Effect of Recycled Concrete Aggregate on the Permanent Deformation of Asphalt Mixtures. In *CTAA 2018: Conference and Exhibition Canadian Technical Asphalt Association.*
7. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Investigation of the effect of recycled concrete aggregate on rutting and stiffness characteristics of asphalt mixtures. Presented at *The Transportation Research Board (TRB) 98th Annual Meeting in Washington, D.C.*
8. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Influence of coarse recycled concrete aggregate on the indirect tensile strength of hot mix asphalt. *In CSCE 2019: Growing with youth -2019 Conference and Exhibition Canadian society for civil engineering.*

1.8.3 Abstract

1. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Examining the Effect of Coarse Recycled Concrete Aggregate on Moisture Damage Resistance of Hot-Mix Asphalt Mixtures. Annual Conference of the Transportation Association of Canada Proceedings (TAC). The abstract has accepted.

CHAPTER 2
LITERATURE REVIEW

In this chapter, many paragraphs have been published in two different journals: Construction and Building Materials (Al-Bayati et al., 2016) and Resources, Conservation & Recycling Journal (Al-Bayati et al., 2018) while other paragraphs have been presented at various conferences.

2.1 Background

The consciousness of the need for sustainable development and preservation of non-renewable aggregate resources has been rising significantly in Ontario, throughout Canada and all over the world over the past 15 years. The increased cost of energy with this consciousness has contributed to make changes in the recycling and reuse ‘landfill’ resulting to considerable increase amounts of these materials which are finished into using in the transportation section (MNRO, 2009). Researchers of transportation believe that warm mix asphalt (WMA) and recycling of waste materials are examples of materials that will achieve the future sustainability in the asphalt highway industry (Mills-Beale & You, 2010).

Sustainability is defined according to the World Commission on Environment and Development (WCED) as *“Meeting the needs of the present without compromising the ability of the future generations to meet their own needs”* (Naik & Moriconi, 2005). For instance, the requirements of sustainable concrete construction development aim to achieve two main goals: reasonable use of natural materials and lowering environmental influence. The first goal is achieved by using waste materials and decreasing the extraction of NA, while the second is accomplished through decreasing carbon emissions (Naik & Moriconi, 2005).

2.2 Waste Materials

2.2.1 Definition

The word "waste" generally refers to undesirable or unusable substances. According to the definition from the Oxford Dictionary, waste is *"(of a material, substance, or by-product) eliminated or discarded as no longer useful or required after the completion of a process."* (Oxford Dictionary). In waste management perspective, there are many definitions for the term waste. However, these definitions have almost the same conception. Earlier, Basel Convention pointed out that *"Wastes are substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law"* (Basel Convention, 1989), whereas the United Nations Statistics Division (UNSD) stated that *"Wastes are materials that are not prime products (that is products produced for the market) for which the generator has no further use in terms of his/her own purposes of production, transformation or consumption, and of which he/she wants to dispose. Wastes may be generated during the extraction of raw materials, the processing of raw materials into intermediate and final products, the consumption of final products, and other human activities. Residuals recycled or reused at the place of generation are excluded."* (UN Statistics Division, 2011).

2.2.2 Classification of Waste Materials

Many types of human activities usually lead to the generation of waste because of the imperfect use of both energy and natural resources (Bartelings, 2003). However, economic growth, expansion of urbanization, and industrialization have led to a considerable increase in the quantities and types of generated wastes. Waste materials can be classified into different categories. The most popular classification is based on the source that generates waste. Figure 2.1 shows the types of waste according to the mentioned classification.

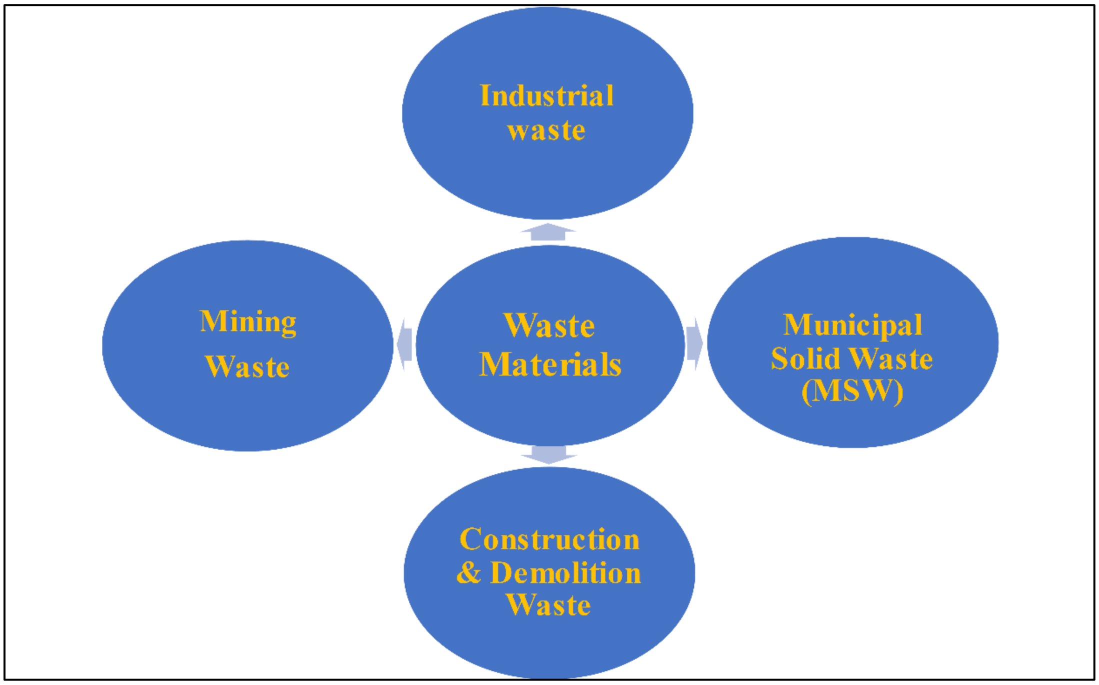


Figure 2.1: Classification of waste materials adopted from (Ahmedzade & Sengoz, 2009; Ektas & Karacasu, 2012; Pepe, 2015).

Globally, there are no accurate calculations for the quantities of wastes. However, there are estimations for some types of wastes. For instance, it is estimated that the global municipal solid waste (MSW) generation is approximately 1.3 billion tonnes per year, and it is expected to reach approximately 2.2 billion tonnes per year by 2025. According to Statistics Canada, the total amount of disposed of solid waste materials was around 26 million tonnes; it was equivalent to 777 kilograms per capita. This amount of waste registered an increase of 7 percent over 2002 as shown in Table 2-1. At the provincial level, the highest increase was recorded in Alberta with an increase of 39 percent, followed by New Brunswick with an increase of 16 percent. Nevertheless, Ontario recorded the highest provincial level of total waste disposal (Statistics Canada, 2012).

Table 2-1: Comparison of Solid Waste Disposal Based on Source, Canada, Provinces, and Territories between 2002 and 2008 (Statistics Canada, 2012)

	Residential Sources[1]		Non-Residential Sources[2]		Total Waste Disposal	
	2002	**2008**	**2002**	**2008**	**2002**	**2008**
				Tonnes		
Canada	8,446,766	8,536,891	15,634,606	17,334,419	24,081,371	25,871,310
Newfoundland and Labrador	216,218	216,992	160,376	193,598	376,594	410,590
Prince Edward Island	X	X	X	X	X	X
Nova Scotia	169,649	148,060	219,546	206,171	389,194	354,231
New Brunswick	203,506	233,703	210,100	245,758	413,606	479,461
Quebec[3]	1,875,235	2,052,182	3,971,225	4,105,970	5,846,459	6,158,152
Ontario	3,438,408	3,231,399	6,207,225	6,400,160	9,645,633	9,631,559
Manitoba	412,612	400,297	483,944	565,902	896,556	966,199
Saskatchewan	278,692	289,760	516,432	613,182	795,124	902,943
Alberta	866,398	958,539	2,023,896	3,070,895	2,890,294	4,029,435
British Columbia	929,101	960,472	1,758,781	1,851,097	2,687,882	2,811,568
Yukon, Northwest Territories and Nunavut	X	X	X	X	X	X

1. Residential non-hazardous waste disposal includes solid waste produced by residences that is picked up by the municipality using its own staff or through contracting firms or that is self-hauled to depots, transfer stations and disposal facilities.
2. Non-residential non-hazardous waste disposal includes solid waste produced by the Industrial, Commercial, and Institutional IC and I) sector and the Construction, Renovation and Demolition (CRD) sector. IC and I waste materials are generated by manufacturing, primary and secondary industries; commercial operations, such as, shopping centres, restaurants, offices, and others; and institutional facilities, such as, schools, hospitals, government facilities, seniors homes, universities, and others. CRD waste generally includes materials, such as, wood, drywall, certain metals, cardboard, doors, windows, wiring, and others, but excludes asphalt, concrete, bricks and clean sand or gravel and materials from clearing previously undeveloped land.
3. Waste disposal data for 2002 were derived from a survey administered by RECYC-QUEBEC.
Note(s): Total amount of non-hazardous waste disposal in public and private waste disposal facilities includes waste that is exported out of the source province or out of the country for disposal. This does not include waste disposal in hazardous waste disposal facilities or waste managed by the waste generator on site.
Source(s): Statistics Canada, CANSIM table 153-0041 (accessed July 18, 2011).

Additionally, the percentage of waste generation is highly variable from one sector to another. For example, the percentage of contribution of the municipal waste sector to the generation of waste is totally different from the energy and industry sectors. Therefore, the generated waste amount is highly dependent on the source of a sector that generates waste. Based on a study by the European Environment Agency (EEA), which included data gathered from the first 15 members of the European Union, the obtained data demonstrated that the construction and demolition sector is the highest contributor to the generation of waste with a percentage of 48% among different types of sectors. The services sector ranked the second largest contributor with a percentage of 17%, whereas the energy sector represented the lowest contribution of waste generation as shown in Figure 2.2 (Pepe, 2015).

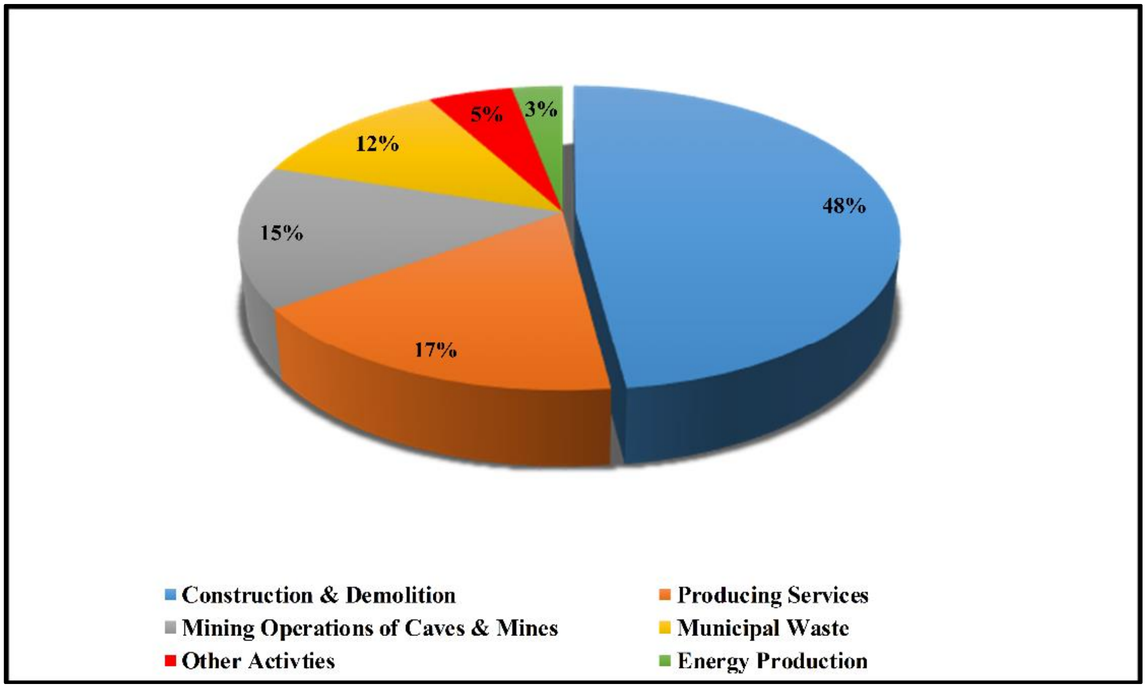


Figure 2.2: The percentage of waste generation for different sectors (Pepe, 2015).

2.3 Construction and Demolition Waste

Billions of tonnes of concrete are extensively consumed in the construction of different structures including buildings, bridges, dams, roads, and others. It was estimated that the world's concrete production ranges annually between 6 (Marinković et al., 2010; Van den Heede and De Belie, 2012) and 15 (Huda & Alam, 2014) billion tonnes, indicating 1 to 2 tonnes per person per year. To construct the above-mentioned structures, massive amounts of C & D waste are generated. More precisely, the amount of C & D waste generated was estimated to be approximately between 900 (Poulikakos et al. 2017) and 1,200 (Purushothaman et al., 2014) million tonnes worldwide. Optical images for different sources of C&D waste are presented in Figure 2.3 (a & b).

Figure 2.3: Different sources of C&D waste: (A) Concrete pavement, (B) Demolition building.

The management of these tremendous waste amounts is becoming a serious problem and an urgent priority at the levels of municipalities, cities, and countries. This is due to different reasons including the considerable increase of waste amounts, significant lack of sufficient landfills for the dumping of waste materials, and the large increase in transportation and waste disposal cost (Al-Bayati et al., 2018). Hence, the disposal of C& D waste into landfills is considered an unsustainable management option and an environmentally unfriendly solution due to serious environmental consequences (Hossain et al., 2016).

Generally, the term C&D is defined as a type of waste from different types of construction, renovation and demolition including land excavation, structure and building construction, site clearance, demolition works, roadwork and building renovation (Sandler, 2003; Shen et al., 2004; Nejad at el., 2013; Pacheco-Torgal & Labrincha, 2013). Concrete waste is usually processed using the crushing process for the local C&D waste to produce smaller particles of crushed concrete. Compared to the fine portion, the coarse portion of the produced crushed concrete is separated as the main product, generally known as RCA, of the crushing process (Wijayasundara et al., 2016). In Europe, the generated amount of C&D waste is approximately 850 million tons per year. This quantity accounts for 31% of the total amount of waste generated in Europe (Pepe, 2015). Annually, the quantity of generated C&D waste from the Canadian construction industry is approximately 9 million tonnes. The generated amount represents about one-third of the total solid waste in Canada (Yeheyis et al., 2013). However, Canada has a high percentage of civil infrastructures that will reach the end of their life span in the near future. Therefore, the quantity of C&D waste is expected to increase when this large portion of infrastructure is replaced **(**Huda, 2014)**.** Among different types of components of C&D wastes, concrete is the most significant component, which makes up a large portion of the total C&D waste. The C&D waste generally consists of 50% concrete waste by weight (Tam, 2008). Nevertheless, the percentage of concrete is highly variable depending on the source and location of C&D waste. In Hong Kong, Li (2002) found that the concrete proportions of different types of C&D wastes collected from various sites were 40% for a general civil work site, 70% for a demolition site, 70% for a renovation work site, and 75% for a construction site (Arabani & Azarhoosh, 2012). In addition to concrete, the C&D

waste also includes a wide range of materials including but not limited to bricks, tiles, ceramics, wood, glass, plastic, metals, and soil (Pacheco-Torgal & Labrincha, 2013; Pepe, 2015). The main components of C&D waste are displayed in Figure 2.4.

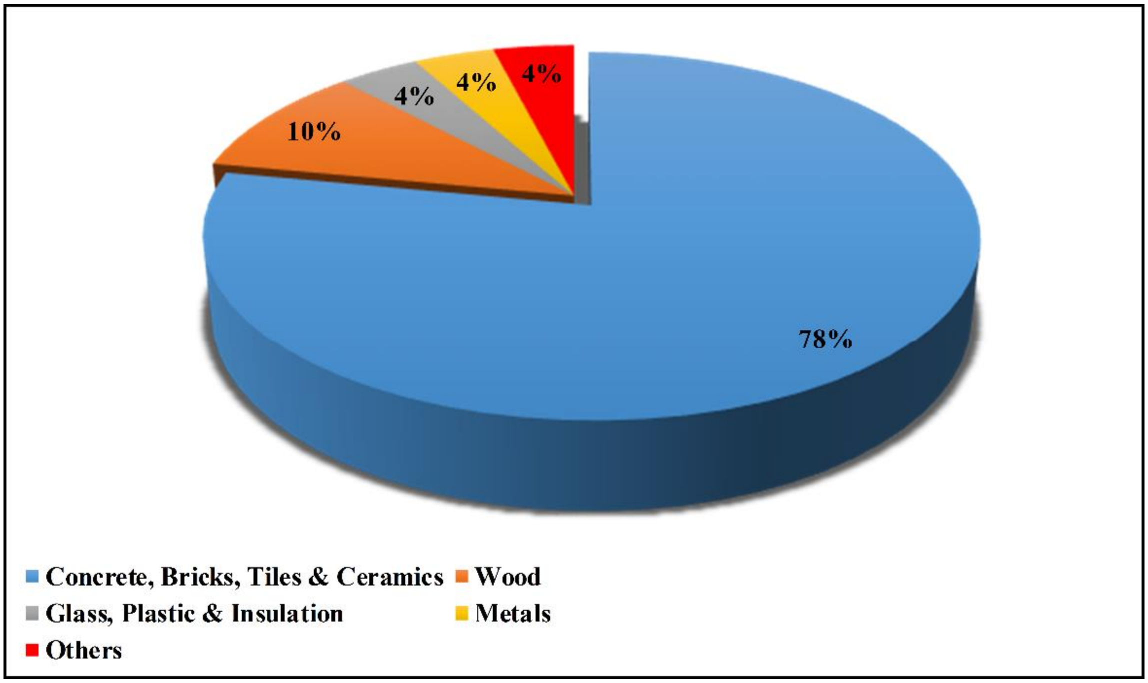


Figure 2.4: The common components and their portions in C&D waste (Pepe, 2015).

Various benefits are obtained by recycling and reusing C&D waste. However, the main advantages can be summarized as follows (Jin et al., 2017):

- Due to the reuse of materials, the consumption of natural resources, more precisely natural aggregates, will be reduced;
- Reduced need for more landfill space. In other words, the availability of space in landfills is increased;
- Lowered energy consumption and decreased greenhouse gas emissions, precisely, the carbon footprint of the concrete industry;
- Minimized serious health concerns related to C& D waste disposal;

- Participation at various levels including government strategies and industry standards for achieving environmental sustainability (Jin et al., 2017).

2.4 Production of RCA

RCA is a material that consists of high quality and well-graded aggregate ranging between 60%-75% and attached mortar layer. It also includes a proportion of asphalt material and sub-base soil materials from the shoulder or composite pavement accounting for 10%-30% approximately. Therefore, RCA can be represented as a type of mixture comprising diverse materials such as concrete, soil, small amounts of asphalt, and other debris that is removed from RCA (Behring, 2013). A picture for a type of RCA is shown in Figure 2.5.

Figure 2.5: Type of RCA produced from crushed concrete

Presently, the two main types of recycling methods which are used to produce recycled aggregate from construction and demolished concrete are the refining and replacing methods. Refining method includes RCA exposure to a high temperature, about 300°C, which causes the adhered mortar to become brittle. Then, by using rubbing crushed concrete, the adhered mortar can easily be separated from the original aggregate. The quality of original coarse aggregate which is produced by this method is comparable to natural coarse aggregate, and without losing integrity, because of a high-quality process. While produced aggregates from this method have good quality due to removing adhered mortar (which contributes to increasing strength for recycled concrete), the mechanical effect of the crushing process has a negative impact which results in cracks and voids. The main advantages of this method are preserving natural resources and reducing carbon dioxide (CO_2) emissions. Related to this, there is a need for more energy and specialized machines to separate the adhered mortar from aggregates. For these reasons, the aggregate replacing method is becoming more effective although there is no removal of adhered mortar through this method (Movassaghi, 2006). Figure 2.6 explains this method which is also known as a closed-loop concrete recycling system.

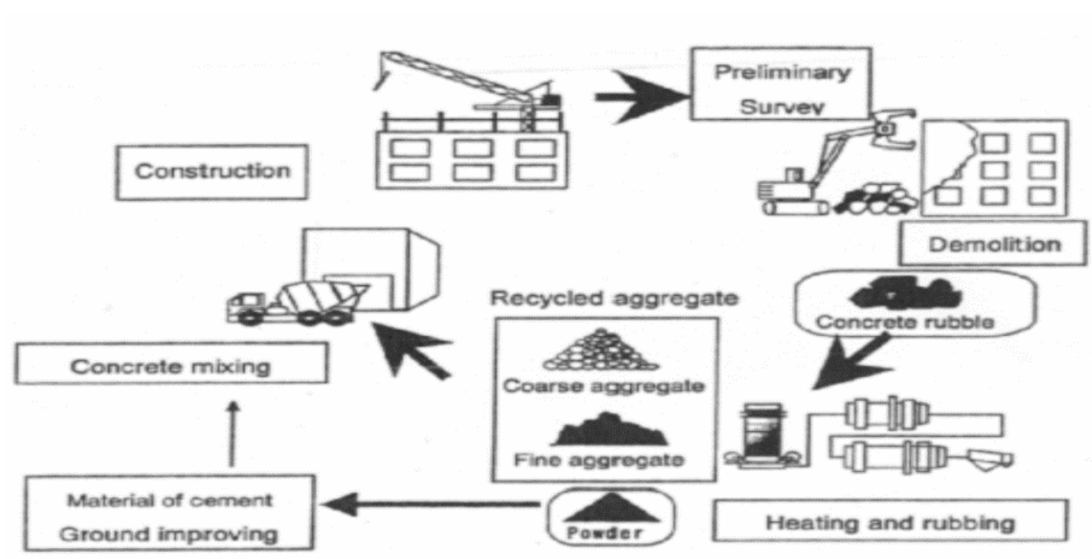


Figure 2.6: Refining method (closed-loop concrete system) (Movassaghi, 2006; Smith, 2009).

For the aggregate replacing method, the demolished concrete is crushed by using one or more of different crushers while ferrous materials such as steel reinforcement and others are extracted through a screening process that uses magnetic separators. Typically, the recycling plants use two main types of crushing equipment compression crushers and impact crushers (Movassaghi, 2006; Smith, 2009; Behring, 2013). Compression crushers can be classified to two known types: cone crusher and jaw crushers. Impact crushers also are categorized into two types: impact (vertical) and horizontal crushers. The production process may use one or more crushers. Generally, the purpose of the primary crusher is to crush demolished concrete into big pieces that then progress to the secondary crusher through a screening process. The secondary crusher works to break recycled concrete into the required size (aggregate size). The percentage use of jaw crushers for the primary crushing is 61% of recycling plants in North America, while 43% of the recycling plants utilize cone crushers for secondary crushing in the same region. (Smith, 2009; Behring, 2013). Figure 2.7 displays different types of crushers used in the RCA production process.

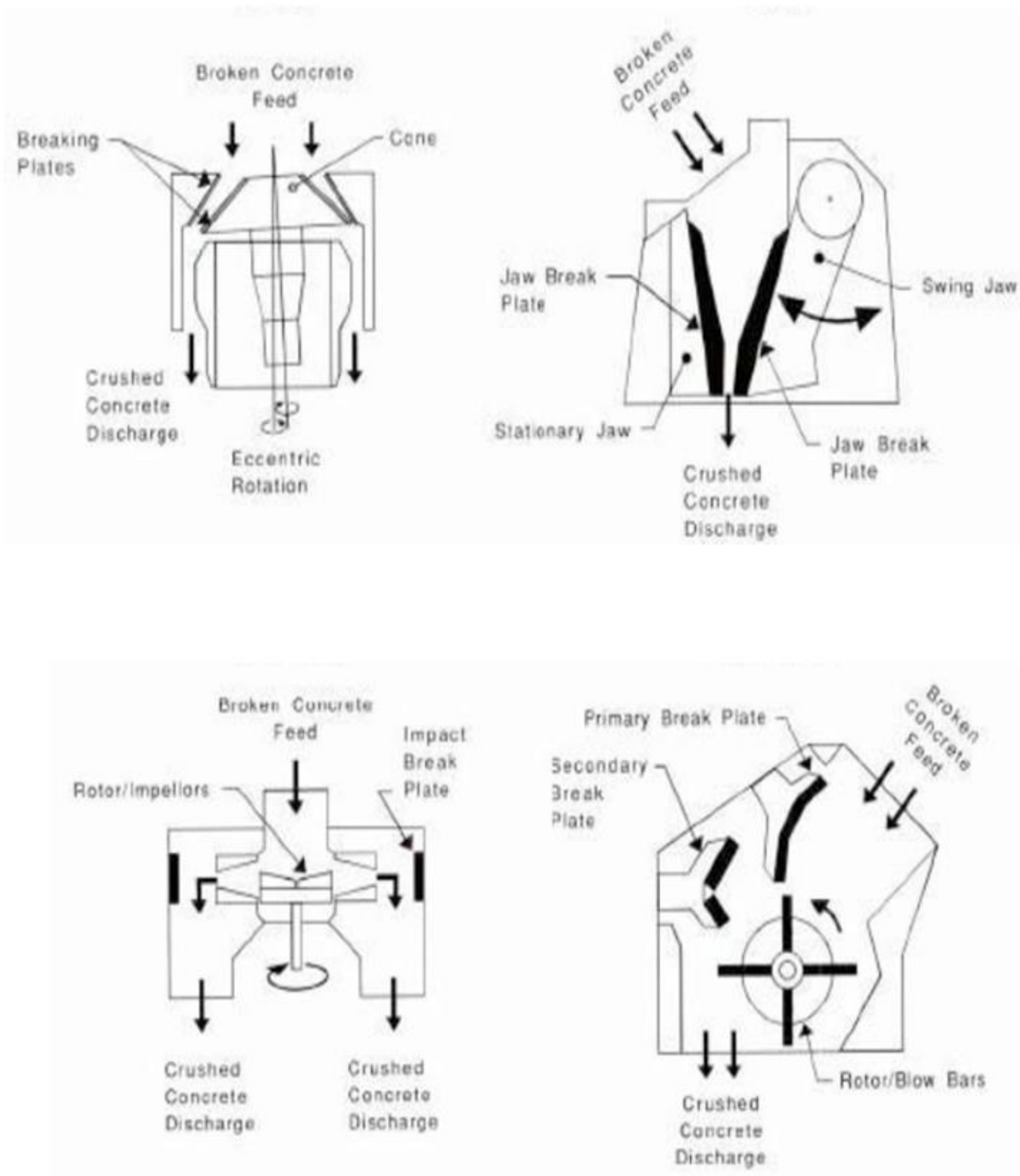


Figure 2.7: Schematic diagrams of various crushers (Movassaghi, 2006; Smith, 2009).

2.5 General Properties of RCA

RCA is produced through a crushing process to demolish concrete from various sources to obtain aggregate of suitable grades that is then utilized in various applications within civil engineering works (Shehata and Thomas, 2000). RCA consists of two major parts: the original natural aggregate and the adhered mortar which is comprised of fine aggregate and cement paste. The cement paste includes both of hydrated and unhydrated cement particles (Butler, 2012; Adams, 2012).

Because of the required crushing process for RCA production to obtain an aggregate of suitable size, RCA is angular and irregular in shape (Saeed et al., 2006; Azari et al., 2006; Wong et al., 2007; Geiger, 2010; Adams, 2012). Many studies found that RCA has a significant water absorption capacity compared to original aggregates (Shen and Du, 2005; Geiger, 2010; Rafi et al., 2011; Pérez et al., 2012; Wu et al., 2013; Singh et al., 2014; Pasandín and Pérez, 2014). Some studies indicated that the fine aggregate type has a higher percentage of adhered mortar than the coarse aggregate type (Tu et al., 2006). The main reason behind increased water absorption is due to the higher porosity of the adhered mortar which is more porous than natural aggregates (Geiger, 2010; Adams, 2012; Zhao et al., 2013; Wu et al., 2013). Adhered mortar can be found to be 20-70% by weight of RCA (Akbarnezhad et al., 2011) or it is between 25%-60% of the RCA by volume (Tu et al., 2006). The main factors which highly affect the amount of adhered mortar are the number and types of crushing methods used in the production plants, and the size of recycled aggregate (De Juan and Gutiérrez, 2009; Etxeberria et al., 2007). Additionally, the presence of adhered mortar layer contributes to creating the rough texture for the RCA surface. Hence, the adhered mortar is the major reason behind the unsatisfactory quality of RCA (Lee et al., 2012; GUL, 2008; Tam et al., 2007; Pérez et al., 2012; Ismail and Ramli, 2013). Compared with natural aggregate, the physical and mechanical properties of RCA can be summarized as follows:

- Increased water absorption, abrasion loss, crushability, and quantity of organic impurities if concrete is mixed with earth during the demolition process.
- Decreased bulk density and specific gravity
- Possibility of the existence of some harmful materials depending on the service condition in the original building that was demolished for RCA production (Malešev et al., 2010).

The main properties of RCA are further discussed in the following subsections.

2.5.1 Water Absorption

According to American Standards and Test Methods (ASTM) standards, absorption can be defined as mass increase of aggregate caused by water penetration into the pores of the aggregate particles during a specific period without wetting the surface of the aggregate (Smith, 2009). Numerous researches have demonstrated that the absorption capacity of RCA higher than NA. Adhered mortar which has a higher porous area than NA results in RCA being more susceptible to absorbed water compared to NA (Tam et al., 2007). These studies are estimated limits of absorption capacity for the coarse aggregate type between 2-10%, and between 3-8% for the fine aggregate type (Adams, 2012). Meanwhile, other studies found that the water absorption of the FRCA was 4-12% and CRCA was 2-6% (Katz, 2003; Smith, 2009), whereas the limits of water absorption for both coarse and fine NAs between was 1-2%, approximately (Adams, 2012). The standard test methods to determine the absorption capacity of coarse and fine aggregate are ASTM C127 and ASTM C128 respectively. The summary of some previous studies regarding water absorption of CRCA types is shown in Table 2-2.

2.5.2 Specific Gravity

In comparison with NA, RCA has a lower specific gravity due to the adhered mortar content which is more porous. Higher porosity means a large number of voids resulting in lowering weight or mass of the material, which is directly related to specific gravity. According to ASTM standards, the specific gravity is defined as the ratio of the density of a material to the density of distilled water at a specific temperature (23 °C) (Smith, 2009). The specific gravity of NA is generally estimated between 2.5-2.8, while the literature shows that the specific gravity of RCA is lower than NA and recorded at between 1.87-2.7. Table 2-3 summarizes some literature results related to the specific gravity of both coarse and fine types of RCA. The standard test methods to determine the specific gravity of coarse and fine aggregate are ASTM C127 and ASTM C128 respectively.

Table 2-2: Literature Studies for Water Absorption of CRCA Types

Researchers	No. of RCA Sources	Absorption of NA, %	Absorption of RCA, %
Shen and Du, 2004	1	0.6	8.8
Shen and Du, 2005	1	0.6	8.8
Paranavithana and Mohajerani, 2006	1	0.3	5.9
Fathifazl et al. 2009*	1	0.34	3.3, 5.4
Rafi et al., 2011	1	1.09	4.57
Cho et al., 2011	1	0.973	2.79
Ektas and Karacasu, 2012	1	0.23	2.1
Pérez et al., 2012	1	0.21, 0.12	6.1
Zhu et al., 2012	1	0.2	6.76
Nassar and Soroushian 2012*	1	2.28	4.35
Wu et al., 2013	1	0.26	6.91
Butler et al., 2013a	3	1.52	4.7, 6.2, 7.8
Younis and Pilakoutas, 2013	4	1.0	4.2, 5.5, 12.7, 4.0
Boyle, 2013	3	1.17	3.87, 3.3, 3.05
Leite et al. 2013*	1	0.4	5.5
Alam et al. 2013*	1	2.17	5.23
Pasandín and Pérez, 2014	1	1.08	5.08
Singh et al., 2014	1	1.1	3.447
Huda, 2014	1	1.2	4.5

*Adopted from (Huda, 2014)

Table 2-3: Literature Studies for Specific Gravity of RCA Types

Researchers	Bulk Relative Density (BRD)		Apparent Specific Gravity		Bulk Relative Density (SSD)		Aggregate Size Fraction
	RCA	**NA**	**RCA**	**NA**	**RCA**	**NA**	
Shen and Du, 2004	2.202	2.655	-	-	-	-	Coarse
Shen and Du, 2005	1.870	2.516	-	-	-	-	Coarse
Du and Shen, 2007	2.20	2.66	-	-	-	-	Coarse
	1.87	2.52	-	-	-	-	Fine
Chen et al., 2011	2.637	2.768	-		-	-	Fine
Rafi et al., 2011,	2.23	2.67	-	-	-	-	Coarse
Arabani and Azarhoosh, 2012	2.457	2.650	2.484	2.685	2.471	2.662	Coarse
	2.463	2.657	2.681	2.496	2.477	2.660	Fine
Zhu et al., 2012	-	-	2.584	2.715	-	-	Coarse
	-	-	2.629	2.681	-	-	Fine
Pérez et al., 2012		2.68	-	-	-		Coarse
	2.63	2.69	-	-	-	-	Coarse
Ektas and Karacasu, 2012	2.39	2.62	-	-	-	-	-
Nassar and Soroushian 2012*	2.4	2.65					Coarse
Nejad et al., 2013	2.676	2.683	2.680	2.697	-	-	Coarse
	2.685	2.672	2.691	2.708	-	-	Fine
Butler et al., 2013a	2.37 2.31 2.23	2.66	2.63 2.67 2.7	2.77	2.47 2.45 2.41	2.70	Coarse Coarse Coarse
Younis and Pilakoutas, 2013	2.35 2.25 1.87 2.40	2.61	2.61 2.57 2.46 2.64	2.68	2.45 2.37 2.1 2.50	2.63	Coarse
Boyle, 2013					2.52 2.53 2.57	2.63	Coarse
Alam et al. 2013*	2.03	2.11					Coarse
Pasandín and Pérez, 2014	2.63	2.79	-	-	-	-	Coarse
Gul and Guler, 2014	2.302	2.684	-	-	-	-	Coarse
	2.280	2.681	-	-	-	-	Fine
Huda, 2014	2.37	2.62	2.66	2.71	2.48	2.65	Coarse

*Adopted from (Huda, 2014)

2.5.3 Abrasion Resistance

The definition of abrasion resistance of the aggregate is the resistance of aggregate to abrasion and degradation due to different conditions such as manufacture, placing, stockpiling, compaction of the HMA and mixing under the influence of actual traffic load (Movassaghi, 2006; Asphalt handbook, 2010). Los Angeles (LA) (ASTM C 131) and Micro-Deval (ASTM D 6928) abrasion test are common standard methods utilized to evaluate the toughness and abrasion resistance of aggregates. The Micro-Deval test was developed to determine the influence of moisture on aggregate abrasion resistance because of various reasons. The first important reason is the evaluated moisture effect on aggregate. This characteristic is not tested through LA abrasion test which is used for only coarse and dry aggregate type while Micro-Deval test utilized for both coarse and fine aggregate types (ASTM D 7428-15) which is the second main reason. Therefore, many researches have recommended using the Micro-Deval test rather than the LA abrasion test because of a better ability to reflect real field conditions and predict field performance (Williamson, 2005). The previous studies showed that abrasion resistance for RCA is lower than NA by 12% due to the presence of weak adhered mortar which is easily removed under friction or abrasion conditions. The abrasion resistance for RCA is estimated to be between 20-45% and the upper limit could reach 50% (Smith, 2009). A summary of some studies covering abrasion resistance of CRCA is presented in Table 2-4.

Table 2-4: Summary of Some Studies for Abrasion Resistance of CRCA

Researchers	No. of RCA Sources Studied	Abrasion Resistance Micro-Deval, %		Abrasion Resistance Los Angeles, %	
		NA	RCA	NA	RCA
Shen and Du, 2004	1	-	-	20.2	40.8
Du and Shen, 2007	1	-	-	20.0	41.0
Rafi et al., 2011	1	-	-	27.21	36.88
Pérez et al., 2012	1	-	-	22.1	34.0
Zhu et al., 2012	1	-	-	24.3	37.8
Arabani and Azarhoosh, 2012	1	-	-	22.6	25.5
Nejad et al., 2013	1	-	-	21.49	28.31
Arabani et al., 2013	1	-	-	22.60	35.50
Younis and Pilakoutas, 2013	4	-	-	23.0	33.0 35.0 43.0 30.0
Butler, 2012	3	11.9	15.1 22.1 25.0	-	-
Pasandín and Pérez, 2014	1	-	-	14.1	32.0
Pickel, 2014	2	10.6	16.2 23.6	-	-

2.5.4 Aggregate Crushing Value (ACV)

The unbound aggregate and asphalt concrete aggregate are subjected to high stresses at contact points, therefore the evaluation of aggregate strength is a very important characteristic for the mixture. Generally, aggregate strength is a significant factor for high-strength concrete and largely traveled pavements. Therefore, the strength of PC concrete and asphalt concrete cannot neglect the impact of aggregate strength. The strength test of aggregate particles is a difficult and uncommon test. Presently, there is no specific method in the various standards: ASTM, Canadian Standards Agency (CSA) and American Association of State Highway and Transportation Officials (AASHTO) standards, to determine aggregate strength in a direct way. However, there is an indirect assessment of aggregate strength through the testing of the original rock sample or bulk aggregate sample (Mamlouk and Zaniewski, 2006). Therefore, British Standard (BS) (812-110) (British Standards Institution, 1990), which is based on the evaluation of the relative strength of aggregate in concrete can be a suitable application to determine aggregate strength.

Rakshvir and Barai (2006) examined ACV tests for two natural coarse aggregate sources and three sources of recycling concrete waste. Generally, the results showed that the values of ACV for RCA were higher than NA values. The values of RCA ranged between 26.2 and 28.1 while the ACV values for the NA were 16.8, 17.7. Table 2-5 summarizes some literature results covering ACV values for different types of RCA.

Table 2-5: Summary of Findings for Literature Studies Covering ACV of CRCA

Researchers	No. of RCA Sources Studied	Natural Aggregate ACV, %	RCA ACV, %
Rakshvir and Barai, 2006	3	16.8,17.7	26.2, 27.3, 28.1
Rafi et al., 2011	1	26.04	31.50
Zhu et al., 2012	1	22.7	27.7
Butler et al., 2013b	3	18.2	23.1, 26.0, 28.5
Wu et al., 2013	1	19.0	25.3
Ismail & Ramli, 2013	1	24.32	29.15
Pickel, 2014	2	18.80	26.1, 28.2
Mukharjee & Barai, 2014	1	15.11	31.52
Zhang et al., 2015	1	8.00	11.3

2.6 Current Applications of RCA

2.6.1 Base and Sub-Base Applications

For base and sub-base applications, the utilization of RCA has become an attractive and successful material because of its characteristics of high resistance and non-expansive behavior (Da Conceição Leite et al., 2011). Globally, many researchers have studied the possibility of using RCA in base and sub-base layers. Park (2003) studied the physical properties and performance of using RCA as a base and sub-base material. Different engineering properties were examined including the moisture-density relationship, particle index, and fine aggregate angularity, whereas various tests such as stability, shear resistance, and particle breakage were used for the performance evaluation of RCA. The results of RCA were comparable to natural aggregate and it was concluded that RCA can be utilized successfully as a base and subbase material. Poon and Chan (2006) investigated the feasibility of using RCA as a sub-base material. The outcomes of this study indicated that the use of RCA at 100% leads to increasing optimum moisture content and decreasing maximum dry density of the sub-base materials compared with the natural sub-base materials. Many other researchers confirmed the possible application of RCA in base and sub-base layers (Bennert et al., 2000; Poon et al. 2006; Da Conceição Leite et al. 2011). In North America, the obtained results of the use of RCA as base material were excellent according to many reports of transportation agencies in Texas, Virginia, Minnesota, and California. These states have recorded strength improvements of the RCA base above that of the NA base used. Minnesota and California concluded that the use of residual cementitious materials can provide the RCA with bonding that cannot be found in NA base. This characteristic with high angularity plays an important role into providing optimum gradation and densification of the RCA material which results in higher stiffness (Bosquez, 2009). Figure 2.8 represents the use of RCA as a base material for road pavement, whereas Figure 2.9 shows the number of US states using RCA as a base material in asphalt roads.

Figure 2.8: RCA placed as base material for pavement project (FHWA, 2004).

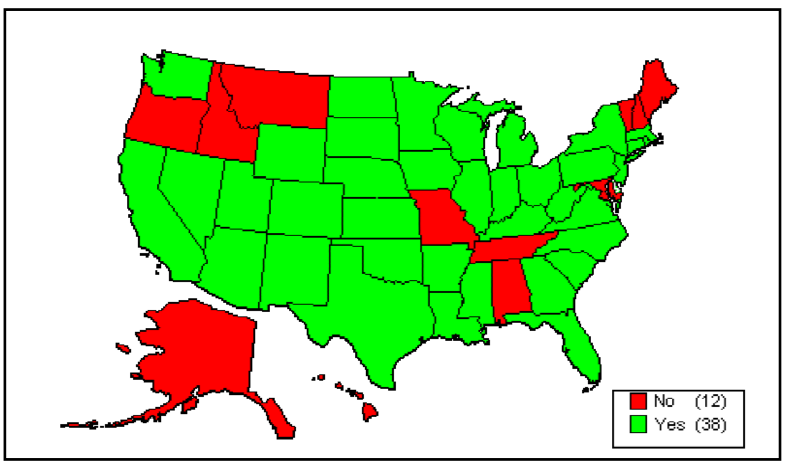


Figure 2.9: Map of US states applying recycling concrete as a base material (FHWA, 2004).

2.6.2 Current Applications in the Province of Ontario

In the Province of Ontario, the MTO has used recycled materials in highway construction since the 1970s due to many different economic, environmental, and engineering factors (Senior et al., 2008). The establishment of Aggregate Recycling Ontario (ARO) in 2011 is one of the main steps which aims to provide a united program for stakeholders which are responsible for generating, operating and consuming recycled aggregate in order to achieve the optimal solution for increasing stockpiles and opportunities for recycling old concrete (ARO, 2014). The use of recycled materials in road construction has increased significantly from approximately 6 million tonnes to 13 million tonnes annually during the period between 1991 and 2006 (MNRO, 2009).

In order to increase the use of RCA in the Province of Ontario, the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo has become one of the leading centers in the use of RCA in new concrete through many successful investigations. Smith (2009) investigated the use of CRCA in concrete sections as shown in Figure 2.10. Four test sections include different percentages of coarse RCA 0%, 15%, 30% and 50%. The results showed that the mixtures which include RCA have similar behavior or better performance in comparison with conventional concrete for different characteristics including compressive and flexural strength, freeze-thaw durability and coefficient of thermal expansion. Butler (2012) examined CRCA usage in structural concrete in a comprehensive study which included the inter-relationships between aggregate properties, concrete properties and the bond properties between reinforcing steel and RCA concrete. Three different sources of CRCA with NA were used in this study. The obtained results indicated that concrete which includes pre-soaked RCA can have higher compressive strengths than conventional concrete at the same water-cement ratios. The outcomes also demonstrated that the production of concrete which includes 100% RCA is a possible application after adjusting the water content, cement content and water-cement ratio in order to achieve different compressive strengths of 30, 40, 50 and 60 MPa with slumps between 75 and 125 mm. Pickel (2014) studied the internal curing potential of RCA in concrete. Different initial saturation levels of RCA were selected within concrete: 0%, 60% and 100%. The RCA percentage ranged from 30% to 100% by volume and there were two curing regimes. The findings of the study showed that a fully saturated RCA mixture contributes to increased compressive strength at early ages compared to NA mixtures. The results also indicated that there is no significant effect of mixtures which include 30% RCA on the tensile strength, elastic modulus, and permeable porosity of the concrete. Permeable porosity for RCA concrete was higher than NA concrete while tensile strength and elastic modulus were lower than NA concrete.

Figure 2.10: Application of CRCA in concrete pavement (Smith, 2009).

2.7 Improvement of the Characteristics and Quality of RCA

The main difference between RCA and NA is the presence of residual aged cement paste (adhered mortar) on the surface of recycled aggregates (Paranavithana and Mohajerani, 2006; Shen and Du, 2005; GUL, 2008). Due to the diverse influence of adhered mortars on the RCA quality, numerous researchers (Shima et al., 2005; Tam et al., 2007; Akbarnezhad et al., 2011; Lee et al., 2012; Sui and Mueller, 2012; Gupta et al., 2012; Ismail and Ramli, 2013; Pasandín and Pérez, 2014; Bru et al., 2014) have investigated various approaches and techniques to improve the characteristics of RCA. However, these approaches and techniques can be fundamentally classified into two categories (Purushothaman et al., 2014; Zhang et al, 2015). While the first category aims to achieve adhered mortar removal, the second category mainly targets enhancing adhered mortar quality. Various approaches including mechanical grinding using balls (Montgomery, 1998), heat application followed by mechanical rubbing (Tateyashiki et al., 2001; Tamura et al., 2002), and ultrasonic cleaning (Katz, 2004) have been successfully applied for adhered mortar removal. To improve adhered mortar quality, several methods have been utilized including mortar surface coating using various material types (e.g. water glass) (Li et al., 2009), pozzolanic materials (e.g. silica fume and fly-ash) (Shayan & Xu, 2003; Tsujino et al., 2007; Li et al., 2009), polyvinyl alcohol emulsion (Kou & Poon, 2010) and biodeposition (Grabiec et al., 2012). Figure 2.11 demonstrates a schematic diagram of various chronologically arranged treatment methods from the literature for enhancing the physical properties of RCA.

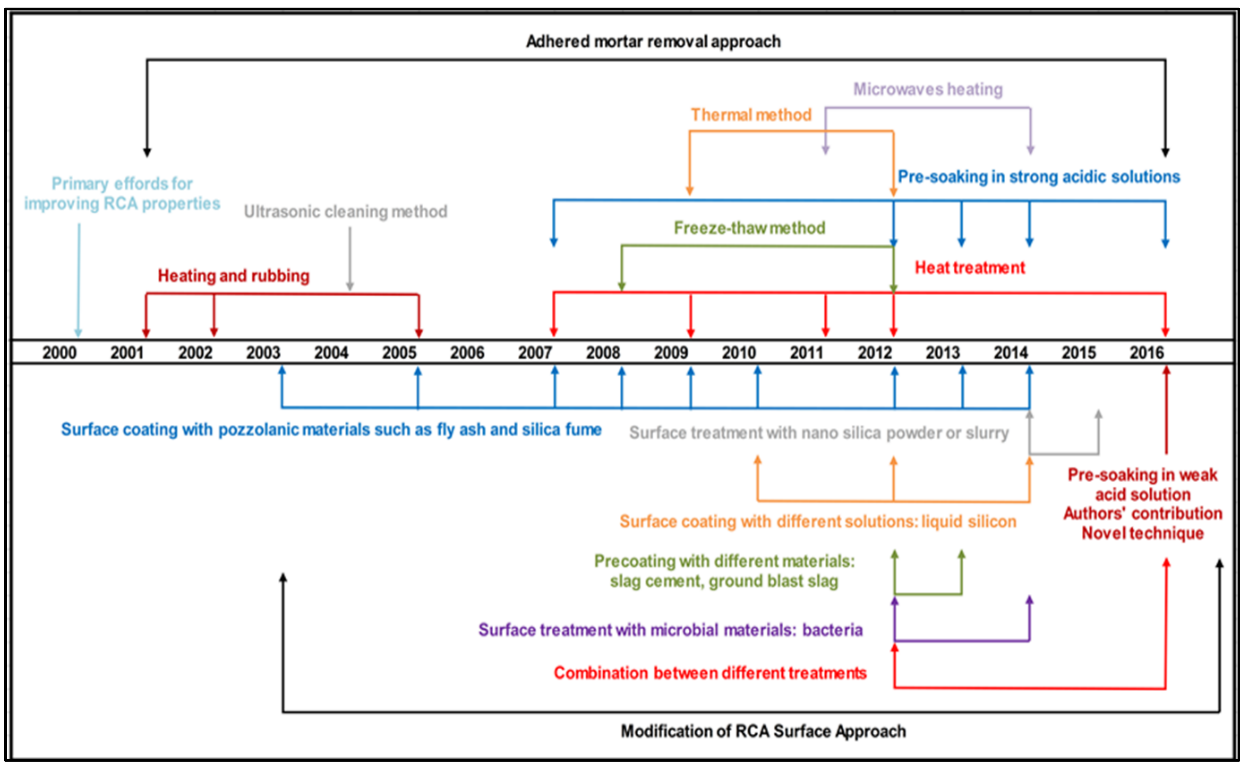


Figure 2.11: Schematic diagram of various treatment approaches for enhancing physical characteristics of RCA in the literature (Al-Bayati et al., 2018).

2.7.1 Adhered Mortar Removal Approach

Many different methods have been used to remove adhered mortar from RCA. The basic idea behind these methods is that the removal of adhered mortar (which has poor quality characteristics) can contribute to enhanced physical properties of RCA. This improvement is highly related to the quantity of adhered mortar which is removed from RCA. Therefore, many researchers are focused on the quantity of adhered mortar removed in order to evaluate the method's performance compared to other methods. The main methods of this approach according to the literature studies can be categorized as the following:

2.7.1.1 Heat Treatment Method

Considerable research has focused on using heat treatment at higher temperatures. Wong et al. (2007) applied the calcination process to RCA, which involved increasing temperatures gradually up to 950 °C for two hours, then decreasing temperatures to 27 °C in order to transform calcium carbonate (calcite) to free lime (calcium oxide). The study concluded that lime can be produced through the calcination procedure, which ultimately enhances the rutting and low temperature cracking performance of hot mix asphalt. However, there was some concrete particle breakdown as well as mass loss because of exposure to higher temperature. Zega and Di Maio (2009) examined the influence of heating at high temperature (500 °C) for one hour on the performance of different concretes prepared with RCA. In concrete mix design, two different water-cement ratios and different coarse NAs (granitic crushed stone, siliceous gravel, and quartzitic crushed stone) were used. It was found that the conventional and recycled concrete specimens prepared with quartzitic crushed stone showed better performance after the heat treatment than that of granitic crushed stone and siliceous gravel. Vieira et al., (2011) examined the effects of heating of RCA at three different temperatures (400 °C, 600 °C and 800 °C) for one hour on the concrete samples with replacement of NA by RCA at different percentages (20%, 50% and 100%). The study reported that there was no heat influence on mechanical behaviour of concrete which contained RCA compared to conventional concrete. Gupta et al., (2012) examined the influence of heating at ranges between moderate and elevated temperatures (200 °C, 400 °C, 600 °C, 800 °C, 1000 °C) for six hours on the mechanical and micro structural properties of concrete containing RCA mixed with NA and fly ash as a replacement for cement. The study concluded that treated and untreated RCA samples exhibited poor behaviour at various higher temperatures in comparison with natural aggregate. Also, concrete suffers from broad degradation after exposure to higher temperatures because of concrete microstructure becoming rougher and increasing total pore volume resulting in higher strain and lower compressive strength. Sui and Mueller (2012) investigated the effect of the combination of heat treatment at various temperatures (100 °C-600 °C) for 30 min and mechanical treatment in a ball mill at different milling times on RCA properties. The obtained results indicated that the adhered mortar can be removed by heating at a temperature range of 250 °C-300 °C, if it was followed by strong and sufficient mechanical treatment and this resulted in comparable properties to that of virgin aggregate.

2.7.1.2 Pre-Soaking Treatment Method

Recently, the use of pre-soaking in acidic solutions to remove the adhered mortar has attracted much research interest. Tam et al., (2007) investigated RCA soaking in three different strong acids solutions: HCl, sulphuric acid (H_2SO_4) and phosphoric acid (H_3PO_4) at low concentration of 0.1 mole at 20 °C for 24 hours. The obtained results indicated that there was a considerable decrease in water absorption, improved mechanical properties, and there was no adverse influence from chloride and sulphate ions on the RCA. Butler (2012) investigated the effect of nitric acid at a high concentration (20% volume) and moderate temperature (85°C) for two to three hours. It was observed that the acid removed the outer layer of RCA; however, there were dyed yellowish spots on the RCA surface. Ismail and Ramli (2013) tested the effect of various concentrations (0.1, 0.5, and 0.8 M) of HCl with different immersion times (one, three, and seven days) on treating the RCA to improve its performance. The findings showed a linear correlation between the amounts of mortar loss with increasing concentration of acid while there was no significant effect for immersion time. Purushothaman et al., (2014) tested the influence of different approaches to decrease the amount of cement paste adhered to RCA. Chemical treatment included pre-soaking in two acidic solutions; namely, HCl and H_2SO_4 at a low concentration of 0.1 mole for 24 hours. The mechanical method consisted of mechanical scrubbing and heating-scrubbing which included heating RCA with hot air at 300 °C, followed by scrubbing. The outcomes of the study indicated that the H_2SO_4 treatment method was more effective than HCl acid, whereas heating and scrubbing was more successful in enhancing RCA and its properties. The two successful methods also showed improved long-term performance that includes water absorption and loss of weight on drying.

Meanwhile, there are many different methods which have received some interest from researchers. These methods can be summarized as the following: ball milling (Montgomery, 1998), ultrasonic cleaning method (Katz, 2003), heating, and then rubbing (Tateyashiki et al., 2001; Tamura et al., 2002; Shima et al., 2005), microwaves heating (Akbarnezhad et al., 2011; Bru et al., 2014), thermal method (De Juan and Gutierrez, 2009; Butler, 2012) and freeze-thaw method (Abbas et al., 2007; Butler, 2012).

2.7.2 Modification of the RCA Surface Approach

This approach mainly includes modification of the quality of adhered mortar without removal through surface coating with different materials such as water glass, pozzolanic materials such as fly ash and silica fume. Li et al., (2009) studied the effect of surface coating with pozzolonic materials powder fly ash and silica fume on the workability and strength of RCA. The obtained results demonstrated that mixing of these materials leads to enhanced workability and compressive strength. It was also noted that surface coating with pozzolans contributes to increased density of ITZ structure which confirms better workability and strength. Cakır and Sofyanlı (2015) examined the impact of adding silica fume to the concrete mix design to enhance the quality of RCA. Different percentages of silica were used (0%, 5%, 10%) as a replacement for Portland cement. Four series of concretes were produced from natural and RCA which was combined with silica fume by using two different size fractions of RCA. The findings of the study showed that the use of silica fume at 10% as a cement replacement for RCA can play an important role to improve the physical and mechanical properties of concrete. Besides these studies, the literature includes other investigations based on the same approach but using the same or different materials. These can be summarized as the following:

- Surface coating through the immersion of RCA in different types of solutions such as poly vinyl alcohol (Kou and Poon, 2010), liquid silicone resin (Zhu et al., 2012) and bitumen emulsion (Pasandin and Perez, 2014).
- Pre-coating RCA through using different materials such as slag cement paste (Lee et al., 2012) and ground granulated blast slag (Zhao et al., 2013).
- Biodeposition technique using bacteria (Grabiec et al., 2012)

2.8 Surface Microstructure of RCA

2.8.1 Interfacial Transition Zone

Concrete is a highly complex, heterogeneous and multiphase composite material at the microstructural level, consisting of three main phases: aggregate, bulk cement paste (matrix) and an ITZ zone between the aggregates and the matrix (Otsuki et al., 2003; Akçaoğlu et al., 2005; Tam et al., 2005; Tam & Tam, 2008; Tam et al. 2007; Xuan et al., 2009; Kong et al., 2010; Erdem et al., 2012; Li et al., 2012). Among the constituents, the ITZ, which is structurally and mechanically different from the matrix and aggregate, is essentially composed of three phases; namely, water film, Ca $(OH)_2$ (CH) crystal layer and porous paste matrix layer (Wong et al., 2009; Erdem et al., 2012; Jawahar et al., 2013).

Though the origin of the ITZ has not been fully understood yet, the common view for the existence of the ITZ is namely titled the “wall effect”. This potential mechanism briefly refers to spatial arrangements of anhydrous cement particles against an aggregate surface due to size discrepancy. More specifically, it is well known that the typical size of cement particles range between (1-100μm), whereas the average size of aggregate is predominantly many times larger than that of cement particles. In freshly compacted concrete, the cement particles are suspended, and their normal packing is disrupted. The cement particles cannot pack effectively when they are close to large solid objects, such as aggregates, due to the phenomenon of the creation of a geometric wall effect within the structure that results in a narrow region around the aggregates, namely the ITZ. The region is characterized by a relatively low concentration of cement particles, high water content and consequently increased porosity (Cwirzen & Penttala, 2005; Leemann et al., 2006; Wang et al., 2009; Gao et al., 2014; Sun et al., 2015; Wu et al., 2016).

As with other composite materials, the properties of the concrete are highly dependent on the properties of each individual component, especially the connection area between major components, and concrete properties are determined by the ITZ to a large degree (Akçaoğlu et al., 2005; Li et al., 2012). It has been widely reported that the ITZ is a weak region (Otsuki et al., 2003; Tam et al., 2005; Tam et al., 2007; Poon et al., 2006; Duan et al., 2013) due to a high presence of voids and microcracks that are highly related to strength properties. Subsequently, the ITZ plays a crucial role in determining the mechanical performance of concrete (Tam et al. 2005; Tam et al. 2007; Güneyisi et al., 2014), though it is generally thin, between 10-50 μm (Kong et al., 2010). Therefore, the improvement of RCA microstructure has been a considerable concern that has interested many researchers and compelled them to enhance the characteristics of concrete (Kong et al., 2010; Jawahar et al., 2013; Purushothaman et al., 2014). However, the factors that play an important role in forming the structure of the ITZ and its properties are the aggregate properties including type, shape and surface conditions, cement and admixtures and particularly the water-to-cement (w/c) ratio of the mixture (Akçaoğlu et al., 2005). Figure 2.12 represents a schematic diagram for the ITZ zone.

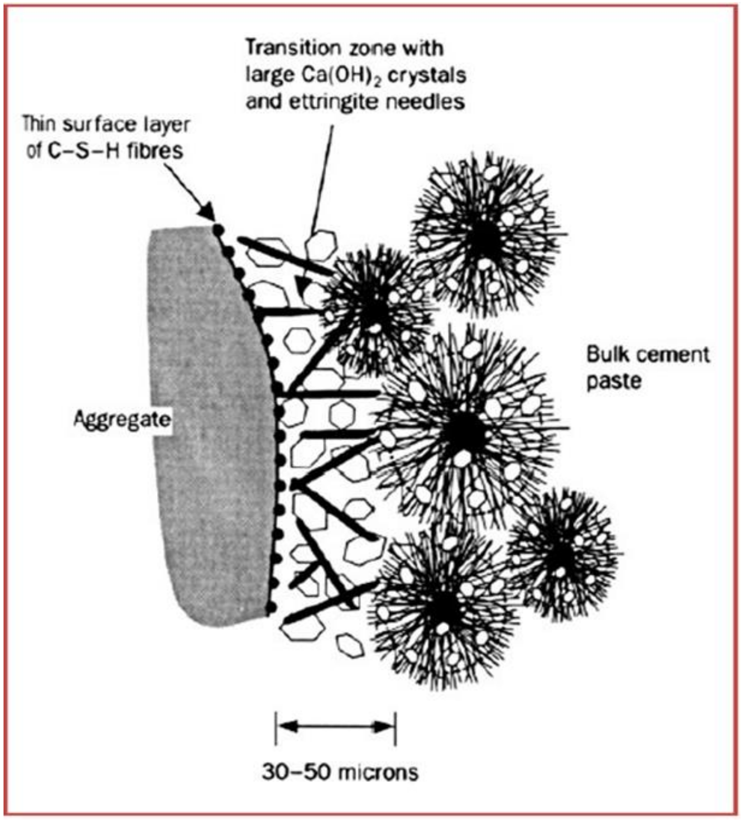


Figure 2.12: Schematic diagram of phases in microstructure of the ITZ zone (Cement Chemical Composition and Hydration).

2.8.2 Microstructure Cracks

Though the matrix and aggregate properties have an important effect on crack initiation and propagation, the ITZ properties have a considerable and particular importance with regards to the cracking of concrete (Akçaoğlu et al., 2005). From the literature, it was concluded that the main reason for initial microcracks is the large difference between the modulus of elasticity of the aggregate and the matrix, resulting in higher tangential, radial and/or shear stresses at the interface zone (Akçaoğlu et al., 2005; Jawahar et al., 2013). The microcracks can be mainly classified as either bond cracks or matrix cracks. The bond cracks typically initiate and appear at the interface zone, whereas matrix cracks generally propagate across the cement paste (Jawahar et al., 2013). However, the typical width of microcracks ranges between 0.5 and 10 μm (Wong et al., 2009) as shown in Figure 2.13. During concrete loading, increased concentration of microcracks makes them behave as sources of subsequent macrocrack development that includes ITZ microcracks growing through the matrix and combining with the matrix cracks to form macrocracks (Akçaoğlu et al., 2005).

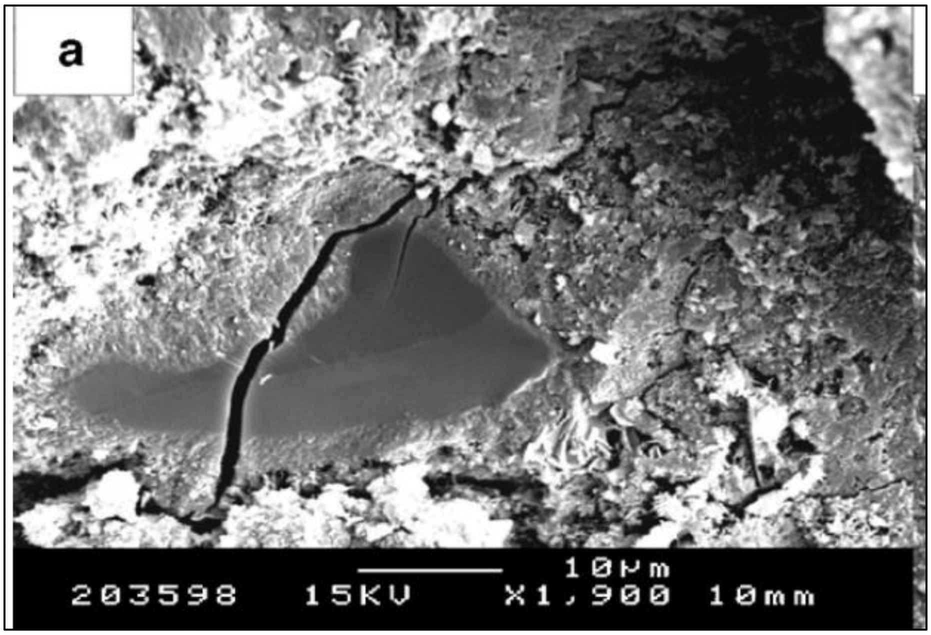


Figure 2.13: SEM image of microcrack for recycled concrete (Mo & Fournier, 2007).

2.8.3 Studies of Microstructure & ITZ Improvement

The effect of different CRCA on the ITZ was examined on six different sources of CRCA with varying strengths and quantities of attached mortar. The obtained results demonstrated that there is a significant influence of the quality of attached mortar on ITZ properties. However, it was observed that there is no obvious impact of the quantity of attached mortar on ITZ properties (Otsuki et al., 2003). Poon et al. (2004) investigated the influence of RCA types on the microstructure of the ITZ in concrete mixes prepared with RCA. Two different types of RCA including recycled normal strength concrete (NSC) and recycled high performance concrete (HPC) with water absorption values of 8.82% and 6.77% respectively were used in concrete mix design with a constant water to cement ratio of 0.5 for both concrete mixes. The outcomes of SEM images showed that the ITZ of NSC mix mainly consists of loose and porous hydrates, whereas the ITZ of HPC mix is fundamentally composed of dense hydrates. The adverse influence of attached mortar on self-compacting concrete (SCC) containing RCA using surface treatments was investigated. Various surface treatment methods were applied including a two-stage mixing approach, pre-soaking in HCl solution, water glass dispersion and cement–silica fume slurry. The captured images of SEM analysis revealed that the new ITZ with treated RCA using the two-stage mixing approach, water glass and HCI solution are characterized by less porous, highly dense and connected microstructure compared to untreated RCA due to the recovery of microcracks and voids in RCAs. In contrast, the use of cement-silica fume treatment resulted in porous microstructure and weaker bonding in the new ITZ. Among different surface treatments, a considerable improvement to the ITZ was recorded for the two-stage mixing approach through providing a layer of cement slurry on the surface of RCA which fills up the microcracks and voids as shown in Figure 2.14 (Güneyisi et al., 2014).

Numerous studies focused on the addition of pozzalanic materials such as fly ash and silica fume as a way for enhancing microstructure, especially the ITZ region of RCA. Tam and Tam (2008) developed two mixing approaches namely two-stage mixing approach (silica fume) and two-stage mixing approach (silica fume and cement). The first approach includes the addition of silica fume into percentages of Recycled Aggregate (RA) in the first mix, whereas the second technique consists of the addition of silica fume and amounts of cement into particular proportions of RA in the first mix. The results of both techniques revealed that the utilization of silica fume and proportional cement percentages lead to filling up the weak areas in the RA, resulting in an improved interfacial region and higher strength of the concrete. Comparable outcomes were noted by other researchers (Tam et al., 2005; Li et al., 2009; Li et al., 2012) who investigated enhancing RCA properties and microstructure using a two-stage mixing approach. The studies concluded that there is an improvement in the ITZ region and RCA properties by using this approach. Compared with the double mixing method it was revealed that there is a further improvement for the ITZ and RCA properties by using a triple mixing method. The technique includes surface coating of RCA with materials such as fly ash and silica fume. The captured images of SEM analysis indicated that the coated pozzolanic particles can consume CH particles that are accumulated in the pores and on the surface of the attached mortar to form new hydration products resulting in successful improvement in ITZ microstructure and enhanced strength of RCA (Kong et al., 2010).

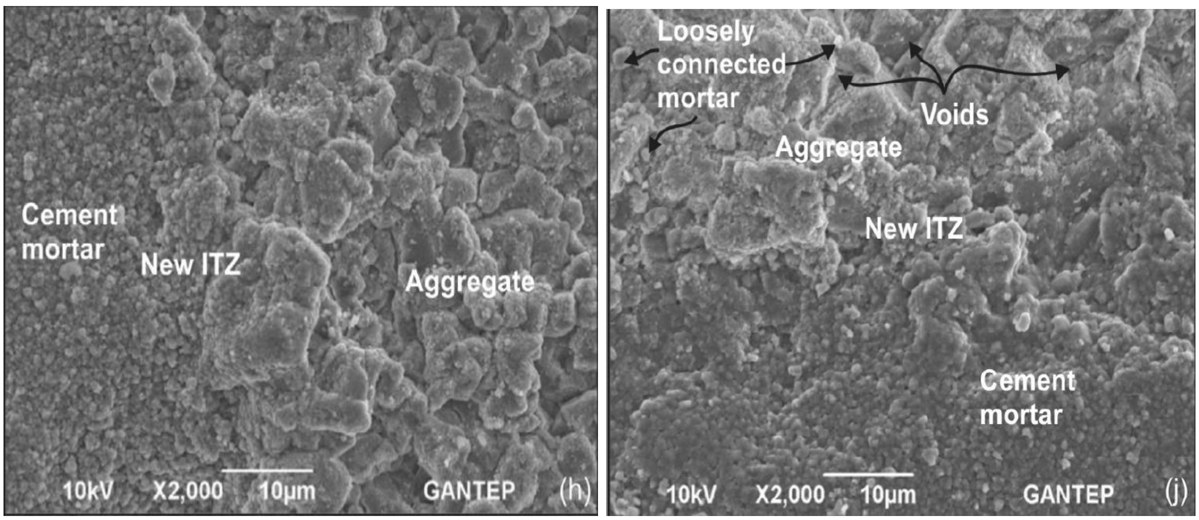


Figure 2.14: Surface microstructure views of SCCs produced from treated RCAs using (j) HCl solution, and (j) cement-silica fume slurry (Guneyisi et al., 2014).

2.9 Volumetric Properties of Asphalt Mixtures

2.9.1 Concept of Volumetric Properties

The design of asphalt mixtures can be described as a complicated process that requires very accurate proportions of aggregate and asphalt binder in order to achieve specific requirements of volumetric and mechanical properties (Anderson & Bahia, 1997). To achieve a desirable performance for the asphalt mixtures, the volumetric properties of pavement mixes are taken into account. The concept of volumetric properties of asphalt mixtures has been progressively developed using various aspects as described in the following brief explanations. The significance of volumetric proportions of the constituents of asphalt mixtures regarding pavement performance was observed by Richardson in 1915. By the 1940s, the integration between two concepts; namely, the degree of saturation of the voids of the mixtures by asphalt, that can be named voids filled with asphalt and voids volume was suggested by Marshall. In the 1950s, the conception of voids in mineral aggregate and its significance in utilization for achieving asphalt durability had become highlighted and widespread due to the contribution of McLeod (Bardini et al. 2013).

Currently, the volumetric properties of asphalt mixtures can be categorized into two main groups: primary and secondary volumetric parameters (Bardini et al. 2013). While the primary volumetric parameters are directly related to the relative volumes of the individual constituents of asphalt mixtures: aggregate volume (Vs), air voids (Va), and asphalt binder volume (Vb), secondary volumetric parameters commonly referred to as volumetric properties of mixtures are Void Volume (Vv), Voids in Mineral Aggregates (VMA), and Voids Filled with Asphalt (VFA). Depending on the primary volumetric parameters, volumetric properties of mixtures (secondary volumetric parameters) can be determined. A summarized interpretation of the secondary volumetric parameters can be provided as follows: Vv is defined as the air volume between the aggregate particles surrounded by the film of asphalt and can be expressed as a percentage of the total volume of the compacted mixture; VMA can be known as the sum of the Vv and volume effective asphalt binder (non-absorbed) (VEAC). This can be expressed as a percentage of the total volume of the compacted mixture whereas VFA is described as the degree of VMA filled by asphalt or the ratio of the volume of effective binder to the VMA and can be expressed in percentage (Hislop, 2000; Bardini et al., 2013). The terminology of volumetric properties for the components of a compacted asphalt mixture can be found in Figure 2.15.

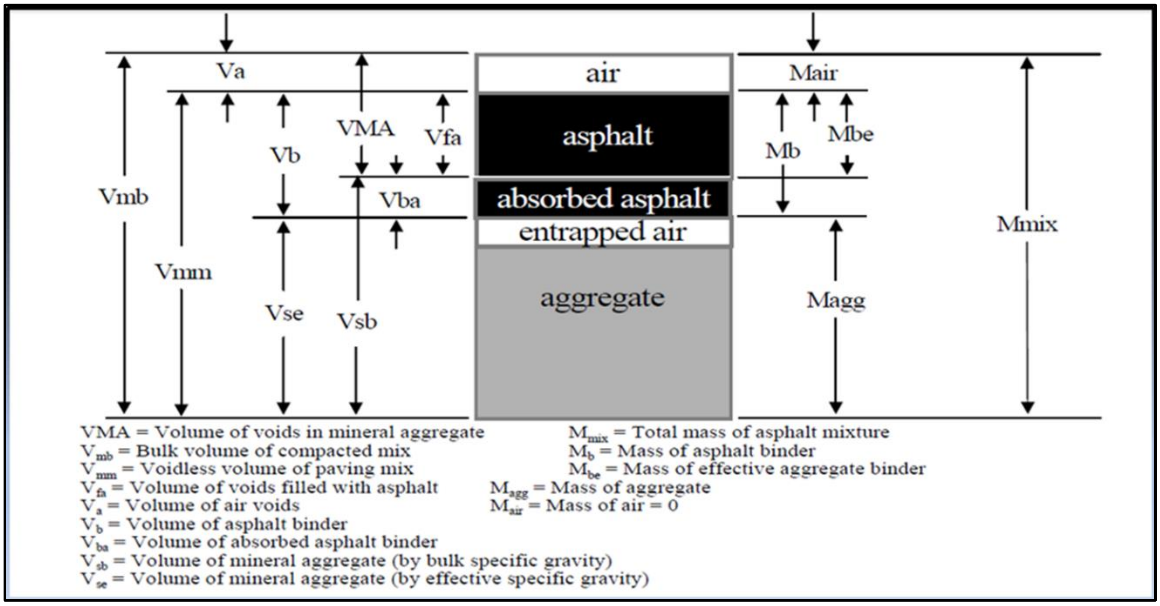


Figure 2.15: Components of a compacted HMA specimen (Hislop, 2000; Huner & Brown, 2001).

2.9.2 Evaluation of Volumetric Properties

It is generally accepted that the three volumetric parameters; namely, air voids (sometimes abbreviated VTM), VMA, and VFA have been identified as important indicators of mix performance. While excessive air voids, VFA, and inadequate VMA could possibly be referred to as durability problems, insufficient air voids or excessive VFA could potentially lead to rutting problems (Hislop, 2000; Bardini et al., 2013). Grain size, the volume of aggregate in the mix, the degree of compaction, the asphalt content and the type and amount of fillers in the mixture are the main factors that influence the volumetric properties (Bardini et al., 2013).

Marshall and Superpave methods are the common methods used in asphalt mixture design and incorporate volumetric criteria mathematically calculated from the volumetric proportions of the constituent materials of the mixtures. In detail, the methods determine the optimum asphalt binder using HMA volumetric properties (Vv, VMA and VFA). Additionally, Superpave method can evaluate the filler content in the mixture and the percentages of initial and maximum compaction as a function of the number of gyrations in the Superpave Gyratory Compactor (SGC) (Bardini et al., 2013). In Superpave, a volumetric mix design protocol was established with limits on all three volumetric parameters (Hislop, 2000). Depending on the mixture's nominal maximum size (NMS) and traffic volume, Superpave method establishes minimum values of VMA, and minimum and maximum values of the VFA as shown in Table 2-6.

Table 2-6: Superpave HMA Volumetric Properties (OPSS 1151, 2007).

Traffic Category (Note 1)	% of Theoretical Maximum Specific Gravity			Voids in Mineral Aggregate (VMA) % Minimum						Voids Filled with Asphalt (VFA)	Dust to Binder Ratio (Note 3)	Minimum Tensile Strength Ratio %
				Nominal Maximum Aggregate Size mm								
	$N_{initial}$	N_{design}	N_{max}	3.75	25	19	12.5	9.5	4.75			
A	91.5	96.0	98.0	11.0	12.0	13.0	14.0	15.0	16.0	70-80 (Note 4)	0.6-1.2	80.0
B	90.5									65-78		
C	89.0									65-75 (Note 5)		
D												
E												

Notes:
1. Traffic category as specified in the Contract Documents.
2. For Traffic Categories C, D, and E Superpave 9.5 mixes shall have a VFA range of 73 to 76%, while Superpave 4.75 mixes shall have a VFA range of 75 to 78%.
3. For Superpave 4.75 mixes, the dust-to-binder ratio shall be 0.9 to 2.0. Superpave mixes with gradation that pass beneath the PCS Control Point in Table 4, the dust-to-binder ratio shall be 0.8-1.6.
4. For Traffic Category A, Superpave 25.0 mixes shall have a VFA range of 67 to 80%
5. Superpave 37.5 mixes shall have a VFA range of 64 to 75%.

2.9.3 Influence of RCA on Volumetric Properties

In terms of volumetric properties, Mills-Beale and You (2010) investigated the feasibility of using RCA for a typical light-duty or low-traffic asphalt highway in Michigan. Various percentages including 25%, 35%, 50%, and 75% RCA with respect to the total percentage of HMA aggregate were used. As part of the research, the change in the volumetric properties of HMA due to RCA addition was evaluated. The findings of the study demonstrated that the increase of RCA proportion leads to a decrease of VMA and VFA in the mixtures while air void content increased. The decrease of VMA could be explained by the fact that the increase in the proportion of RCA that generally has a high porosity characteristic leads to the absorption of some amounts of asphalt, resulting in a reduction of the effective asphalt content in the HMA mixture. As the effective asphalt content was reduced, VMA decreased. In research by Topal et al., (2006) various proportions of RCA (10%, 20%, and 30%) were utilized as a substitute for limestone aggregate in HMA mixtures. The results of the study showed a discrepancy in terms of volumetric properties. When RCA percentage increases in the mixtures, the values of VMA and VFA decreased. A similar behaviour was registered for specific gravity of HMA mixtures. An increase in RCA proportion leads to decreased specific gravity. In contrast, Marshall stability increases to higher values while the amounts of RCA increased. The research concluded that the RCA application as a substitute for NA is highly successful due to meeting Marshall stability and ITS requirements. This could be attributed to RCA crushing under the impact of the compaction process. Table 2-7 summarizes some literature results for the volumetric properties for different types of RCA.

Table 2-7: Literature Studies Covering the Influence of RCA on Volumetric Properties

Researchers	RCA, %	Volumetric Properties
Paranavithana & Mohajerani, 2006	Coarse aggregate	VMA and VFA are lower than the C.M.
Bhusal et al., 2011	20%, 40%, 60%, 80%, and 100%	VMA, Gmb and Gmm decreased as the percentage of RCA increased.
Rafi et al., 2011	10%, 20% and 30%	VMA increases with increasing RCA percentage and Gmb decreased as the percentage of RCA increased
Motter et al., 2015	25%, 50%, 75%, and 100%	VFA, Gmb and Gmm decreased as the percentage of RCA increased, whereas VMA increases as the RCA percentages increased.

2.10 Relationship of RCA and Moisture Damage

Moisture damage in asphalt mixtures has become a widely discussed topic due to its high influence on asphalt mixture behavior. Moisture damage plays an important role in many different types of distress including rutting, fatigue cracking, raveling, and potholes (Moraes et al., 2011; D’Angelo and Anderson, 2003) as shown in Figure 2.16. Therefore, the reduction of moisture damage impact is becoming one of the significant challenges for researchers, agencies and departments of transportation. In asphalt pavements, moisture damage can be defined as deterioration of mechanical properties such as stiffness, durability and strength due to the presence of water. More specifically, it is the deterioration of a pavement mixture through losing adhesive bonding at the binder-aggregate interface or losing cohesive resistance in asphalt binder (Zollinger, C. J., 2005; Moraes et al., 2011; Geiger, 2010; Pasandín and Pérez, 2013; D’Angelo and Anderson, 2003; Solaimanian et. al., 2003). Many different factors influence moisture damage such as asphalt film thickness, permeability, the bond between asphalt and aggregate (chemical and mechanical bonding), aggregate shape distribution and the aggregate crushing process (Zollinger, 2005; D’Angelo and Anderson, 2003). Figure 2-15 displays the influence of moisture damage on asphalt mixtures.

Figure 2.16: Effect of moisture on asphalt pavement (Pavement Interactive, 2008).

Based on the literature review, it is noted that some studies indicated that asphalt mixtures which include RCA have higher moisture susceptibility than NA asphalt mixtures (Pasandín and Pérez, 2013). These indications are predictable results due to higher water absorption of RCA material which has a porous structure. However, some other investigations revealed that the addition of RCA as a coarse or fine aggregate can improve the moisture susceptibility of asphalt mixtures (Du and Shen, 2007, Cho et al., 2011, Chen et al., 2011). In order to achieve better behavior for moisture sensitivity, some researchers stated that the use of treated RCA possibly improves this characteristic in asphalt mixtures. Lee et al., (2012) used a slag cement paste as a coating material for RCA before its introduction to asphalt mixture. The obtained results for water resistance were within the Taiwanese specification requirements. Zhu et al., (2012) utilized liquid silicone resin for RCA coating prior to its use in asphalt mixture. The findings showed improved moisture resistance through using this method. Pasandín and Pérez (2013) used a method which includes leave mixture with RCA in an oven for four hours at a mixing temperature of 170 °C before compaction. The Marshall mix design procedure was used in this study. The outcomes of moisture resistance for this study was acceptable and within Spanish specifications. The Superpave mix design method originally includes leaving the mixture in an oven at 135 °C for four hours. Therefore, the short-term ageing process is very comparable to this type of treatment to improve moisture sensitivity (Pasandín and Pérez, 2014). Finally, the use of type of treatment to enhance RCA properties before it's utilized in asphalt mixtures is highly recommended by researchers (Lee et al., 2012; Zhu et al., 2012; Pasandín and Pérez, 2013) to produce mixtures with better moisture resistance. Therefore, it is highly expected that the use of Superpave method and a type of treatment especially a treatment combination, can lead to promising results.

2.11 Possible Application of RCA in HMA

Very recently, the use of RCA has become an attractive topic for many researchers all over the world. The successful use of RCA in the base and sub-base applications is one of the main reasons to examine the feasibility of using RCA in HMA. One of the first efforts to use RCA in asphalt mixtures was made in a study by Wong et al., (2007). The research examined the use of fine aggregate of RCA as a partial substitution for NA (granite type) in HMA. Three hybrid mixtures that contain added RCA were prepared to include 6% and 45% untreated RCA, and 45% heat treated RCA. The obtained results indicated that the mixture that included 6% RCA fillers give comparable results to NA in terms of resilient modulus and creep resistance while the use of a high percentage of RCA in the two other mixtures achieved better performance. The findings showed that the utilization of RCA leads to increased resilient modulus and reduced dynamic creep. The resilient modulus test was conducted at two different temperatures (25 ºC and 40 ºC); the addition of RCA increased resilient modulus for both temperatures. It was concluded that the use of RCA as a partial percentage of aggregate is possible in HMA. Pérez et al., (2009) evaluated the resistance of asphalt mixture which includes mixed RCA with NA to fatigue cracking. Two different mixtures, a semi-dense mixture and a coarse mixture, and one type of RCA were used to prepare various HMA mixtures. The fatigue test and dynamic modulus test were performed to evaluate HMA. The results revealed that fatigue behavior for the coarse mixture with 50% RCA is similar to the behavior of the same type without RCA. In contrast, the semi-dense mixture with 50% RCA had a lower fatigue behavior than the same type without RCA. The findings indicated that the mixture which includes RCA has higher dynamic modulus than the mixture without RCA. It was concluded that RCA leads to increased stiffness values for HMA even if using a large amount of bitumen. Wu et al., (2013) investigated the effect of RCA on the performance of an asphalt mixture. The RCA used was divided into two different sized coarse recycled aggregate and fine recycled aggregate. Three different asphalt mixtures were prepared: the first consisted of CRCA and natural limestone fine aggregate; the second consisted of FRCA and natural limestone coarse aggregate; and the third mixture consisted of natural limestone coarse and fine aggregate. Many laboratory tests were conducted to evaluate the performance of asphalt mixture including the Marshall test, freeze-thaw split test, bending test at low temperature and rutting test at high temperature. The obtained results demonstrated that the CRCA asphalt mixture has higher rutting resistance than the other two types and higher OAC. In terms of water damage resistance, the results showed that the FRCA asphalt mixture is better than CRCA, which has better cracking resistance at low temperature compared to FRCA. It was concluded that all the results meet the specification requirements in China. Table 2-8 demonstrates some literature studies for the utilization of RCA in asphalt mixtures.

2.12 Identification of Research Gaps

After a comprehensive study of the literature related to the methods and techniques of RCA treatment, microstructural studies of RCA, and the use of RCA in asphalt mixtures, the following research gaps have been identified for which further research study is required:

- ❖ In the global literature, very limited studies have investigated the physical and mechanical properties of RCA as a specific comprehensive study covering a large number of physical and mechanical properties.
- ❖ Very few studies have evaluated the effect of various treatments types on the enhancement of physical and mechanical properties of RCA. However, it was evident that most of the previous studies were mainly focused on the influence of individual treatment methods on various RCA characteristics.
- ❖ There is a considerable lack of information about the combination between different treatment types to enhance the physical properties of RCA because combinations of various treatments are very rarely addressed in the global literature. Though very limited investigations have explored the combination between various treatment methods, none of the literature studies has ever explored the application of weak acid as an acidic treatment technique. However, the use of strong acids as a type of treatment is known. Therefore, the application of combined techniques among various treatment methods seems to be quite reasonable to result in promising outcomes compared to individual treatment utilization.
- ❖ While thoroughly examining the literature related to methods and techniques of RCA treatments and microstructural studies of RCA, it was clearly observed that there is a considerable lack of knowledge regarding the effects of RCA treatments on ITZ properties such as microcracks and macrocracks. The previous literature investigations have extensively focused on the effects of various treatment types on the enhancement of physical properties of RCA, resulting in the knowledge gap mentioned above.

Table 2-8: Summary of Available Literature Studies for RCA Application in Asphalt Mixtures

Literature	RCA Type & %	RCA Properties	RCA Treatment	Results & Notes
Shen & Du, 2004	100% RBM coarse & fine, 50% RBM coarse & fine, 100% RBM coarse.	C.S. G= 2.202 F.S. G= 1.870 W. A= 8.8	-	Results indicated that mixture (50% RBM) has the lowest permanent deformation at 25°C, but the highest permanent deformation at 60°C. Mixtures (100% RBM) and (CRBM only) are better than the mixture (100% NA) in permanent deformation. The types of asphalt binder used have no significant effect on the permanent deformation performance.
Mills-Beale and You, 2010	25%, 35%, 50% and 75% in place of total aggregate.	S.G = 2.433 W.A = 2.341	-	Mixes passed rutting specification and passed specification of moisture susceptibility with one exception at 75%. Dynamic modulus is increased with decreasing ratios of RCA and test temperature influenced the resilient modulus more than the effect of RCA percentages
Chen et al., 2011	Fine aggregates powder as filler	S.G = 2.637	-	Properties of water sensitivity, high temperature properties (dynamic creep) and fatigue resistance were improved with little decrease of low temperature performance (crack resistance).
Cho et al., 2011	100% CRCA and FRCA, 100% CRCA+100% NFA, 100% FRCA+100% NCA	-	-	Mixtures with (100% CRCA and 100% FNA) and (100% FRCA+100% NCA) showed good performance compared to the mixture with NA only in terms of indirect tensile strength ratio, deformation strength, permanent deformation, and ITS. The mixture with RCA (100% coarse and 100% fine) showed not good performance.
Zhu et al., 2012	CRCA & FRCA	C.S. G= 2.584 C.W. A= 6.76 F.S. G= 2.629 F.W. A= 16.8	Pretreatment (pre-coating) method to the coarse RCA by using liquid silicone resin	Addition coarse RCA without treatment causes poor moisture resistance and low temperature flexibility. The addition of treated RCA work to improve these properties. The addition of treated RCA improves strength, absorption and adhesion with asphalt while it has a negative effect on permanent deformation at high temperature. However, mixture properties at high temperatures are still acceptable.
Pasandín and Pérez, 2013	0%, 5%, 10%, 20% and 30% in size 4/8 mm and 8/16 mm	S.G = 2.63, W.A = 5.08	Mixtures left in an oven for 4hrs at 170°C before compaction	Resilient modulus, permanent deformation (up to 30%), fatigue life (up to 20%), Marshall stability showed good results with high stiffness and a strong dependence on temperature.

C.S.G= Coarse recycled concrete aggregate specific gravity; F.S.G= Fine recycled concrete aggregate specific gravity; C.W.A= Coarse recycled concrete aggregate water absorption; F.W.A= Fine recycled concrete aggregate water absorption; RBM= Reclaimed building materials; CRBM= Coarse reclaimed building materials

- ❖ It should be noted that investigation of RCA impact on the volumetric properties of the asphalt mixtures is rarely found in the relevant literature, and hence, a considerable lack of knowledge in this area presently exists. In addition, to the best of the authors' knowledge, there are no investigations that have examined the influence of treated RCA on the volumetric properties of HMA mixtures.
- ❖ Globally, there are limited studies involving the use of RCA in asphalt mixtures, while there are no studies about this topic in the Canadian literature. As the use of RCA in asphalt mixtures has become a new topic in the literature recently, the investigation into the effect of moisture damage in RCA asphalt mixtures will be an innovative topic that will contribute to the global literature.

CHAPTER 3
RESEARCH METHODOLOGY, MATERIALS, AND TESTING

3.1 Research Methodology

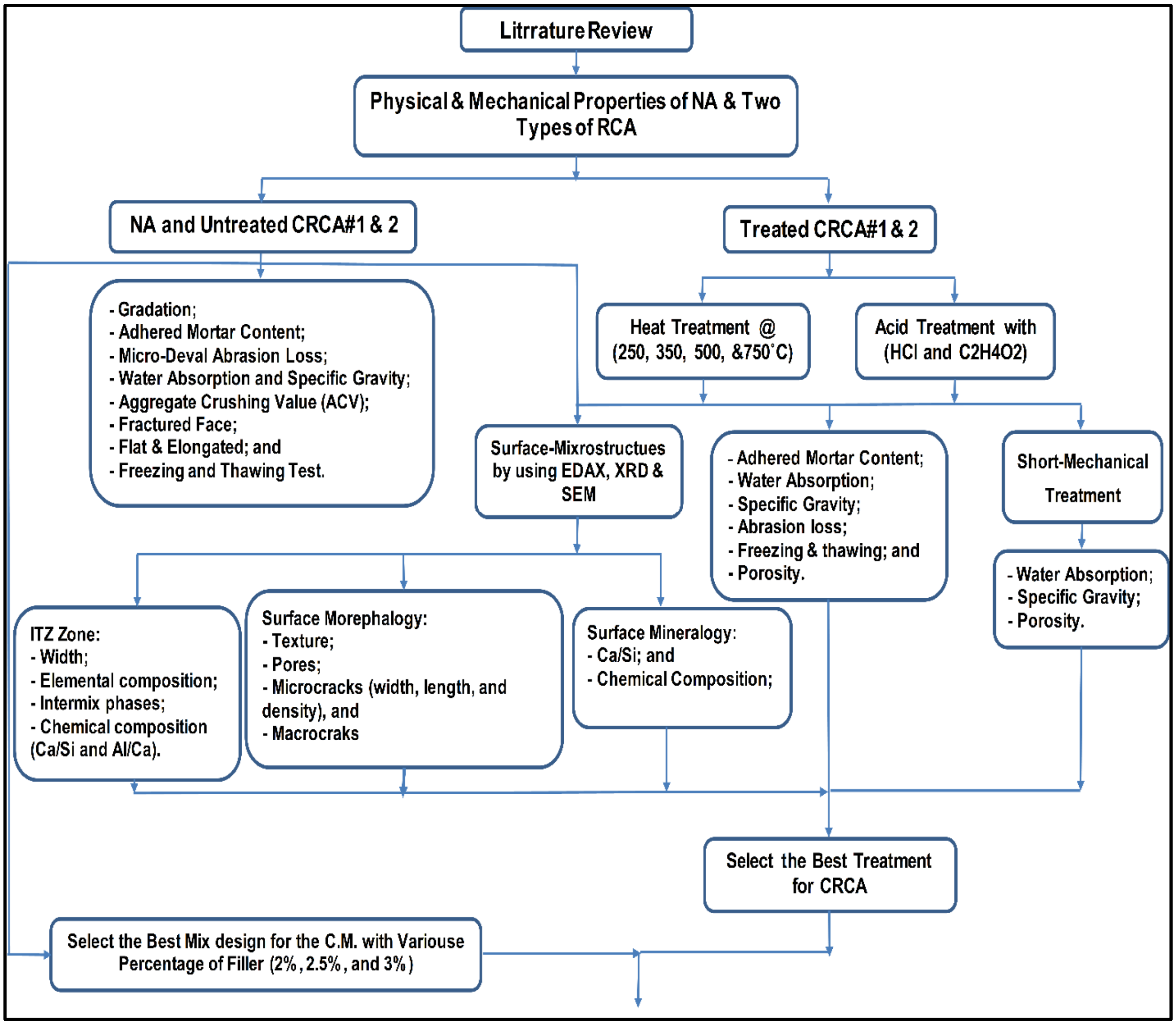
The overall objective of this study is to investigate the use of CRCA as an alternative for coarse NA in HMA according to Ontario specifications. This objective is achieved through a number of major goals: the first goal is the assessment of improving physical and mechanical properties of various CRCA types. The second goal is the evaluation of surface microstructure of different CRCA types, and the third goal is the assessment of volumetric properties of asphalt mixtures. The fourth major goal is the assessment of the application of treated and untreated CRCA of different types in typical Ontario HMA mixtures.

A study of the literature indicated that there is an urgent need to verify the impact of these materials on typical Ontario HMA mixtures. Both the lack of information within the Province of Ontario about the use of this type of material in asphalt mixtures, and the large available quantities of these materials, are the main reasons behind this urgent necessity. This study is conducted to evaluate the performance of several prepared samples in the University of Waterloo's CPATT laboratory and various other laboratories at the University of Waterloo.

This experimental program is designed to evaluate the mechanistic properties and performance of typical Ontario HMA mixtures with two different types of RCA at different percentages with one type of NA. The research also includes the study of physical, mineral and morphological properties of both untreated and treated CRCA. In addition, it evaluates combinations of different treatment types, which includes two different types of acids, various temperatures and two types of mechanical treatment after the evaluation of each separate type of treatment. The primary outlined test protocols for the characterization of physical and mechanical properties of NA and CRCA cover various factors including gradation, specific gravity, water absorption, ACV, flat and elongated, adhered mortar loss content and Micro-Deval abrasion. In addition, the primary test protocols for evaluating the performance of the HMA mixtures include various tests such as ITS test, dynamic modulus test, TSRST test, and rutting test. The evaluation of surface characterization of untreated and treated CRCA and NA includes the use of advanced techniques such as SEM, XRD, and EDAX. These techniques are utilized to examine morphological and mineralogical analyses. The research structure and experimental test combinations used to meet the outlined objectives in this study are shown in Figure 3.1.

3.2 Materials

One NA type and one filler type (commonly utilized for preparing asphalt mixtures; namely, dust plant) were obtained from the Miller Group, and one type of asphalt binder; namely, PG 64-28 was used. In this research, two different RCA types were utilized. RCA#1 was provided from a ready-mix concrete plant through the crushing process of concrete that has unsatisfactory properties, performance, and age. Hence, RCA#1 can be categorized as fresh concrete that has not been used in civil engineering works. The second type, RCA#2, is classified as a granular A according to the Ontario provincial standard specifications (OPSS.MUNI 1010). RCA#2 was produced by Steed and Evans Limited in St. Jacobs, Ontario. From the relevant literature, it has been previously reported that coarse recycled aggregate has a lower proportion of adhered mortar compared to fine recycled aggregate (De Juan and Gutiérrez, 2009; Akbarnezhad et al., 2013). Accordingly, it is expected that coarse recycled aggregate possesses higher quality properties; thus, its use is likely to be more successful; than the fine recycled aggregate type. Hence, from the economic and the potential success perspective, enhancing the properties of a material that has a relatively high quality in comparison with the poor-quality characteristics of other materials appears to be quite reasonable. Based on the factors mentioned above, the present investigation primarily focuses on the CRCA fraction in recycled concrete aggregate. In this investigation, the CRCA is described as the fraction of RCA that is retained during sieving, ranging between 4.75 and 19 mm. The optical images of NA, RCA#1 & RCA#2 are shown in Figure 3.2 (a, b, and c), respectively.


Litrrature Review
Physical & Mechanical Properties of NA & Two Types of RCA
NA and Untreated CRCA#1 & 2
Treated CRCA#1 & 2
- Gradation;
- Adhered Mortar Content;
- Micro-Deval Abrasion Loss;
- Water Absorption and Specific Gravity;
- Aggregate Crushing Value (ACV);
- Fractured Face;
- Flat & Elongated; and
- Freezing and Thawing Test.
Heat Treatment @ (250, 350, 500, &750˚C)
Acid Treatment with (HCl and C2H4O2)
Surface-Mixrostructues by using EDAX, XRD & SEM
- Adhered Mortar Content;
- Water Absorption;
- Specific Gravity;
- Abrasion loss;
- Freezing & thawing; and
- Porosity.
Short-Mechanical Treatment
- Water Absorption;
- Specific Gravity;
- Porosity.
ITZ Zone:
- Width;
- Elemental composition;
- Intermix phases;
- Chemical composition (Ca/Si and Al/Ca).
Surface Morephalogy:
- Texture;
- Pores;
- Microcracks (width, length, and density), and
- Macrocraks
Surface Mineralogy:
- Ca/Si; and
- Chemical Composition;
Select the Best Treatment for CRCA
Select the Best Mix design for the C.M. with Variouse Percentage of Filler (2%, 2.5%, and 3%)

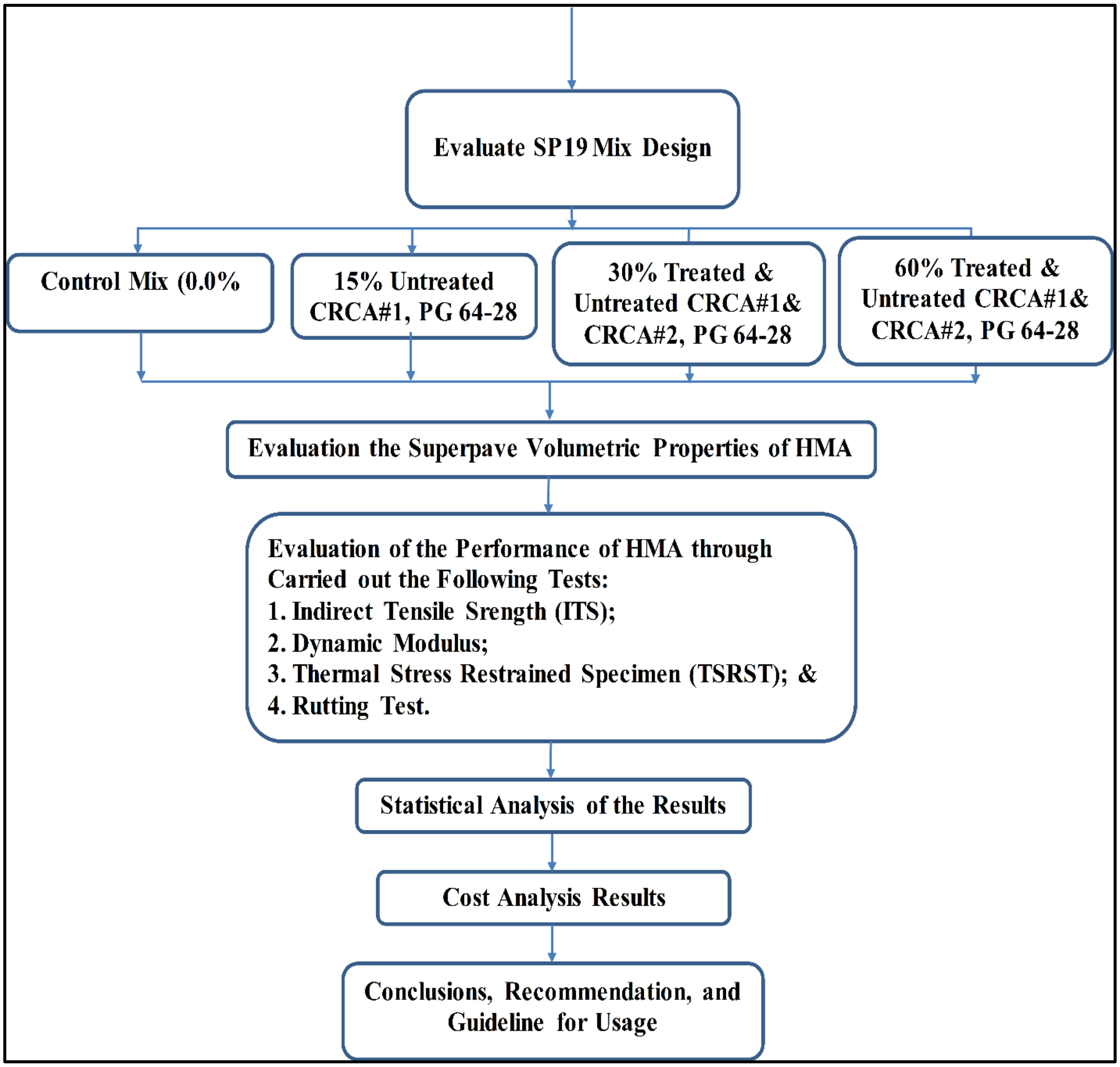
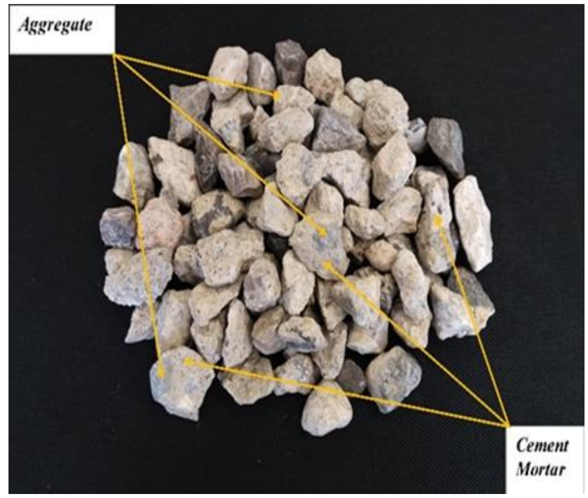
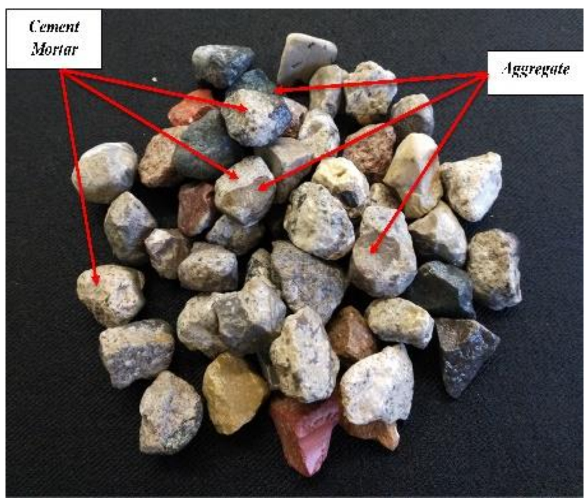


Figure 3.1: Research Methodology.



(a) NA **(b) RCA#1**



(c) RCA#2

Figure 3.2: Optical images of NA & RCA types.

3.3 Description of Test Protocols of Aggregate

In order to determine the suitability of aggregate types NA and RCA for pavement construction and comparison between the properties of CRCA and NA, the physical properties of all aggregate types are tested and evaluated in the CPATT laboratory at the University of Waterloo. The CRCA is washed thoroughly, so that all noticeable impurities such as wood chips and others are removed. Then, the CRCA is dried in an oven at 110±5 °C for 24 hours. Then CRCA is then cooled to room temperature before conducting various types of treatments and tests. The tests on untreated CRCA are performed at room temperature, whereas the treated CRCA samples are subjected to different treatment types and conditions. For acid treatment, the CRCA is soaked in 0.1 mole of acidic solution for 24 hours, then the sample follows the same required steps as the untreated CRCA for conducting specific tests. The CRCA aggregate is heated to the treatment temperature (250 °C, 350 °C, 500 °C and 750 °C) for one hour, then the sample follows the same required steps as the untreated CRCA for conducting each specific test.

3.3.1 Specific Gravity and Absorption

The bulk and apparent specific gravity and water absorption testing of coarse NA and untreated and treated RCA is conducted in accordance with the test procedures outlined in ASTM C127. The steps of this procedure can be summarized as the following:

- Approximately 3 kilograms (kg) (which is the required weight for the test) of oven dry aggregate of 19 mm size is sieved to remove any passing material using a 4.75 mm sieve;
- The sample is immersed in water for 24 ± 4 hours at room temperature, then the excess water is removed, after which the aggregate is dried with a towel to remove surface moisture and ensure the aggregate has reached a saturated surface dry condition (SSD) and then the weight of aggregate in this case is taken “B”;
- The sample aggregate is immersed in water at a temperature 23 ± 2.0 °C in a basket, then the sample is weighed in water “C”.
- The sample is removed from the water and dried in an oven at a temperature of 110 ± 5 °C, then it is cooled with air to room temperature for 1 to 3 hours; the dry sample is weighed “A” (ASTM, 2012).

The results of this test can be calculated using the following equations:

$$Relative\ density\ (Specific\ gravity\ (oven\ dry) = \frac{A}{(B-C)} \quad \ldots\ldots\ldots\ldots\ (3\text{-}1)$$

$$Apparent\ Specific\ gravity = \frac{A}{(A-C)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3\text{-}2)$$

$$Relative\ density\ (specific\ gravity)(SSD) = \frac{B}{(B-C)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3-3)}$$

$$Absorption, \% = \frac{B-A}{A}\ x100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-4)}$$

3.3.2 Determination of the Porosity

The porosity is calculated by the equation which is adapted from the literature depending on water displacement method by taking advantage of the results of the specific gravity test as in the following equation (Abbas et al., 2009):

$$Porosity, n = \left[\left(1 - \frac{W_{OD}}{W_{SSD}}\right) \times SG_{SSD}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-5)}$$

Where: W_{OD} = weight of oven dry sample, W_{SSD} = weight of saturated surface dry sample, SG_{SSD} = specific gravity of saturated surface dry sample.

3.3.3 Abrasion Resistance

The method which is used to determine the abrasion resistance of aggregate is the Micro-Deval method. This method is used to evaluate the durability of aggregate under moisture condition according to ASTM D 6928-10 (ASTM, 2010). The Micro-Deval test is conducted using the following steps and an image of the device is displayed in Figure 3.3.

- Approximately 1500 ± 5 gram (g) (required weight for the test) of oven dry aggregate which of 19 mm size is recorded as a weight "A" and graded according to the ASTM D 6928 standard using the following gradation:

Passing, mm	Retained, mm	Mass, g
19.0	16.0	375
16.0	12.5	375
12.5	9.5	750

- The sample is soaked in 2.0 ± 0.05 liters of tap water at 20 ± 5 °C for minimum1 hour before conducting the test, then the soaking water which includes the sample along with 5000 ± 5 g of steel balls are placed in the stainless-steel container inside the device. After the lid of the container is closed, the device is operated at 100 revolutions per minute for two hours;

- The sample is removed from the device and poured over two types of sieves: 4.75 mm and 1.18 mm, then the steel balls are separated by using a magnetic rod;
- The retained samples on the sieves (4.75 mm and 1.18 mm) are mixed together and then dried at a temperature 110 + 5 ºC, then the weight of sample is taken "B".

The Micro-Deval abrasion loss is calculated using the following equation:

$$Micro - Deval\ Percent\ Loss = \frac{(A-B)}{A}\ x100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3\text{-}5)$$

Figure 3.3: Micro-Deval device.

3.3.4 Aggregate Crushing Value (ACV)

This method is used to determine the crushing value of all the types of aggregate according to BS 812-110: 1990. The concept of this method is based on compaction of the loose aggregate in the test cylinder through the application of a constant load rate 40 kN/min. The device image is presented in Figure 3.4 while the application of this test is conducted using the following steps:

- 25 kg of the oven dry aggregate is sieved to obtain a required gradation between 19 mm and 12.5 mm, then the graded material is divided into three samples which weigh 3 kg each.
- The steel cylindrical measure is filled with aggregate sample in three equal layers which are tamped using a tamping rod 25 times for each layer.
- The sample is transferred from the steel cylindrical measure to the test cylinder after the steel cylinder is placed on the base plate.
- The surface of the sample in the test cylinder is levelled, then the plunger is inserted into the cylinder. The uniform loads are then applied at a rate of 40 kN/min on the sample, then the load is stopped when the total load of 400 kN is reached during 10 min ± 30 s.
- The crushed material is removed from the test cylinder after the load is released, then the weight of crushed material is taken "M1".
- The crushed material is sieved on a 2.36 mm sieve, then the weight of crushed material which passes from the 2.36 mm sieve is taken "M2" (Butler, 2012; Pickle, 2014).

The ACV of the sample is calculated using the following equation:

$$ACV = \frac{M_2}{M_1} \times 100 \quad \text{(3-6)}$$

The ACV of the aggregate type is calculated as an average for three samples.

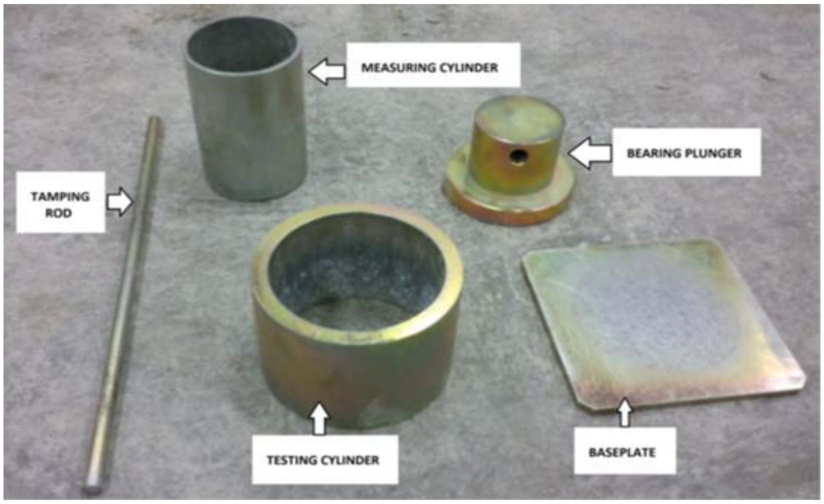


Figure 3.4: ACV testing equipment (Pickle, 2014).

3.3.5 Analysis of Adhered Mortar Loss

The method used to measure the amount of adhered mortar is adopted from Ismail and Ramli's study (2013) because there is no standard test method in the standard specifications. The amount of adhered mortar loss of CRCA is measured after conducting two types of treatment methods which are acid and heat treatment on both types of CRCA. This test is conducted through the following steps:

- 500 g of oven dry untreated and treated CRCA is taken "M1";
- The sample is placed in the Micro-Deval device with and without steel balls for 15 minutes;
- The sample is washed and sieved with a 4.75 mm sieve to ensure that only the coarse aggregate is retained, then the sample is dried in an oven at 105°C for 24 hours and weighed again "M2".

The adhered mortar loss for each aggregate is calculated by the following equation:

$$Adhered\ Mortar\ Loss\ Percent, \% = \frac{M1-M2}{M1} \quad \text{(3-7)}$$

3.3.6 Freezing and Thawing

This method is used to measure the resistance of coarse aggregate to degradation under the effect of repeated freezing and thawing in a sodium chloride solution. The results provided from this test can help in judging the durability and strength of aggregate under the impact of freezing and thawing, especially in the case of insufficient information for the materials that are exposed to real weathering circumstances in service records (LS-614, 2012). The test procedure is summarized as follows:

- For each type of dried aggregates (NA and CRCA#1 & CRCA#2), the required quantity of each size fraction of aggregate was prepared according to the LS-614 (2012) specification. The required quantity was represented by 500 g of 4.75 mm size fraction, 1000 g of 9.5 mm size fraction, 1250 g of 13.2 mm size fraction, and 2500 g of 19 mm size fraction. The above-mentioned weights were represented as an original mass.
- The samples were kept fully saturated in a 3% sodium chloride solution in suitable jars, then the jars were sealed with lids to prevent evaporation. The samples were kept at room temperature in this situation for 24 ± 2 hrs.
- The solution was drained from the samples except a remaining amount of two or three ml, the jars were sealed again.
- The samples were maintained under the impact of daily cycles of freezing and thawing for five days. The repeated cycles were performed at -18.0 ± 2.0 °C for freezing for 16 ± 2 hr and approximately 8 hours at room temperature for thawing.
- To evaluate the mass of each size fraction of aggregate after drying, the samples were put in the sieve shaker for a specific time as mentioned in the LS-614 specification. Then, the mass was recorded as a retained mass after the test.
- The percentage of loss for each fraction size of aggregate was calculated using the following equation:

$$\text{Percentage of loss} = \frac{\text{Original Mass} - \text{Retained Mass after Test}}{\text{Original Mass}} * 100 \quad \text{.............(3.8)}$$

- Then, to determine the weighted average freeze-thaw loss, the following procedure is followed:
  - Based on the total mass that is returned by the 4.75 mm sieve (Step 1), the percentage of each size fraction of the coarse aggregate was calculated.
  - Then, the Product was calculated through multiplying the percentage of each size fraction of the coarse aggregate by the percentage of loss for the same size fraction.
  - The percentage of weighted average of freezing-thawing loss for a sample was evaluated by taking sum of the calculated products and dividing by 100.

3.4 Description of Treatment Methods of CRCA

This section describes the treatment methods used to enhance the physical properties of CRCA.

3.4.1 Pre-Soaking in Acidic Solution

The oven dry untreated CRCA is soaked in an acidic solution composed of HCl (37%) and $C_2H_4O_2$ (99.7%) obtained from Sigma-Aldrich at a low concentration of 0.1 molar concentration (M) for 24 hours at room temperature around 20 °C. A low concentration of acidic solution is chosen to provide a suitable acidic environment for CRCA without an influence on the RCA quality. The CRCA is submerged in distilled water and drained to remove acidic solution, then the samples are dried at 105±5 °C for 24 hrs to prepare for testing as shown in Figure 4. The treatment method using strong HCl is adopted from the literature (Tam et al., 2007; Ismail and Ramli, 2013; Purushothaman et al., 2014), whereas, there is no mentioned use of $C_2H_4O_2$ in the literature studies.

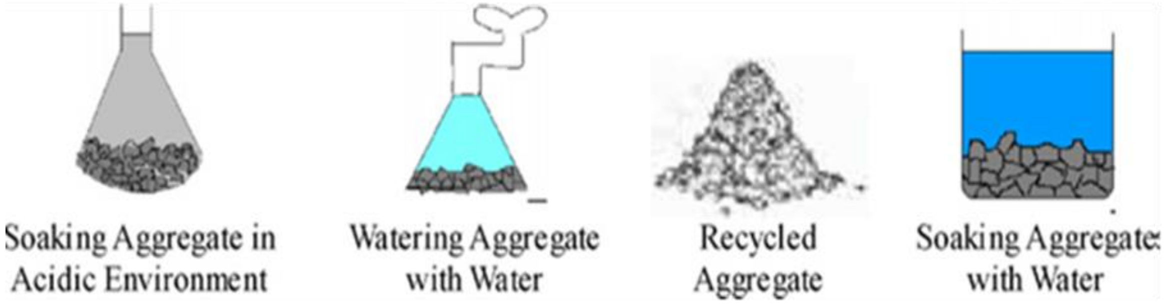


Figure 3.5: Pre-soaking treatment procedures for recycled concrete aggregate (Tam et al., 2007).

3.4.2 Heat Treatment

The oven dry untreated CRCA samples are heated at four different temperatures: 250 °C, 350 °C, 500 °C and 750 °C for a period of one hr in a conventional electric oven.

3.4.3 Short Mechanical Treatment

The oven dry samples of untreated and treated CRCA are placed in the Micro-Deval device for 15 minutes in dry condition. This method is used in two different techniques. The first includes the use of 5000 g of steel balls with the sample while the second technique is applied without steel balls. The sample is washed and sieved with a 4.75 mm sieve to ensure that only the coarse aggregate is retained, then the sample is dried in an oven at 105 °C for 24 hrs, after which the sample is used for various tests.

3.5 Surface Characterization of CRCA

3.5.1 Scanning Electron Microscopy (SEM) and Dispersive X-ray Analyzer (EDAX)

The microstructure surface morphology, ITZ and chemical composition of CRCA are investigated at Waterloo Advanced Technology Laboratory (WATL) at the University of Waterloo using SEM (Zeiss Ultra plus microscope), and EDAX, respectively. To carry out SEM and EDAX, the specimens of approximate 10 mm size are prepared, dried and coated with a thin layer of gold. The specimens are analyzed under an accelerating voltage (20 kV) at various working distances and magnification factors for SEM analysis, whereas EDAX samples are examined at an accelerating voltage of 20 kV and 100x magnification. The specimens included untreated and treated CRCA with diverse treatment types and temperature conditions. The optical image of SEM is displayed in Figure 3.6.

Figure 3.6: Optical image of SEM.

3.5.2 X-Ray Diffraction Analysis (XRD)

XRD analyses were performed using a Panalytical Empyrean diffractometer equipped with a Cu-X-ray tube and a PIXcel 3D detector, operated at 45 kV and 40 mA. Each sample was loaded into two XRD sample holders (with a diameter of 27 mm) by using back-loading technique. Data were collected in Bragg-Brentano geometry with a continuous scan over the 2θ range between 5-120°, with a step size of 0.01°. For each sample, 10 repeated 2hr-scans were performed and summed up for data analysis, corresponding to a total acquisition time of 20 hr. The optical image of XRD is displayed in Figure 3.7.

Figure 3.7: Optical image of XRD analysis.

3.5.3 Characterization of Intermix Phases

To distinguish intermix hydrate phases rich in calcium-silicate hydrate CSH, high calcium hydroxide (CH) and monosulfate (AFm), the following criterion was used in this investigation (Erdem et al., 2012; Tragardh, 1999):

CSH phase: $0.8 \leq Ca/Si \leq 2.5$, $(Al+Fe)/Ca \leq 0.2$

CH phase: $Ca/Si \geq 10$, $(Al+Fe)/Ca \leq 0.4$

AFm phase: $Ca/Si \geq 4$, $(Al+Fe)/Ca > 0.4$

3.6 Description of Test Protocols of HMA

3.6.1 HMA Superpave Mix Design

HMA Superpave mix design was performed according to AASHTO R 30-2 (2006). The design equivalent to a single-axle load ranged between 10 and 30 million. The main characteristics of the design procedure can be simply explained in the following brief descriptions. The design gyration level (N_{des}) was 100, whereas the maximum gyration level (N_{max}) was 160. The viscosity of 1.7 Poises and 2.8 Poises were established to define the mixing and compaction temperatures, respectively. Aggregate gradations of HMA specimens were individually prepared. After asphalt binder addition and mixing, samples were maintained for two hours at the compaction temperature to simulate short-term aging and ensure the asphalt binder absorption by the aggregates. The samples were mixed by using a drum mixer. The mixing temperature was 163 °C, whereas compaction temperature was 150 °C. Compaction was performed by using a Superpave gyratory compactor as shown in Figure 3.8. A picture for the samples after compaction is presented in Figure 3.9. For the included CRCA mixtures, four proportions (0%, 15%, 30%, and 60%) were added as a partial substitute for coarse NA, then mixes were prepared by following the same previous design procedure.

Figure 3.8: Superpave gyratory compactor.

Figure 3.9: Some of the compacted specimens used in the study.

3.6.2 Mechanistic Properties of HMA Mixtures

The HMA mixture behavior and mechanistic properties will be tested through the application of various tests such as:

- Indirect tensile strength,
- Dynamic modulus test,
- Thermal stress restrain specimen test (TSRST), and
- Hamburg wheel rut test (HWRT).

3.6.2.1 Indirect Tensile Strength Test (Modified Lottman Test- AASHTO T283)

The adoption of this method was by AASHTO in 1985. It was a highly accepted method from many states and transportation departments therefore it was applied in the Superpave mix design procedures to evaluate moisture susceptibility of asphalt mixtures. The ITS was determined for mixtures that included both types of CRCA: untreated and treated with various treatment methods in accordance with AASHTO T-283 method. By using a Superpave gyratory compactor with a height of 95 ± 5 mm, the samples with air voids of 7%

± 0.5 were compacted. The compacted samples were divided into two main groups in which three specimens for each group; namely, unconditioned (control) strengths and conditioned strengths. While the test temperature and loading rate were 25 °C and 50 mm/min, respectively, for the unconditioned samples, the other specimens were applied for moisture-conditioning. The conditioning firstly includes achieving a saturation between 70% and 80% for the samples. At a minimum period of 16 hrs, the samples then were placed in a freezer at a temperature of -18 ± 3 °C. After that, the specimens were placed in a hot water bath at 60 ±1 °C for 24 ±1 hr. After the hot water bath, the samples were kept in a water bath at a temperature of 25 ±0.5 °C for 2 hrs ±10 mins before the specimens were prepared for testing. Thus, the TSR ratio was determined by dividing conditioned strength by unconditioned strength. According to the standard OPSS 1151 (2007), the TSR value should be more than 80%. The ITS and TSR are calculated using the following equations (Solaimanian et. al., 2003; Zollinger, 2005):

$$ITS = \frac{2000 * P}{\pi * t * D} \quad \text{...} \quad (3\text{-}9)$$

Where: ITS = indirect tensile strength, kPa; P = maximum load, N; t = sample thickness before test, mm; D = sample diameter, mm; and π = 3.14.

$$TSR = \frac{ITS_{conditioned}}{ITS_{control}} \quad \text{.................................} \quad (3\text{-}10)$$

Where: TSR = tensile strength ratio; $ITS_{con.}$ = tensile strength of conditioned; $ITS_{uncon.}$ = tensile strength of unconditioned. The optical image of master load device for measuring ITS is displayed in Figure 3.10.

Figure 3.10: Indirect tensile strength test setup.

3.6.2.2 Hamburg Wheel Rutting Tester (HWRT)

It is known that pavement rutting represents one of the serious types of asphalt road distress that can influence the safety of the road and quality of ride, especially when its depth reaches critical values (Walubita et al., 2012; Oufa & Abdolsamedb, 2016). In this research, the HWRT was used to examine the rutting resistance of the asphalt mixtures using the AASHTO T 324-04 standard. The application of HWRT test typically simulates the impacts both of vertical compression and horizontal compaction generated by a wheel that runs over the asphalt pavement (Lee et al., 2012). In this study, the test was conducted for four replicates for each mix to obtain reliable results. By using a Superpave gyratory compactor, each mix was compacted with a height of 63 ± 2 mm and air voids of 7 ± 2%. Under the influence of a solid steel wheel with an equivalent load of 705 ± 4.5 N, the samples were tested in a hot water bath at 50 °C for 10,000 cycles, approximately equivalent to 20,000 passes, or until the rutting depth reached 20 mm (Asphalt Institute, 2010). To evaluate the rutting depth, linear variable differential transducers (LVDTs) were applied for realizing the depth under the impact of wheel loads as shown in figure 3.11.

Figure 3.11: CPATT HWTD testing setup.

3.6.2.3 Shear Flow of HMA Mixture

To obtain a better understanding of the influence of the CRCA type on the rutting resistance for the HMA mixtures, the shear upheaves on the rutting sides was evaluated. To examine the shear upheave, the following method was used. By using simple techniques such as rutting bar, the total rutting depth was firstly determined and named $total_{rutting\ depth}$. The application of this procedure simulates the method used to evaluate rutting depth in the field. As previously discussed, the rutting depth was measured in the lab using the HWRT test. The obtained value was named $lab_{rutting\ depth}$. The shear flow, known also as lateral creep, was calculated by taking the difference between $total_{rutting\ depth}$ and $lab_{rutting\ depth}$as in the following equation. A schematic drawing of the method used to evaluate shear flow is provided in Figure 3.12.

$$Shearflow\ (upheave) = total_{rutting\ depth} - lab_{rutting\ depth} \ldots\ldots\ldots\ldots \text{(3-11)}$$

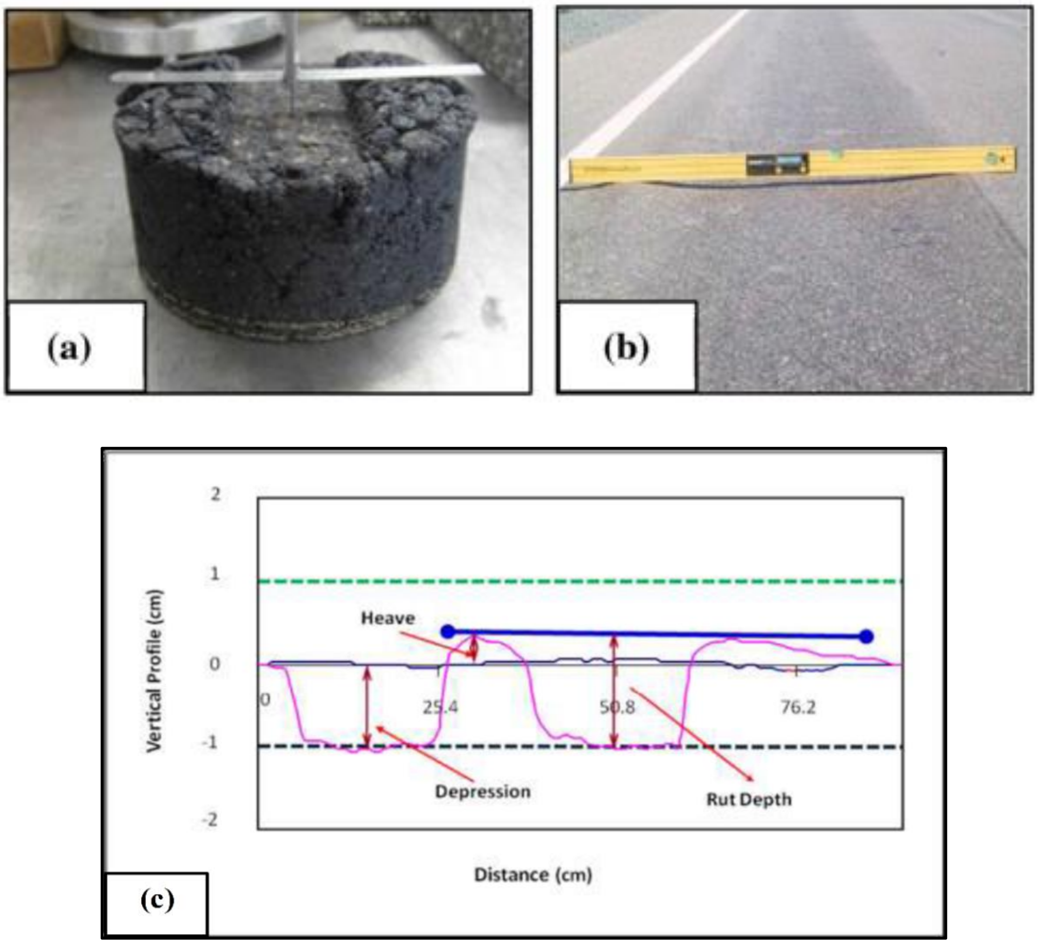


Figure 3.12: The procedure used for evaluating shear flow (upheave): (a) Total rutting depth measured with a rutting bar (Shaheen et al., 2017); (b) Rutting depth evaluated in the field (Shaheen et al., 2017); and (c) Rut profile example (Gul, 2008).

3.6.2.4 Dynamic Modulus Test

Based on AASHTO R 30-02 (2010), the loose HMA mixtures were exposed to a short-term condition at 135 °C for a period of four hrs before compaction to simulate the plant mixing and placement effects. In accordance with AASHTO TP 62-07 specification, the test was carried out to characterize stiffness for HMA mixtures at different temperatures (-10, 4, 21.1, 37, and 54.4 °C) and various load frequencies (25, 10, 5, 1, 0.5, 0.1Hz). Elevated temperature and low frequencies are regarding with slow movement of traffic, which represent the conditions for rutting. At low temperatures, the mixtures were evaluated for thermal cracking, whereas the fatigue cracking of the mixtures was examined at moderate temperatures.

Using a Superpave gyratory compactor, the cylindrical specimens were compacted. Then, the specimens were cored and cut into dimensions of 150 mm height and 100 mm diameter with air void content of 7 ± 1% as shown in Figure 3.13. A master curve was used to evaluate the dynamic stiffness (MPa) versus the reduced frequency (Hz). Figure 3.14 shows the dynamic modulus test setup in CPATT.

Figure 3.13: Coring procedure and the gyratory compacted specimen before and after cutting.

Figure 3.14: Typical dynamic modulus test setup.

3.6.2.5 Thermal Stress Restrain Specimen Test (TSRST)

Based on AASHTO R 30-02 (2006), the loose HMA mixtures were exposed to a short-term condition at 135 °C for a period of four hours before compaction to simulate the plant mixing and placement effects. An asphalt shearbox compactor (PReSBOX) was used to compact the beam specimens that were approximately 390mm x150mm x130mm in length, height, and width, respectively. Then, the beams were saw-cut into TSRST specimens with approximate dimensions 250mm× 50mm × 50mm at air voids of 7±1% as shown in Figure 3.15, that represent the typical values for compaction (AASHTO TP 10-93 1993, NCHRP 2007). The TSRST test was performed in accordance with AASHTO TP 10-93 (1993). The test specimens were conditioned at 5 °C in an environmental test chamber for six hours before starting the test. An initial tensile load is applied to the compacted beam specimens. Simultaneously, the specimen is exposed to a constant cooling rate of -10 ºC/hr and is restrained from the contraction by re-establishing the initial length of the specimen. The optical image of the TSRST test setup is shown in Figure 3.16.

Figure 3.15: Saw-cut TSRST beam procedure and the compacted asphalt beam before and after cutting.

Figure 3.16: Typical TSRST test setup.

CHAPTER 4

EVALUATION OF VARIOUS TREATMENT METHODS FOR ENHANCING THE PHYSICAL AND MECHANICAL PROPERTIES OF CORSE RECYCLED CONCRETE

In this chapter, the obtained findings of CRCA#1 have been published in the Construction and Building Materials Journal (Al-Bayati et al., 2016). The outcomes of CRCA#2 have been presented at the Transportation Association of Canada (TAC) Conference (Al-Batayti et al., 2016).

4.1 Particle Size Gradation

As mentioned earlier, the present study mainly focuses on the CRCA fraction in RCA. In this research, the CRCA is described as the fraction of RCA that is retained during sieving, ranging between 4.75 and 19 mm. The obtained sieve analysis of NA and different RCA types is given in Figure 4.1.

4.2 Properties of NA and RCA before Treatment

After utilizing different tests and protocols, the obtained results of the physical and mechanical properties of NA and different types of untreated CRCA are presented in Table 4-1.

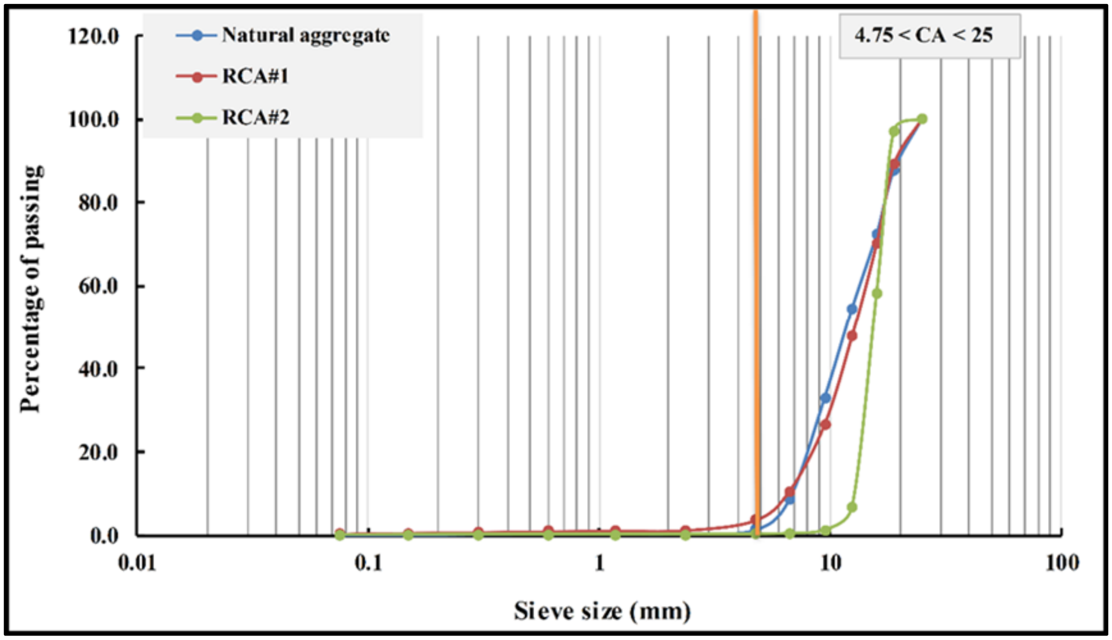


Figure 4.1: Particle size gradations of NA and RCA types.

Table 4-1: Physical and Mechanical Properties of NA and Untreated CRCA Types

Aggregate Properties/ Aggregate Types			NA	Untreated CRCA#1	Untreated CRCA#2
Bulk Relative Density (BRD), (ASTM C 127)		Physical Properties	2.658	2.295	2.421
Absorption, %, (ASTM C 127)			0.8	5.91	3.74
Fractured Particles, %, (ASTM D5821)			95.5	89.9	95.7
Flat & Elongated, %, (LS-608)			0.95	2.87	0.44
Micro-Deval Abrasion Loss, %, (ASTMD6928)		Mechanical Properties	15.89	23.57	16.03
Adhered Mortar, %	With Steel Ball		-	-	2.53
	Without Steel Ball		-	3.02	1.08
Aggregate Crushing Value (BS 882)			19.48	27.42	23.28
Freezing & Thawing (LS- 614)			17.4	18.03	15.04

4.2.1 Physical Properties of NA and CRCA before Treatment

In terms of physical properties, namely, bulk relative density (BRD) and water absorption, a considerable difference is registered between NA and both untreated CRCA#1 and untreated CRCA#2 as shown in Table 4-1. Additionally, the findings indicate that a significant difference is highly noticeable between CRCA#1 and CRCA#2 in the physical properties. The existence of adhered mortar on the RCA is the main reason behind the difference. Adhered mortar, which has a higher porosity than NA, results in the RCA being more susceptible to absorbing more water compared to NA (Al-Bayati et al., 2016). It has been previously found that the presence of adhered mortar can lead to increased water absorption, decreased density, and lower bond strength (Wong et al., 2007). While the value of water absorption that can generally range between 0-2% is 0.8%, the water absorption of untreated CRCA is considerably higher with values of 5.91% and 3.74% for CRCA#1 and CRCA#2, respectively. These findings confirm the outcomes of previous investigations which demonstrated that the absorption capacity of RCA is significantly higher than NA (Wu et al., 2013; Butler et al., 2013a; Pasandín & Pérez, 2014). A significant difference regarding the BRD property between NA and both of untreated CRCA types is also noticeable with a value of 2.658 for NA and values of 2.295 and 2.421 for CRCA#1 and CRCA#2, respectively. A more detailed discussion related to the BRD and water absorption is provided in the section of main properties of treated CRCA.

4.2.2 Mechanical Properties of NA and CRCA before Treatment

With respect to mechanical properties; namely, freezing and thawing, abrasion loss, aggregate crushing value, and adhered mortar loss, various aspects can be observed as presented in Table 4-1. For freezing and thawing, it is important to note that a small difference is registered between NA and untreated CRCA#1 with values of 17.4% and 18.03%, respectively. Surprisingly enough, untreated CRCA#2 has a lower value for freezing and thawing with a value of 15.04% compared to the value of NA. As it is widely known, this test is considered as a measure of loss of aggregate strength and cohesion under the impact of repeated freezing and thawing cycles. Hence, it has a high importance for the countries that have extreme weather conditions, more precisely, drastic changes in weather conditions. Such regions include Canada, USA, Western Europe, and Russia. Based on this, the obtained results can be applied to the durability properties of CRCA, and this represents a critical factor for RCA applications in the above-mentioned countries.

Testing of abrasion resistance for a certain aggregate type generally refers to the durability and strength of aggregate under wet conditions. This test is widely used for evaluating the hardness and abrasion resistance of aggregates. Generally, a minimum percentage of abrasion loss indicates that lower amounts of adhered mortar are lost and vice versa. It is interesting to note that the abrasion loss values of both NA and untreated CRCA#2 are almost equal, with 15.89%, and 16.03%, respectively. In contrast, a significant difference is observed between NA and CRCA#1. The obtained results suggest that CRCA#2 has a high degree of hardness and strong resistance to deterioration. To obtain a better understanding, the results are further evaluated by comparison with previous studies as shown Figure 4.2. Though literature studies indicate various values of abrasion loss, it is demonstrated that the majority of RCAs have an abrasion loss of approximately 35% - 45%. Compared to the RCA literature, the graphical data revealed that the abrasion loss of CRCA is quite low, indicating strong types of CRCA, especially CRCA#2. This conclusion is strongly supported by various other results.

Adhered mortar loss is an important issue. It is known that adhered mortar loss refers to an amount of attached mortar that could be removed from the RCA surface using different mechanical methods and various chemical techniques. By using a mechanical method with two different techniques, the Micro-Deval device was used to evaluate adhered mortar loss of CRCA surface. It is important to note that the percentage of adhered mortar loss from CRCA#2 was only approximately 1.1% under no impact, and 2.5% under the impact of steel balls. In contrast, with no impact of steel balls, the percentage loss of adhered mortar for CRCA#1 was 3.0%. The obtained values also indicate a type of CRCA that has a strong resistance to degradation. Hence, these findings strongly support the results of other mechanical tests.

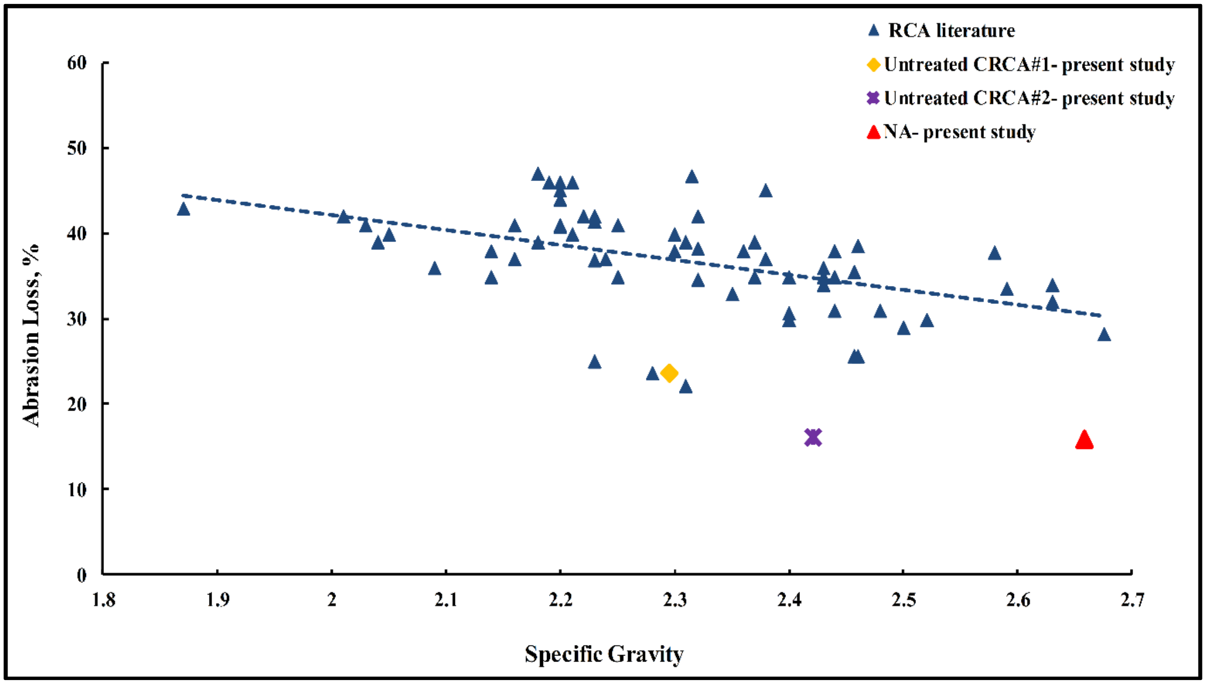


Figure 4.2: Abrasion loss of untreated CRCA compared with some available RCA literature studies.

Another important issue is the strength of aggregate. In general, aggregate strength represents an important factor for concrete, particularly high strength concrete, and frequently traveled asphalt pavements. Thus, the influence of aggregate strength should not be neglected when evaluating the strength of PC concrete and asphalt pavements. BS (812-110) evaluates the relative strength of aggregate in concrete and seems to be a quite reasonable option for determining aggregate strength (British Standards Institution, 1990). Based on BS (882:1992), the applications of different aggregate types are categorized according to maximum crushing values of various aggregate kinds as shown in Table 4-2. An important difference is recorded in the ACV values for NA and untreated CRCA types with an approximate value of 19.5% for NA and approximate values of 27.4% and 23.3% for CRCA#1 and CRCA#2, respectively. Depending on the above-mentioned categorization, the outcomes indicate that NA and untreated CRCA#2 can be used in the production of concrete that is utilized in heavy-duty applications. Meanwhile, untreated CRCA#1 is suitable for pavement wearing surfaces according to the same classification. These findings also emphasize the obtained results of previous mechanical properties that refer to a strong type of CRCA.

Table 4-2: Aggregate Crushing Value Classifications Based on BS (882:1992)

ACV	Applications
< 25%	Aggregate could be used in the production of heavy-duty concrete floor finishes
Between 25%-30%	Aggregate type could be utilized in the concrete used for pavement wearing surfaces
Between 30%-45%	Aggregate could be utilized in concrete used for other applications

4.3 Effect of Treatments on Physical Properties of CRCA

4.3.1 Influence of Treatments on Absorption and Specific Gravity

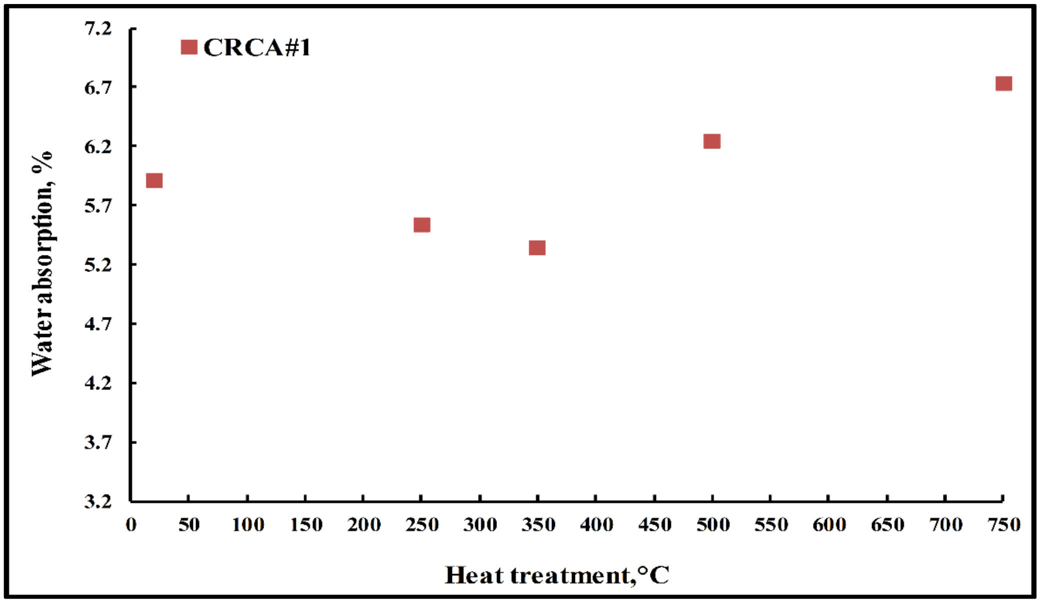
Table 4-3 shows the obtained results of water absorption, specific gravity (BRD), apparent specific gravity and bulk relative density (SSD) for various CRCA types after applying different treatment types and conditions. It is well known that there is an inverse relationship between density and the water absorption for CRCA due to the presence of attached mortar, which results in higher water absorption, lower density and weaker bond strength (Wong et al., 2007). Therefore, the water absorption of CRCA increases as the attached mortar increases (Butler, 2012). It is well known from the literature that the use of treatments improves CRCA quality through increasing density and decreasing water absorption, depending on treatment type and treatment condition (Tam et al., 2007; Ismail and Ramli, 2013; Güneyisi et al., 2014). The results show that the applied treatments, heat treatment and acid treatment, have effectively removed a great portion of cement mortar from CRCA, which helps to improve the density and absorption of CRCA. Similar findings were reported by other researchers (Shima et al., 2005; Tam et al., 2007; Sui and Mueller, 2012; Ismail and Ramli, 2013; Güneyisi et al., 2014). As can be seen in Table 4-3, both types of CRCA exhibit the same behavior in response to the two types of heat and acid treatment. The heat treatment for CRCA#1 and CRCA#2 has a maximum influence at 350 °C, which results in higher specific gravity, apparent specific gravity, SSD and lower absorption with an approximate decrease of 9.5% and 11.23% for water absorption of CRCA#1 and CRCA#2, respectively. Regarding acid treatment, HCl has more effect than acetic acid on both types of CRCA, generating a decrease of 4.23% and 10.43% for water absorption for CRCA#1 and CRCA#2, respectively. It is also observed that the results of specific gravity and water absorption at 500°C and 750°C for both types of CRCA are in contrast with the other results. This indicates that the exposure of CRCA to thermal expansion and consequent internal stresses highly affected the mechanical performance of concrete in the temperature range between 400 °C and 600 °C. CRCA suffers from decarbonation (the release of carbon dioxide) which causes severe microcracking of the cement matrix between 600 °C and 800 °C (Vieira et al., 2011). Therefore, CRCA suffers from degradation, and there is a breakdown and mass loss of concrete particles due to exposure to high temperatures (Gupta et al., 2012; Wong et al., 2007).

Table 4-3: Influence of Treatments on Specific Gravity and Water Absorption for Various CRCA Types

CRCA Treatment/ Property	Bulk Relative Density (BRD)		Apparent Specific Gravity		Bulk Relative Density (SSD)		Absorption*, %	
	CRCA#1	CRCA#2	CRCA#1	CRCA#2	CRCA#1	CRCA#2	CRCA#1	CRCA#2
Untreated CRCA	2.295	2.421	2.638	2.662	2.425	2.512	5.91	3.74
Treated CRCA heat at 250°C	2.309	2.436	2.648	2.668	2.437	2.523	5.54	3.57
Treated CRCA heat at 350°C	2.334	2.454	2.667	2.672	2.458	2.536	5.35	3.32
Treated CRCA heat at 500°C	2.254	2.409	2.623	2.659	2.394	2.503	6.25	3.90
Treated CRCA heat at 750°C	2.302	-	2.652	-	2.434	-	6.73	-
Treated CRCA soaking in $C_2H_4O_2$	2.299	2.431	2.651	2.663	2.432	2.518	5.79	3.51
Treated CRCA soaking in HCl	2.305	2.452	2.651	2.671	2.435	2.534	5.66	3.35

* The MTO OPSS 1003 specification limit is 2.0% Max.

To obtain a better understanding, the obtained findings are further assessed. The behaviour of both water absorption and apparent specific gravity are graphically plotted in Figures 4.3 and 4.4. Within the temperature range between 20 °C and 350 °C, the outcomes indicate a good relationship between these properties and the temperature of treatment is observed. However, heat treatment at high temperatures that range between 350 °C and 500 °C has a negative influence by lowering apparent specific gravity and increasing water absorption. Moreover, it can be clearly concluded that these characteristics have an opposite behavior when the heat treatment method is used.



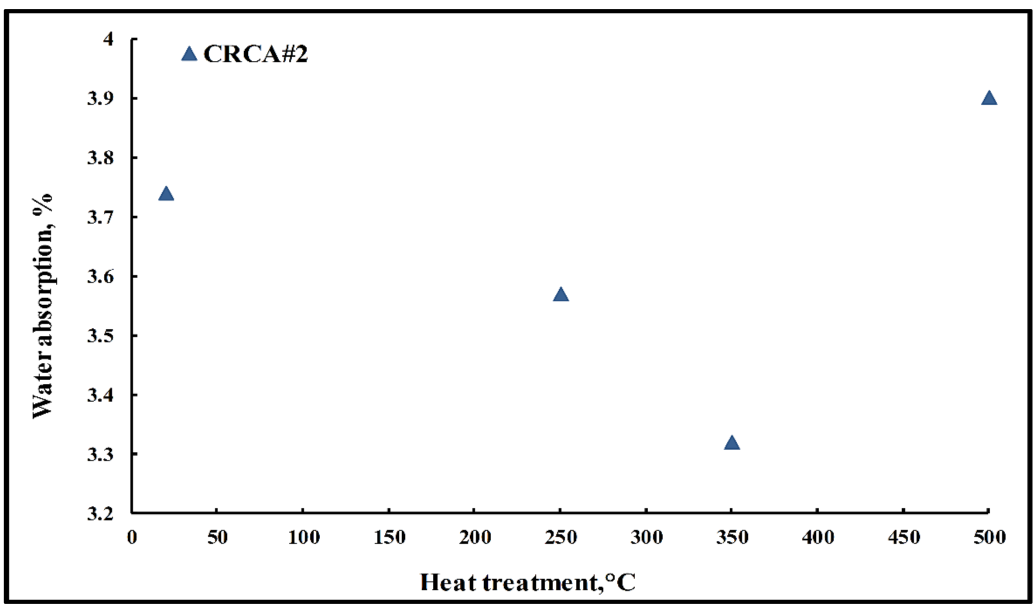


Figure 4.3: Behaviour of water absorption through heat treatment.

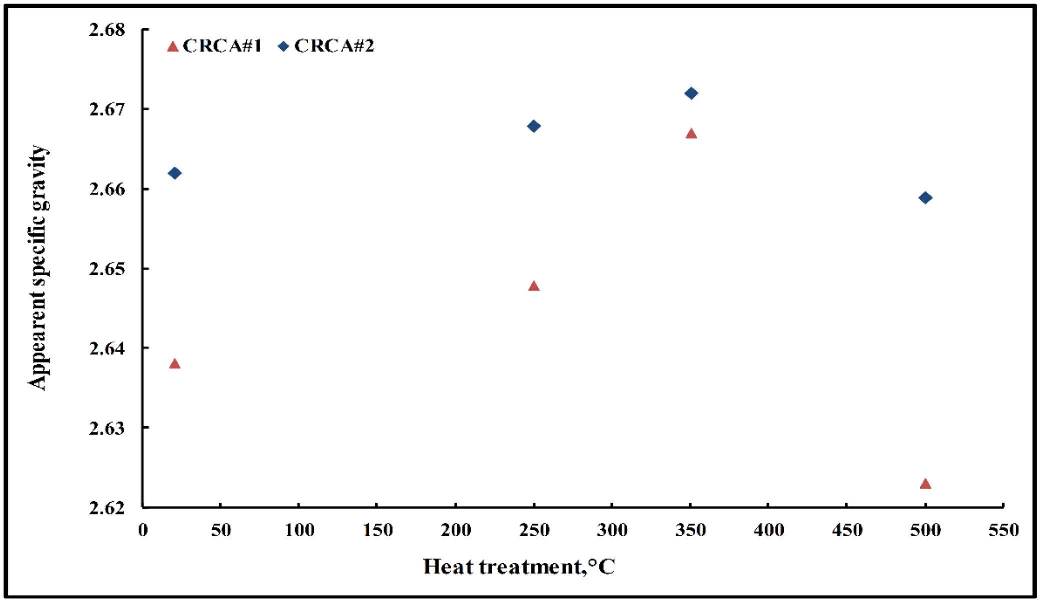


Figure 4.4: Apparent specific gravity through heat treatment.

4.3.2 Influence of Treatments on Porosity

Generally, a slight porosity improvement for different types of CRCA is obtained after the different treatment types are applied. However, a significant reduction in porosity is recorded for heat treatment at 350 °C with approximate reductions of 8% and 10.3% for CRCA#1 and CRCA#2, respectively. Interestingly, it is observed that there is a weak influence with acid treatment on the porosity of CRCA#1 with a decrease of only 3.7% and 1.6% for HCl and acetic acid respectively as shown in Table 4-4. In contrast, a significant improvement in the porosity of CRCA#2 was obtained after the same above-mentioned acid treatment types with approximate decreases of 9.9% and 4.4% for HCl and acetic acid treatment, respectively. However, acid treatment with strong acid appears to be more effective than weak acid for improving the porosity of CRCA. At higher temperatures above 350 °C, it is also demonstrated that heat treatment has a negative influence on the porosity of CRCA. This was found for both CRCA types.

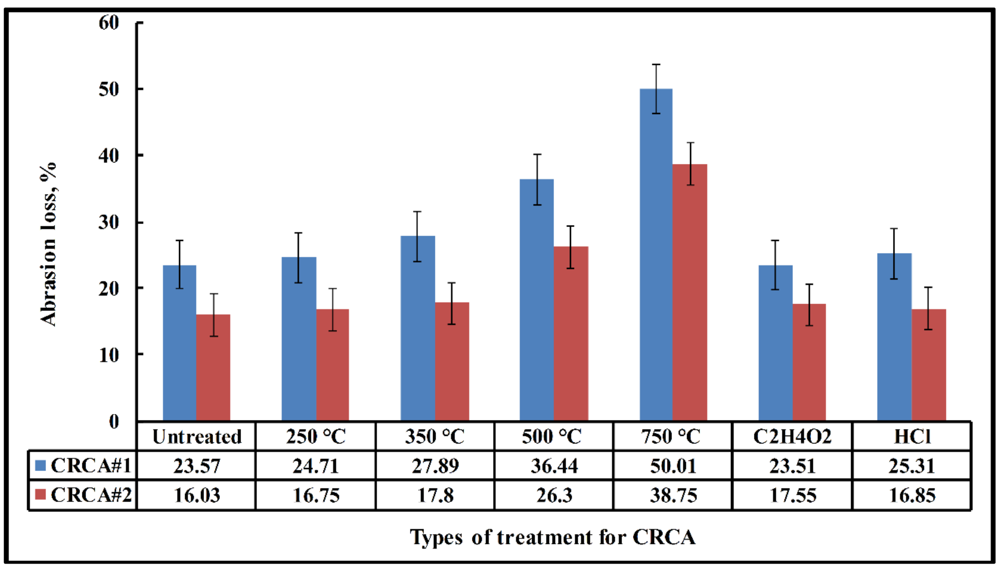
Table 4-4: Porosity Percentage of CRCA with Different Treatments

CRCA Treatment Type	Porosity, % RCA#1	Porosity, % RCA#2
Untreated CRCA at 20°C	13.56	9.1
Treated CRCA heat at 250°C	12.80	8.7
Treated CRCA heat at 350°C	12.48	8.16
Treated CRCA heat at 500°C	14.10	9.4
Treated CRCA heat at 750°C	15.35	-
Treated CRCA soaking in $C_2H_4O_2$	13.34	8.7
Treated CRCA soaking in HCl	13.06	8.2

4.4 Effect of Treatments on Mechanical Properties of CRCA

4.4.1 Influence of Treatments on Abrasion Resistance

An abrasion resistance test for aggregate materials measures the durability of aggregate under wet conditions. The obtained results after one cycle of the abrasion resistance test in the Micro-Deval device are shown in Figure 4.5. Generally, a higher percentage of abrasion loss corresponds to losing greater amounts of adhered mortar. For both CRCA types, it can be observed that CRCA without treatment has a lower percentage of abrasion loss compared to CRCA that underwent various treatment types. This indicates that treatment results in a positive effect with respect to the removal of attached adhered mortar from CRCA. The obtained outcomes demonstrated that there is a significant difference in the percentage of loss between the types of CRCA. However, the results indicated that CRCA#2 has a lower percentage of loss than CRCA#1. Compared to untreated CRCA, the percentage of loss for CRCA when treated with heat at 250 °C and 350 °C increased by 4.8% and 18.3% for CRCA#1, whereas the percentage of abrasion loss increased by 4.5% and 11% for CRCA#2 at the same temperatures. For high temperatures, the test results also showed that there is considerable difference in the percentage of abrasion loss, increasing for CRCA which, when treated with temperatures of 500 °C and 750 °C, reached 54.6%, 112.2% for CRCA#1 and 64.1%, 141.7% for CRCA#2, respectively. Therefore, the results of abrasion resistance tests at 500 °C and 750 °C confirm water absorption behaviour at the same temperatures. The aggregate types suffered from thermal expansion followed by internal stresses due to exposure to high temperature between 400 °C and 600 °C (Wong et al., 2007; Vieira et al., 2011; Gupta et al., 2012). There is serious microcracking of the cement matrix as a result of the decarbonation process when the material is exposed to a higher temperature range between 600 °C and 800 °C (Vieira et al., 2011). As a result, breakdown of material and mass loss predominantly occurred, leading to easy removal of adhered mortar under the influence of steel balls in the Micro-Deval test. For acid treatment, soaking in the low concentration of HCl solution increased the percentage of abrasion loss by 7.4% and 5.1% for CRCA#1 and CRCA#2, respectively. Previous research from Ismail and Ramli (2013) confirmed that HCI has the potential to remove the loose adhered mortar. It is interesting to note that the treatment with weak acid solution had no impact on the percentage of abrasion loss of CRCA#1, whereas the percentage of loss was 9.48% for CRCA#2 using the same acidic solution.



	Untreated	250 °C	350 °C	500 °C	750 °C	C2H4O2	HCl
CRCA#1	23.57	24.71	27.89	36.44	50.01	23.51	25.31
CRCA#2	16.03	16.75	17.8	26.3	38.75	17.55	16.85

Figure 4.5: Micro-Deval abrasion loss through different treatment types.

The abrasion loss behavior through heat treatment is presented for both CRCA types in Figure 4.6. For different CRCA types, the obtained results demonstrated that abrasion loss is strongly correlated with the temperature of heat treatment due to obtaining an optimum regression. Although there are different CRCA types, a polynomial equation obviously reflects the behavior of abrasion loss through this type of treatment.

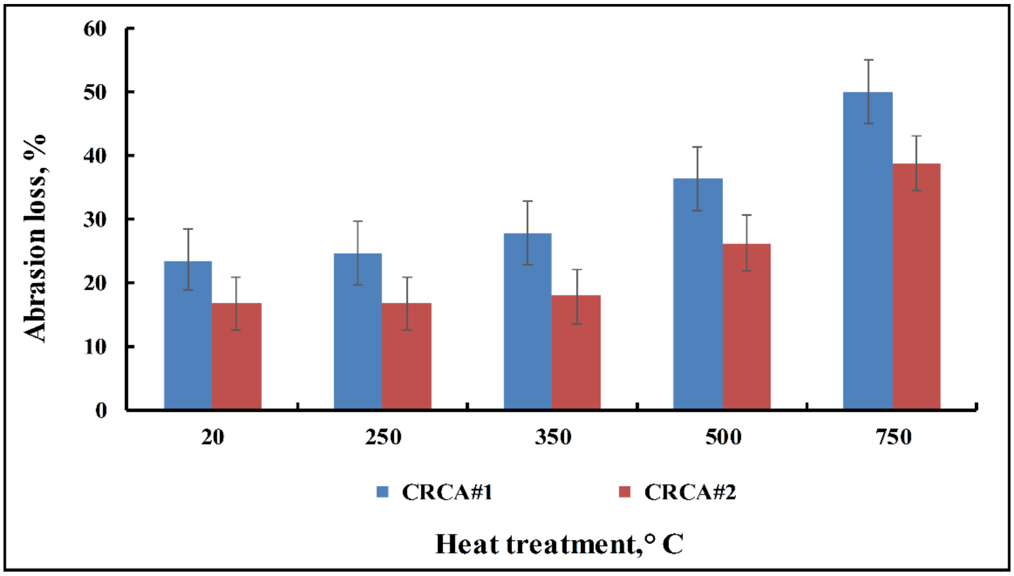


Figure 4.6: Behaviour of abrasion loss through heat treatment.

4.4.2 Influence of Treatments on Freezing and Thawing

The experimental results after five cycles of freezing and thawing are illustrated in Table 4-5. It shows there is an improvement in the resistance of freezing and thawing of CRCA after various treatment types. However, a significant improvement is registered for the acetic acid treatment to the resistance of freezing and thawing which is decreased by more than 16%, whereas the resistance of freezing and thawing is lowered by only 7% with HCl treatment. In addition, it can be observed that heat treatment at 250 °C enhanced the resistance of freezing and thawing by 9.0% which is decreased to only 3.0% when the temperature reached 350°C. In contrast, resistance to freezing and thawing is increased by 16.0%, recording a negative influence on these parameters for heat treatment type at 500 °C.

Table 4-5: Freezing and Thawing Percentage of CRCA#1 with Different Treatments

CRCA Treatment Type	(%) Percentage of Loss
Untreated CRCA at 20 °C	18.03
Treated CRCA heat at 250 °C	16.40
Treated CRCA heat at 350 °C	17.56
Treated CRCA heat at 500 °C	20.99
Treated CRCA soaking in $C_2H_4O_2$	15.09
Treated CRCA soaking in HCl	16.77

4.4.3 Influence of Treatments on Adhered Mortar Loss

The obtained results of adhered mortar loss and its behavior through heat treatment were further analyzed and presented in Figures 4.7 and 4.8, respectively. As mentioned earlier in the abrasion loss section, the amounts of adhered mortar loss thoroughly reflect the results of the abrasion loss test, which can be defined as resistance to mechanical abrasion, consequently it is highly related to durability characteristics. The obtained findings revealed that untreated CRCA has a minimum percentage of adhered mortar loss compared to CRCA treated with different treatment types. This indicates an effective outcome for different treatment methods on removing adhered mortar from the CRCA surface at various percentages. Generally, CRCA#2 has a smaller adhered mortar loss less than CRCA#1. Among the test results, CRCA#1 treated with acetic acid and a temperature of 350°C has very close values: 3.92% and 3.98%, respectively. Similarly, CRCA#2 treated with the same treatments has relatively convergent values: 2.61 and 2.42, respectively. One may also observe that the adhered mortar loss for CRCA#1 treated with HCI acid is 4.56%. As mentioned in abrasion resistance results, the abrasion loss was increased by 18.3% and 7.4% for CRCA treated with a temperature of 350°C and HCl solution, respectively. This behaviour was also found for CRCA#2. This indicates that there is an inconsistent result regarding abrasion loss and adhered mortar loss. This is because a material which has a high percentage of abrasion loss usually has a high adhered mortar loss. This could be explained by the fact that there is a noticeable difference between the two tests. The abrasion loss test uses water, whereas there is no water present during the operation of the adhered mortar loss test. The assumption is that the water fills CRCA pores, creates a layer when pores are saturated, and works as a lubricant film to reduce friction during the abrasion test. It is noted that there is a relationship between temperature and adhered mortar loss, which increases with rising temperature for both types of CRCA. In terms of the values of adhered mortar loss, a significant difference is also observed between the two CRCA types as can be seen in Figure 4.8.

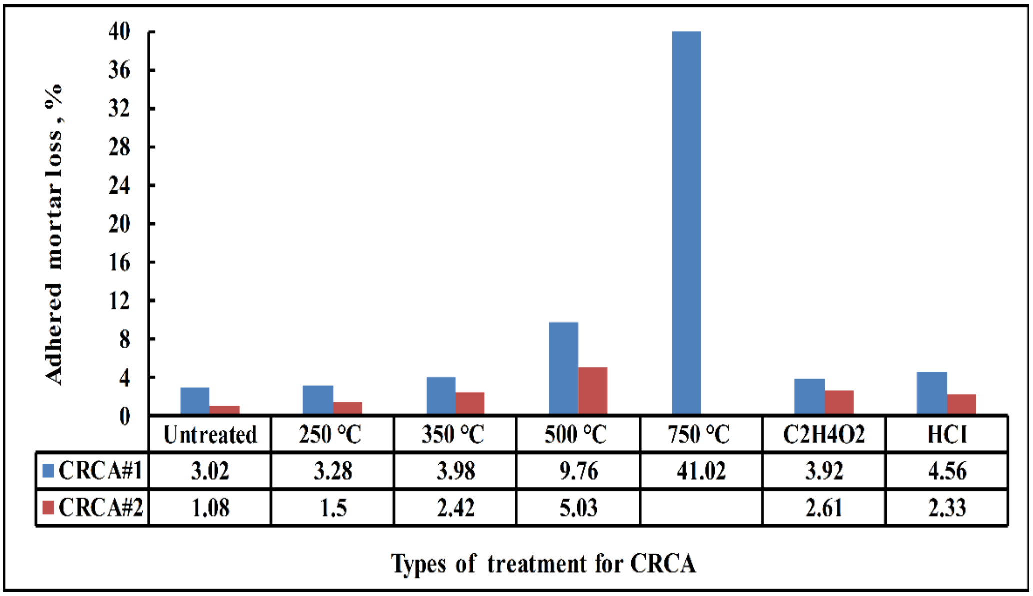


Figure 4.7: Adhered mortar different loss with treatments.

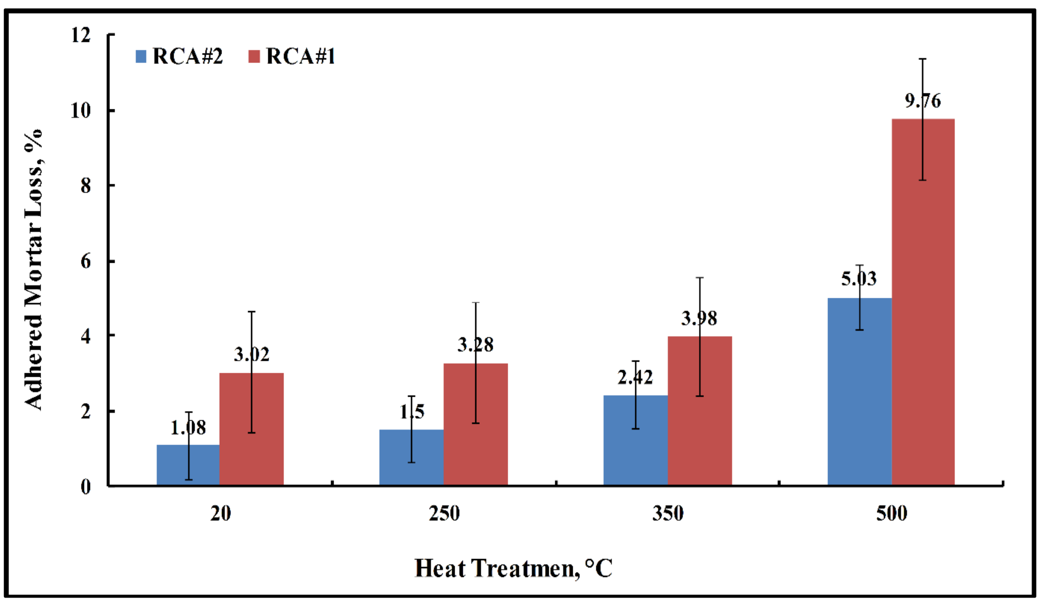


Figure 4.8: Behaviour of adhered mortar loss through heat treatment.

4.5 Relationship between Physical and Mechanical Properties

Figures 4.9 and 4.10 demonstrate the relationship between water absorption of CRCA and abrasion loss and resistance to freezing and thawing under impact of heat treatment.

Complicated and nonlinear relations are obtained that obviously reflect the behaviour of these characteristics. A considerable correlation thoroughly indicates a strong connection between water absorption and two different mechanical properties. Figure 4.11 shows the relationship between porosity and durability of CRCA in terms of abrasion loss. It is observed that there is a second order equation with a significant regression which indicates a strong connection between physical property and other mechanical factors, namely, porosity and abrasion loss under the effect of heat treatment. As a result, it is clearly noticeable that physical properties of CRCA including porosity and water absorption are strongly correlated with durability characteristics in terms of resistance to freezing and thawing and resistance to abrasion.

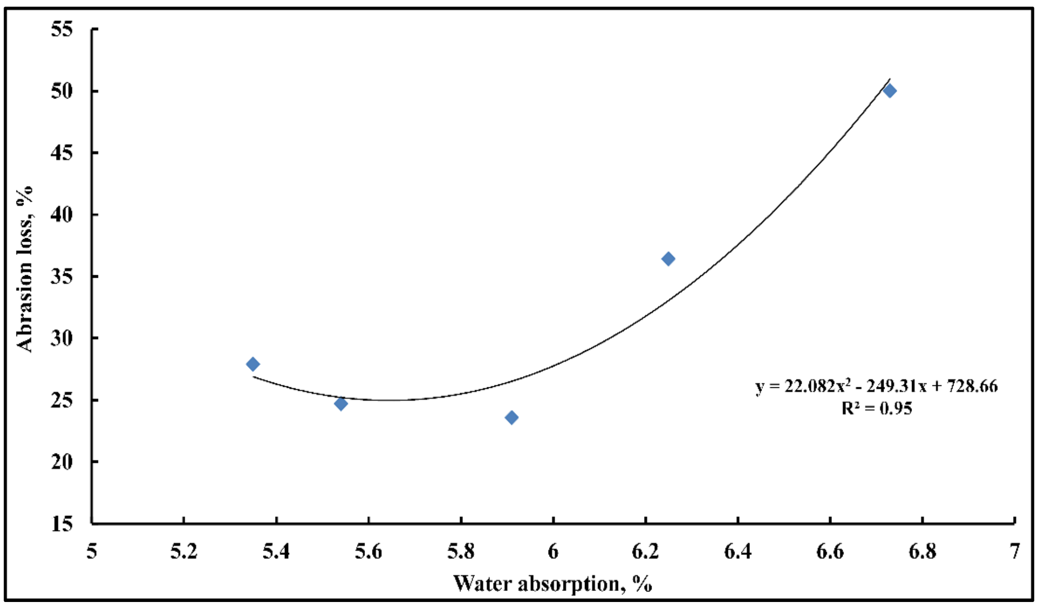


Figure 4.9: Relation between absorption and abrasion loss through heat treatment (Al-Bayati et al., 2016 a).

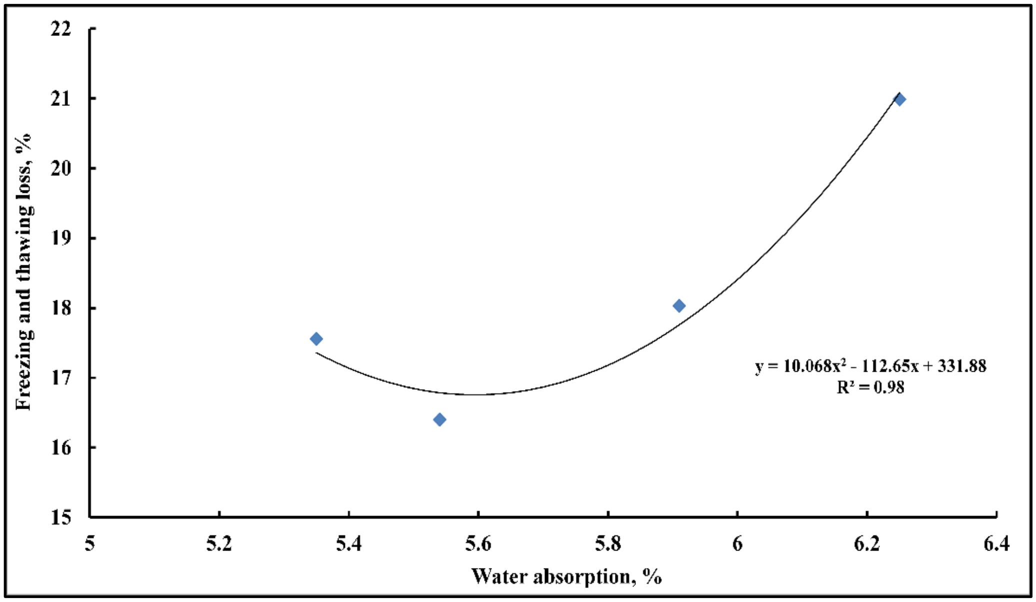


Figure 4.10: Relation between absorption and freezing thawing through heat treatment (Al-Bayati et al., 2016 a).

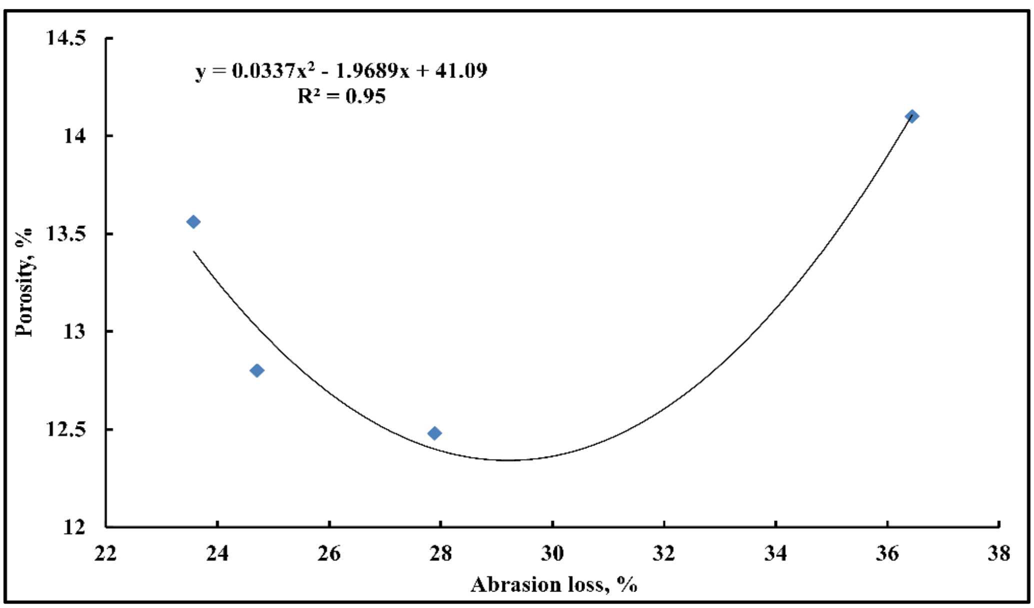


Figure 4.11: Relationship between porosity and abrasion loss through heat treatment (Al-Bayati et al., 2016 a).

4.6 Summary of This Chapter

This chapter focused on assessing the effect of various treatment techniques on enhancing the physical and mechanical properties of two different RCA types. The main findings of this chapter are summarized as follows:

- Compared to NA, a significant difference is registered between NA and both types of untreated CRCA in terms of physical and mechanical properties.
- Compared to untreated CRCA, an important improvement is registered in the physical and mechanical properties of both types of treated CRCA due to the utilization of different treatment techniques.
- A significant difference is highly noticeable between CRCA#1 and CRCA#2 in regard to physical and mechanical properties. The amount of adhered mortar on the RCA and the original parent of aggregate used in RCA are the main reasons behind this difference.
- The acid treatment at low concentration is an effective technique to enhance the physical and mechanical characteristics of CRCA; however, the application of this method depends on the used acid type due to the corrosive influence on the aggregate surface. Therefore, the use of weak acid is more effective and suitable for all aggregate types.
- In terms of water absorption, HCl has more effect than acetic acid on both CRCA types, registering a percentage reduction of 4.23% and 10.43% for CRCA#1 and CRCA#2, respectively.
- Of different treatments, the heat treatment at 350 °C had a maximum influence with respect to enhancing various CRCA properties. This method leads to increased specific gravity and lower water absorption with an approximate decrease of 9.5% and 11.23% for CRCA#1 and CRCA#2, respectively.
- With respect to the porosity of RCA, the findings show that a significant reduction in porosity is recorded for heat treatment at 350 °C, with an approximate reduction of 8% and 10.3% for CRCA#1 and CRCA#2, respectively. Interestingly, it is observed that there was little influence of acid treatment on the porosity of CRCA#1 with decreases of only 3.7% and 1.6% for HCl and acetic acid respectively. In contrast, a significant improvement in the porosity of CRCA#2 was obtained after the same above-mentioned

acid treatment types with approximate decreases of 9.9% and 4.4% for HCl and acetic acid treatment, respectively.

- The obtained results of the abrasion test suggest that CRCA#2 has a lower amount of attached adhered mortar to aggregate surface.
- For acetic acid treatment, a significant improvement was recorded for the resistance to freezing and thawing, with a decrease of more than 16%, whereas this characteristic is lowered by only 7% with HCl treatment. Meanwhile, heat treatment at 250°C enhanced the resistance of freezing and thawing by 9.0%.
- The application of ACV is a useful test to obtain a good categorization for RCA applications.
- Physical properties of CRCA including porosity and water absorption are strongly correlated with durability characteristics in terms of resistance to freezing and thawing and resistance to abrasion under the influence of heat treatment.

CHAPTER 5

INFLUENCE OF THE APPLICATION OF THE COMBINATION OF VARIOUS TREATMENT TYPES ON ENHANCING THE PROPERTIES OF CRCA

In this chapter, the obtained findings of CRCA#1 have been published in the Construction and Building Materials Journal (Al-Bayati et al., 2016). The outcomes of CRCA#2 have been presented at the Transportation Association of Canada (TAC) Conference (Al-Batayti et al., 2016).

5.1 Influence of Combination Approach on Physical Properties

5.1.1 Effect of Combination Approach on Absorption and Specific Gravity

Tables 5-1 and 5-2 summarize the results of water absorption and density for both CRCA#1 and CRCA#2 after the adhered mortar loss test. These results represent two stages of treatment: the first stage included the acid and heat treatment, whereas the adhered mortar test or short mechanical treatment was performed in the second stage, which was conducted using two different techniques with and without steel balls. Therefore, comparison with the untreated CRCA is an equitable evaluation of diverse conditions and methods.

In general, compared with untreated CRCA, there is a substantial improvement in both the specific gravity and water absorption of the two types of CRCA. The outcomes also revealed that the type of mechanical technique used to alter the water absorption of CRCA plays a significant role, as indicated by the noticeable difference in results. For the short mechanical treatment (without balls) technique, it can be observed in Tables 5-1 and 5-2 that the percentage of water absorption is reduced from 5.91% to 4.29% and from 3.74% to 3.14% for CRCA#1 and CRCA#2 respectively, due to the combination of thermal treatment at

350°C and short mechanical method, which is recorded as the highest performance of 27.4% and 16% reduction for CRCA#1 and CRCA#2 respectively. This was followed by the integration of weak acid and short mechanical treatment: 20.6%, then the combination of strong acid and the same mechanical process: 16.4%, compared to untreated CRCA-1. Whereas, in terms of the sequence of best treatments among various treatment methods, it was recorded that there was an opposite result with regards to CRCA#2. The second-best performance was with the combination of strong acid and short mechanical treatment resulting in a 13.1% reduction, then the combination of weak acid and the same mechanical process, resulting in an 11.8% reduction. This can be explained due to the type of original aggregate or the existence of material in the mortar that is more reactive to acid.

Interestingly, the results of the combination between short mechanical treatment with ball technique and various treatment types demonstrated that the reduction of water absorption with this technique is greater than the technique without balls for all types of combinations. Generally, compared with untreated CRCA#2, there is a considerable improvement in both the specific gravity and water absorption. It is interesting to note that the percentage of water absorption is reduced from 3.74% to 2.36% due to the combination of acetic acid and short mechanical method with steel balls, which recorded the best performance, with a 36.9% reduction. This was followed by the integration of thermal treatment at 350 °C and short mechanical treatment with steel balls resulting in a 26.7% reduction; then the combination of strong acid and the same mechanical process, resulting in a 23% reduction, compared to untreated CRCA#2. Surprisingly enough, a considerable difference in decreased water absorption was obtained between weak and strong acid treatment through combination with short mechanical treatment with steel balls. This indicates that weak acid seems to be more effective and preferable due to different concerns related to aggregate surfaces being attacked by acid.

Table 5-1: Specific Gravity and Absorption of CRCA#1 with Different Treatments Followed by Short Mechanical Treatment without Steel Balls

RCA Treatment/ Property	Bulk Relative Density (BRD)		Apparent Specific Gravity		Bulk Relative Density (SSD)		Absorption**, %	
	Before M.* Treatment	After M.* Treatment	Before M.* Treatment	After M.* Treatment	Before M.* Treatment	After M.* Treatment	Before M.* Treatment	After M.* Treatment
CRCA without treated	2.295	2.329	2.622	2.638	2.445	2.440	5.91	4.80
CRCA heated at 250 °C	2.309	2.367	2.648	2.674	2.437	2.482	5.54	4.85
CRCA heated at 350 °C	2.334	2.384	2.667	2.656	2.458	2.486	5.35	4.29
CRCA heated at 500 °C	2.254	2.379	2.623	2.663	2.394	2.486	6.25	4.48
CRCA heated at 750 °C	2.302	2.167	2.652	2.629	2.434	2.343	6.73	8.13
CRCA soaking in $C_2H_4O_2$	2.299	2.359	2.651	2.653	2.432	2.470	5.79	4.69
CRCA soaking in HCl	2.305	2.363	2.651	2.675	2.435	2.479	5.66	4.94

* M. = Mechanical, ** The MTO OPSS 1003 specification limit is 2.0% Max.

Table 5-2: Specific Gravity and Absorption of CRCA#2 with Different Treatments Followed by Short Mechanical Treatment with and without Steel Ball

RCA Treatment/ Property	Bulk Relative Density (BRD)			Apparent Specific Gravity			Bulk Relative Density (SSD)			Absorption****, %		
	B.M.T*	A.M.T Wt.B**.	A.M.T W.B***.	B.M.T	A.M.T Wt.B.	A.M.T W.B.	B.M.T	A.M.T Wt.B.	A.M.T W.B.	B.M.T	A.M.T Wt.B.	A.M.T W.B.
CRCA without treated	2.421	2.432	2.453	2.662	2.663	2.664	2.512	2.519	2.532	3.74	3.58	3.23
CRCA heated at 250 °C	2.436	2.441	2.477	2.668	2.671	2.673	2.523	2.527	2.551	3.57	3.52	2.96
CRCA heated at 350 °C	2.454	2.497	2.524	2.672	2.710	2.712	2.536	2.576	2.594	3.32	3.14	2.74
CRCA heated at 500 °C	2.409	2.426	2.441	2.659	2.661	2.662	2.503	2.514	2.524	3.90	3.64	3.41
CRCA soaking in $C_2H_4O_2$	2.431	2.450	2.551	2.663	2.665	2.715	2.518	2.531	2.612	3.51	3.30	2.36
CRCA soaking in HCl	2.452	2.461	2.484	2.671	2.674	2.676	2.534	2.540	2.556	3.35	3.25	2.88

B.M.T* = Before mechanical treatment; A.M.T.Wt.B** = After mechanical treatment without steel ball; A.M.T.W.B*** = After mechanical treatment with steel ball; and **** The MTO OPSS 1003 specification limit is 2.0% Max.

5.1.2 Behavior of Water Absorption

Experimental results of water absorption during heat treatment and after the combination with short mechanical treatment are shown in Figure 5.1. The results demonstrate that there is a considerable decrease of water absorption with increasing temperatures that range between (20 °C-300 °C) for both types of CRCA. The water absorption suddenly underwent breakdown and increased dramatically at a high temperature range between (500 °C-750 °C). This outcome matches findings of previous investigations (Wong et al., 2007; Gupta et al., 2012), who found that the exposure to high temperatures leads to degradation, breakdown, mass loss and microcracking.

To demonstrate a better understanding, Table 5-3 shows some findings of material decomposition at various temperatures. Thermal Gravimetric Analysis (TGA) provided more details about the mass loss that included chemical breakdown of compounds such as H2O and CO2 due to exposure to different temperatures. TGA studies indicated that the mass loss between 105 °C-200 °C is related to vaporized water in pores and poorly hydrated CSH, whereas mass loss is correlated with water dissociation from well hydrated CSH between 200 °C-420 °C. $Ca(OH)_2$ decomposes between temperatures of 420 °C-550 °C, whereas poor and well crystalline $CaCO_3$ molecules dissociate to release CO_2 between 550 °C-720 °C and 720 °C-950 °C, respectively (Zhang et al., 2015; El-Hassan et al., 2013). These ranges of temperatures are slightly different due to many factors such as aggregate type and chemical composition.

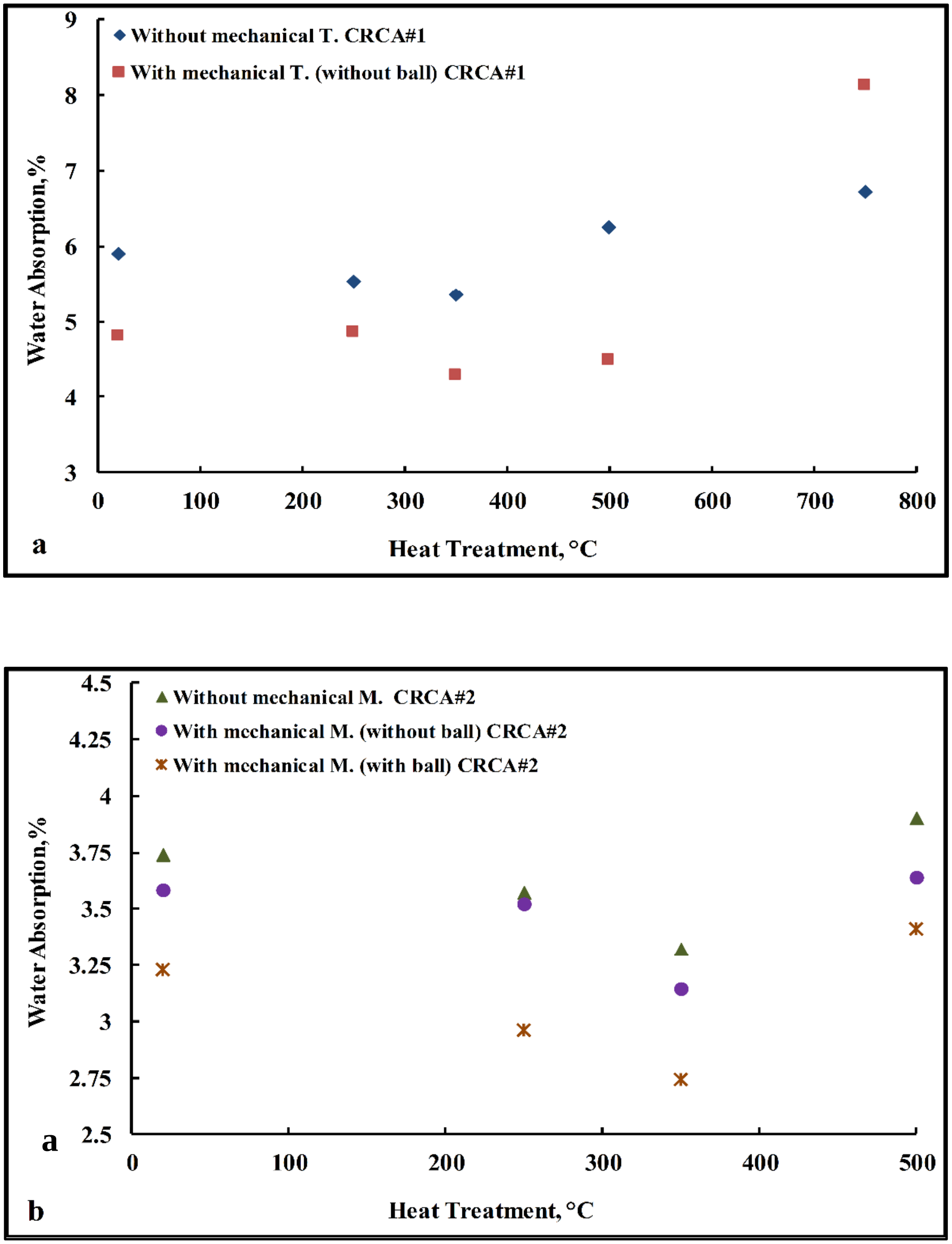


Figure 5.1: Behaviour of water absorption through combination of heat and mechanical treatment: (a) CRCA#1; (b) CRCA#2.

Table 5-3: Decomposition of Materials at Various Temperatures

Author	$Ca(OH)_2$ TGA decomposition, °C	$CaCO_3$ TGA decomposition, °C
Stern (2001) *	---	827–927 calcite
Huijgen et al. (2005) *	---	>500
Huntzinger (2006) *	300–500	500–800
Chang and Chen (2006) *	425–550	550–950
Zhang et al., (2015)	430–520	530–950
El-Hassan et al., (2013)	420–550	550 – 720 poor crystalline 720 – 950 well crystalline

*Adopted from Haselbach (2009).

Experimental results of water absorption through combination between acid treatment with both types of short mechanical treatment were graphically analyzed in Figure 5.2. The findings show that there is a high influence for the type of mechanical technique used to alter the water absorption of CRCA due to a significant variation in the obtained results. The obtained results showed that the percentage of water absorption decreased, with reduction values of 16.4% and 13% for CRCA#1 and CRCA#2 respectively due to the combination of strong acid treatment and mechanical treatment without steel balls. Using the same mechanical technique after weak acid treatment, a significant decrease was registered in water absorption with reduction ratios up to 20.6% and 11.8% for CRCA#1 and CRCA#2, respectively. Interestingly, the combination of acid treatment and mechanical method with steel balls led to a greater reduction in water absorption than the use of the same mechanical process without steel balls. For CRCA#2, the combination of weak acid and short mechanical treatment with steel balls resulted in a 36.9% reduction, whereas the combination of strong acid and the same mechanical technique resulted in a 23% reduction in water absorption for the same CRCA type. This indicates that weak acid appears to be highly influential and more preferable than strong acid due to various concerns related to acid attacks on aggregate surfaces.

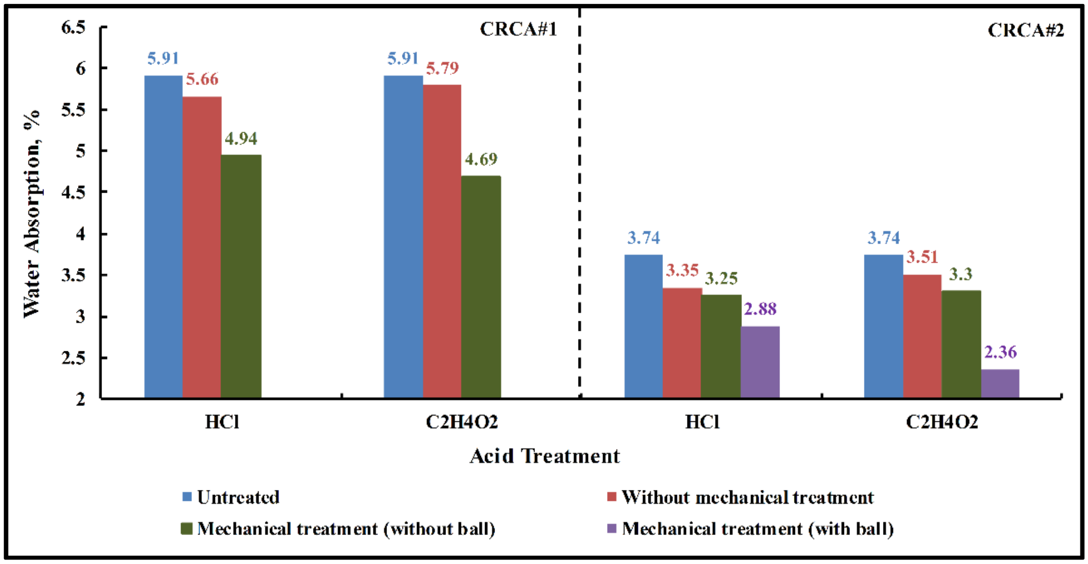


Figure 5.2: Water absorption through the combination of acid treatment and different mechanical treatments.

To obtain a better evaluation, the laboratory results of water absorption and specific gravity are further evaluated by comparing them with RCA literature studies. The values of the above-mentioned characteristics are graphically presented in Figure 5.3. From the mentioned figure, it can be stated that the majority of RCA studies demonstrated water absorption ranging between 4%-8%. However, extreme values can be found outside of that range with water absorption values between 9%-13%. Therefore, the water absorption and specific gravity of untreated CRCA can be categorized within the first half of the majority range with respect to the physical properties of RCA according to available graphical data. This obviously refers to relatively good CRCA types that are used in the present study compared to RCA available in the literature studies. It is clearly noted that a considerable difference, more precisely, a significant improvement in terms of the above-mentioned physical properties, is registered for the findings of the present study using various combined treatment techniques compared to the findings in the literature. This indicates successful utilization of combination techniques due to the significant improvement in water absorption and specific gravity. However, aggregate type, origin of RCA and amounts of adhered mortar are still crucial factors that play important roles in the enhancement of RCA properties.

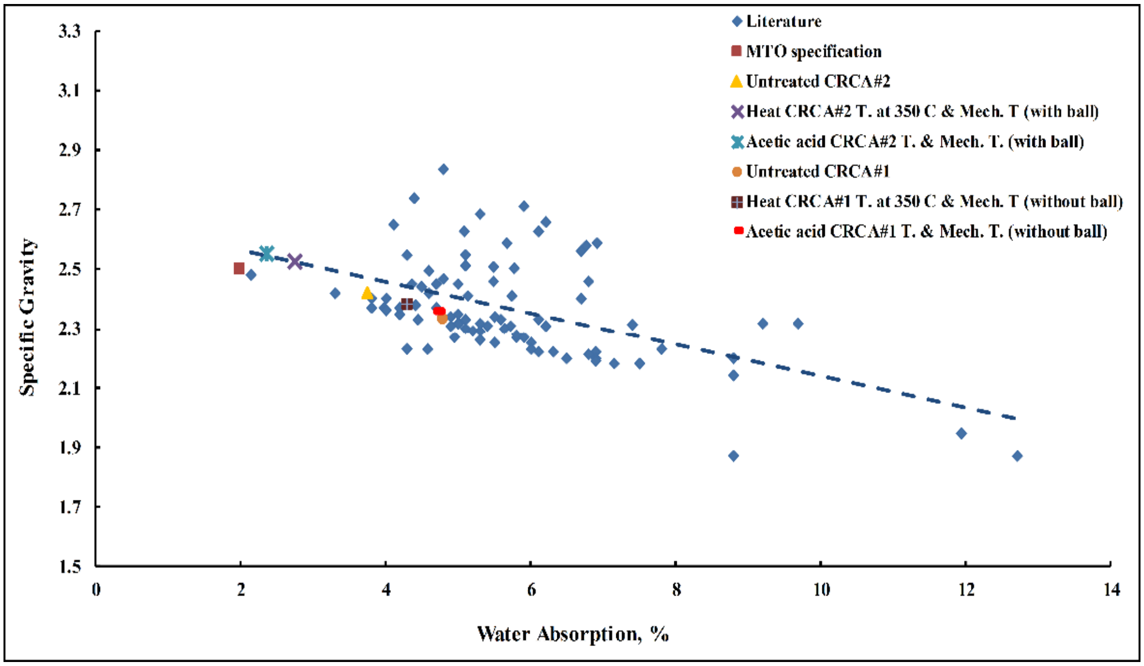


Figure 5.3: The obtained water absorption and specific gravity of treated CRCA using combination approach in comparison with RCA literature studies.

5.1.3 Effect of Combination Approach on Porosity

The effects of combinations of various treatments on porosity are presented in Figure 5.4 (a & b). Generally, the outcomes indicated that the porosity behaviour of both CRCA types through heat treatment is similar, although CRCA#1 has a higher percentage of porosity. The porosity decreased with rising treatment temperatures and there was a noticeable decrease in the porosity of CRCA between 20 °C-350 °C as shown in Figure 5-4. At higher temperatures above 350 °C, the porosity percentage gradually increased, and then the percentage of porosity sharply increased at temperatures of 500 °C and higher, indicating a negative impact for heat treatment at elevated temperatures on porosity. This behavior can be explained by the fact that the temperatures, which ranged between 20 °C-350 °C, produced a successful heat treatment. The laboratory test results for the water absorption test confirmed the success of the heat treatment because the water absorption of a material is highly related with the porosity of the material. In comparison, CRCA suffered from thermal expansion and internal stress due to exposure to high temperatures between 400 °C and 800 °C, which led to severe microcracking of the cement matrix, breakdown and mass loss of concrete particles (Wong et al., 2007; Vieira et al., 2011; Gupta et al., 2012). Therefore, these conditions were responsible for greatly increasing the porosity of both types of CRCA.

The outcomes of porosity through combinations of different acid treatments and various mechanical methods are shown in Figure 5.5 (a & b). Generally, the obtained results revealed that there is a significant improvement to the porosity of different CRCA types. However, the findings indicate that the type of applied mechanical method has a high impact on the porosity of CRCA due to a high variance in the results. It is important to note that the porosity decreased by 18.4% and 12.1% for CRCA#1 and CRCA#2 respectively due to the combination of weak acid treatment and mechanical treatment without steel balls. A good improvement is obtained when CRCA was treated with strong acid followed by the same mechanical treatment with reduction values of 14% and 11% for CRCA#1 and CRCA#2, respectively. This indicates that weak acid appears to be highly influential and preferable compared to strong acid due to various concerns related to acid attacks on aggregate surfaces. Hence, the application of weak acid followed by mechanical method without steel balls seems to be highly effective and more practical than the combination of strong acid and the same mechanical technique. Importantly, a considerable improvement is obtained for the porosity of CRCA through the combination of acid treatment and mechanical treatment with steel balls. For CRCA#2, the obtained results showed that the combination of strong acid treatment and short mechanical treatment with steel balls resulted in a 34.1% reduction of porosity while the combination of weak acid and the same mechanical procedure led to a 20.9% reduction of porosity. Thus, acid treatment with strong acid appears to be more effective than weak acid for improving porosity of CRCA with this mechanical method type.

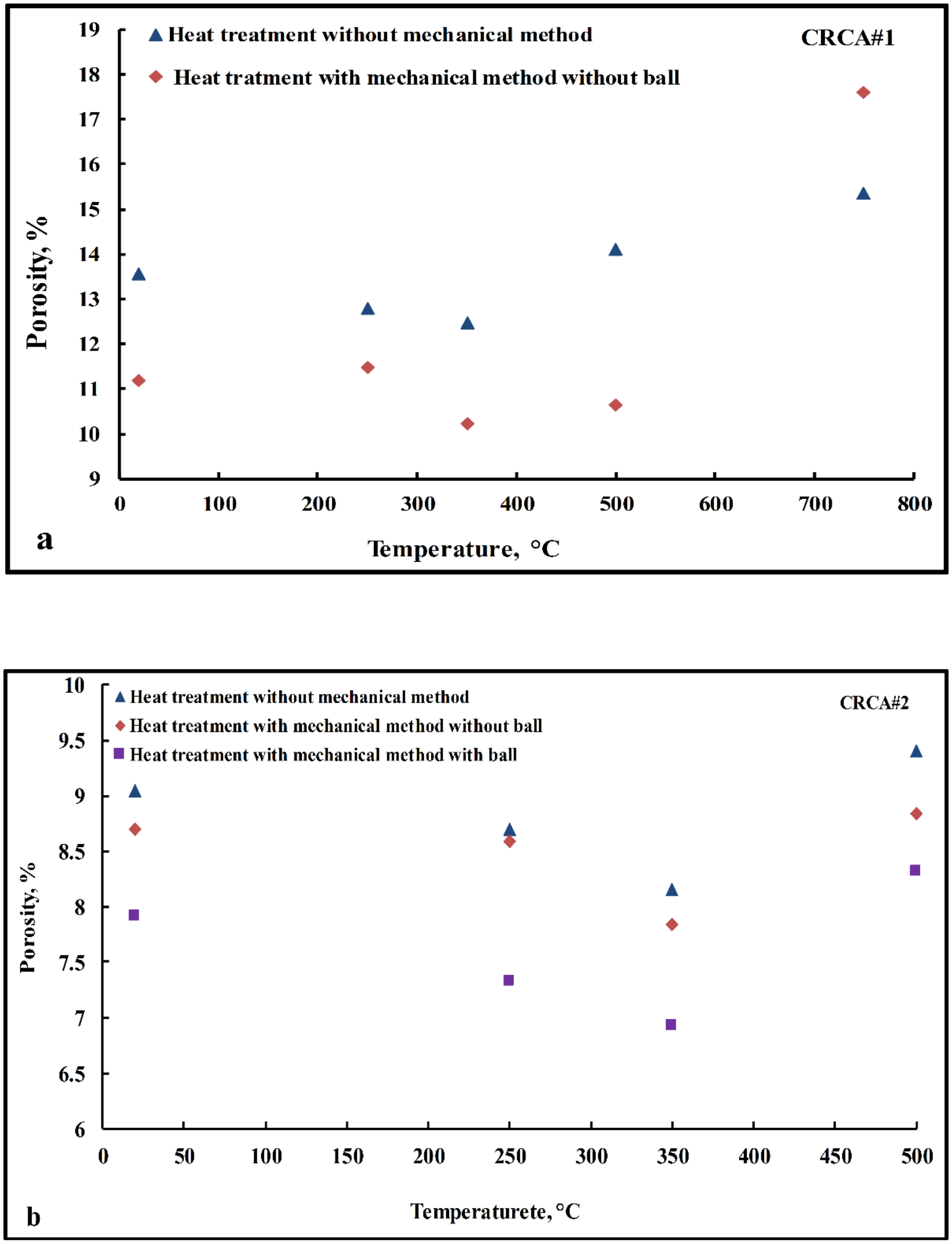


Figure 5.4: Porosity behavior for CRCA through combinations of heat and mechanical treatment: (a) CRCA#1, (b) CRCA#2.

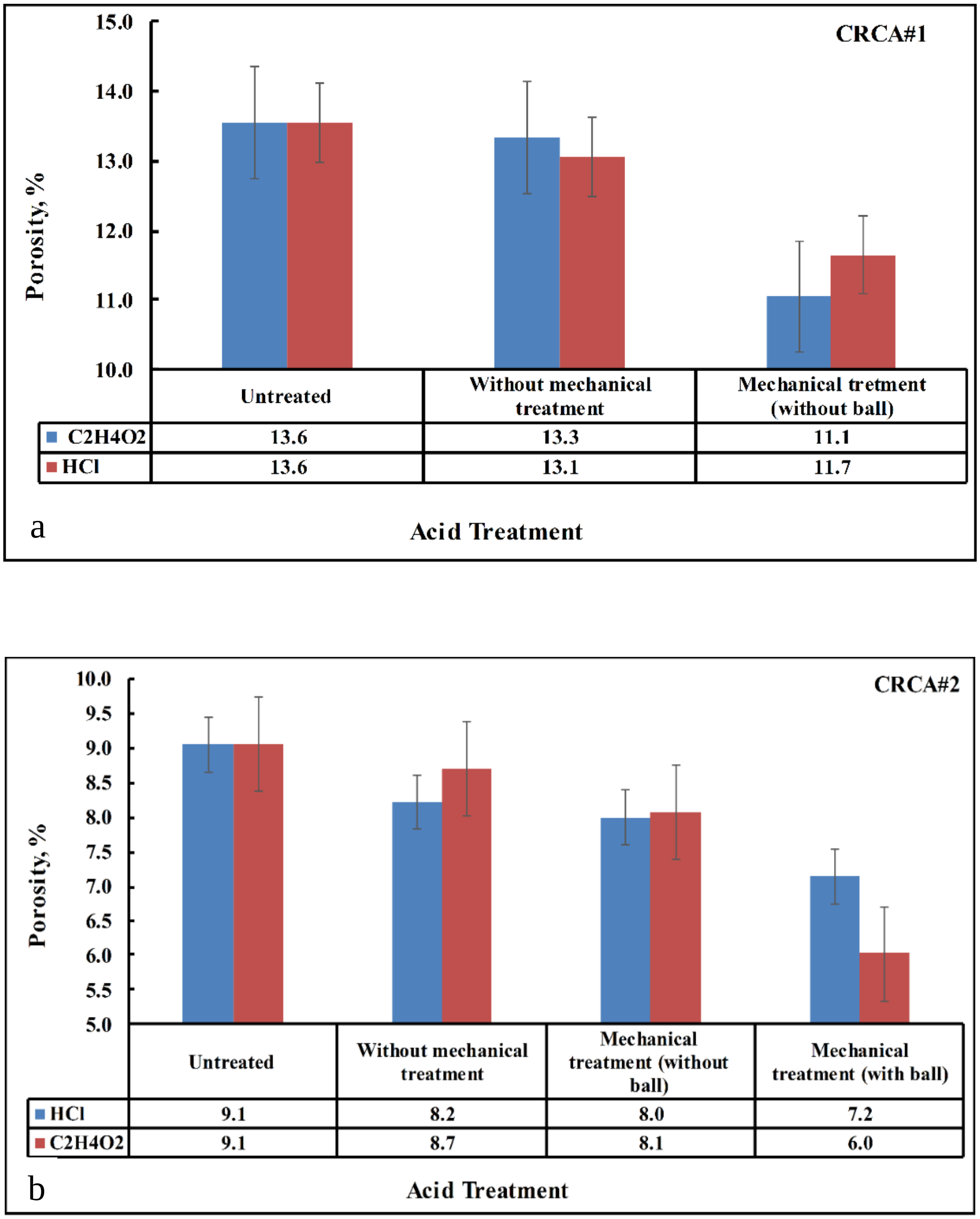


Figure 5.5: Porosity of CRCA through combination of acid treatment and mechanical treatment: (a) CRCA#1, (b) CRCA#2.

5.2 Influence of Combination Approach on Mechanical Properties

5.2.1 Effect of Combination Approach on Adhered Mortar Loss

The behavior of adhered mortar loss for CRCA through the combination of various treatment methods is investigated in Figure 5.6. The mentioned figure reflects the obtained outcomes due to the combination of heat treatment and different mechanical methods. In general, the obtained results demonstrated that the adhered mortar loss has a similar behaviour although there is a significant difference based on the mechanical method used. For CRCA#2, the adhered mortar loss increased with rising treatment temperatures and there was a considerable increase in the percentage of removal at high temperatures of 350°C and above. It is important to note that the adhered mortar removal for CRCA#2 could be described with a polynomial equation for both types of mechanical treatments. A strong correlation is registered for the combination of heat treatment and different mechanical techniques due to obtaining high regression values. However, the type of mechanical method has a big influence on the amount of adhered mortar removal due to a large difference in the results.

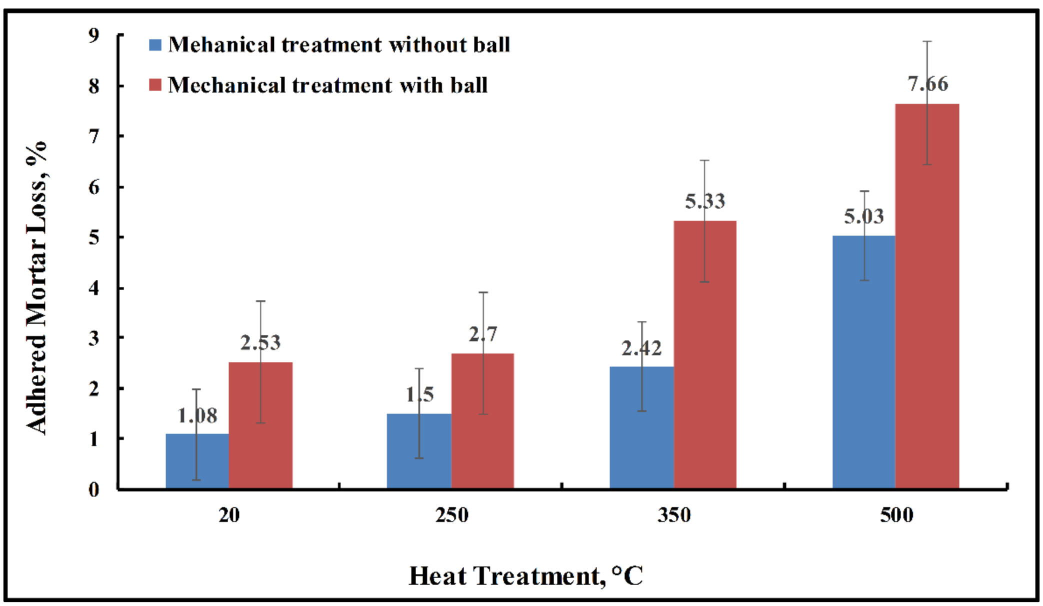


Figure 5.6: Adhered mortar loss for CRCA#2 through combination of heat and mechanical treatments.

The findings of adhered mortar loss through combinations of different acid treatments and various mechanical methods are displayed in Figure 5.7. There is generally little effect for this combination approach on the adhered mortar removal of CRCA#2. Compared to untreated CRCA#2, a slight increase is obtained for the adhered mortar loss due to the combination of strong and weak acid treatments and mechanical treatment without steel balls, with values of 2.33% and 2.61%, respectively. Similarly, the combination of strong and weak acid treatments and mechanical treatment with steel balls resulted in a small increase in adhered mortar loss for CRCA#2 with values of 3.25% and 3.5% respectively compared to untreated CRCA#2. As a result, the type of acid and the type of mechanical technique have very little (approximately negligible) effect on the adhered mortar removal.

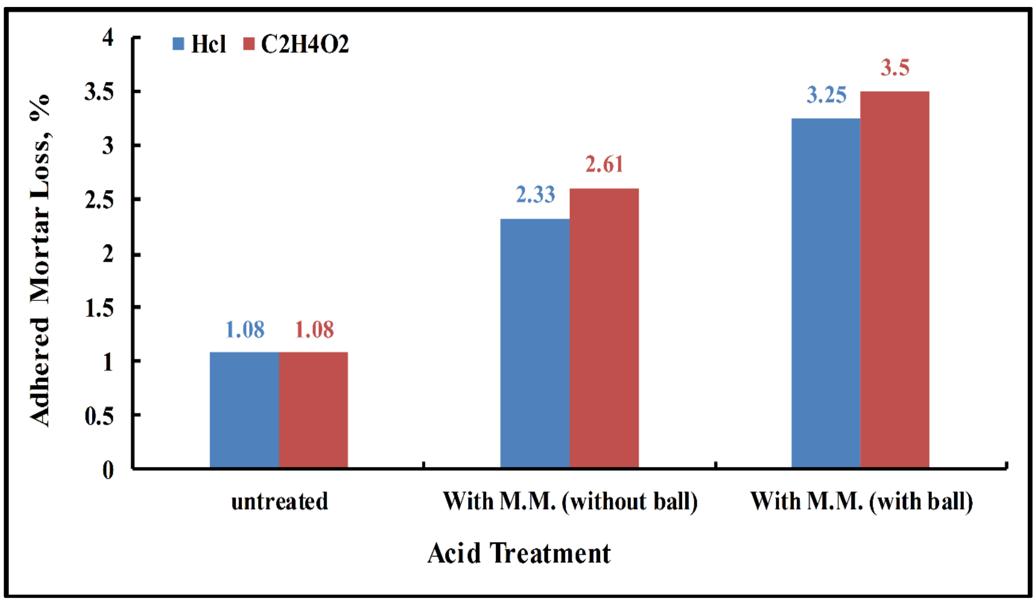
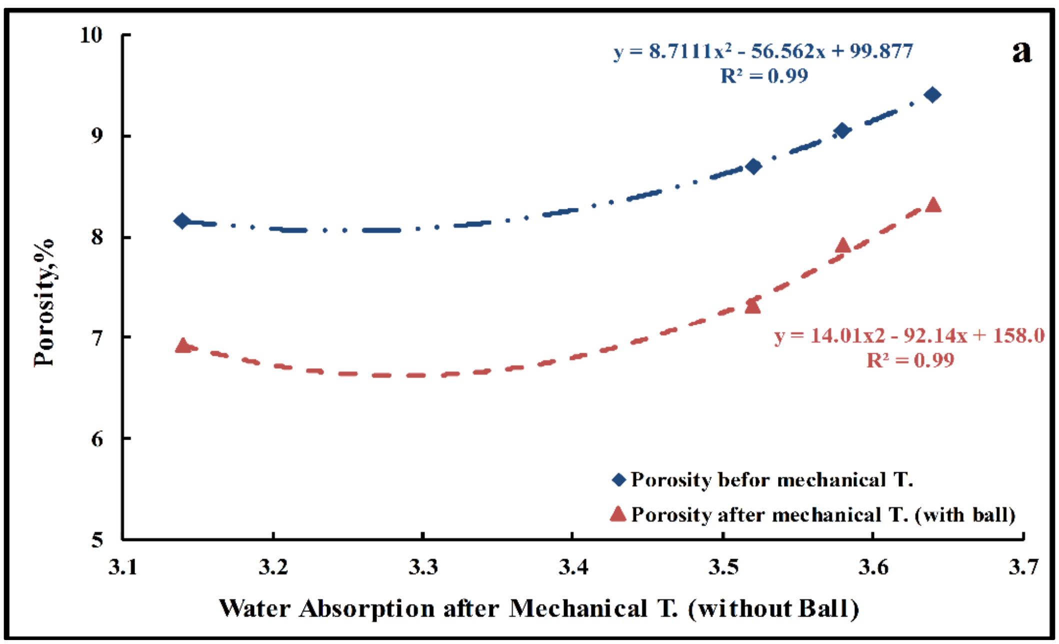


Figure 5.7: Adhered mortar loss for CRCA#2 through combination of different acids and various mechanical methods.

5.3 Influence of Combination Approach on Relation between Physical Properties

The relation between two physical properties; namely, porosity and water absorption through the combination of heat treatment and various mechanical treatments is presented in Figure 5.8. It is observed that a considerable regression is obtained for various techniques, indicating a strong relation between porosity and water absorption, and successful treatment methods for enhancing different characteristics of CRCA#2 without any negative impacts on consistency between various properties. However, it is interesting to note that the behaviour of the relation between porosity and water absorption completely transforms from a polynomial (second order) equation to exponential and logarithmic equations for no combination, combination with mechanical treatment without ball technique, and combination with mechanical treatment with ball method, respectively.



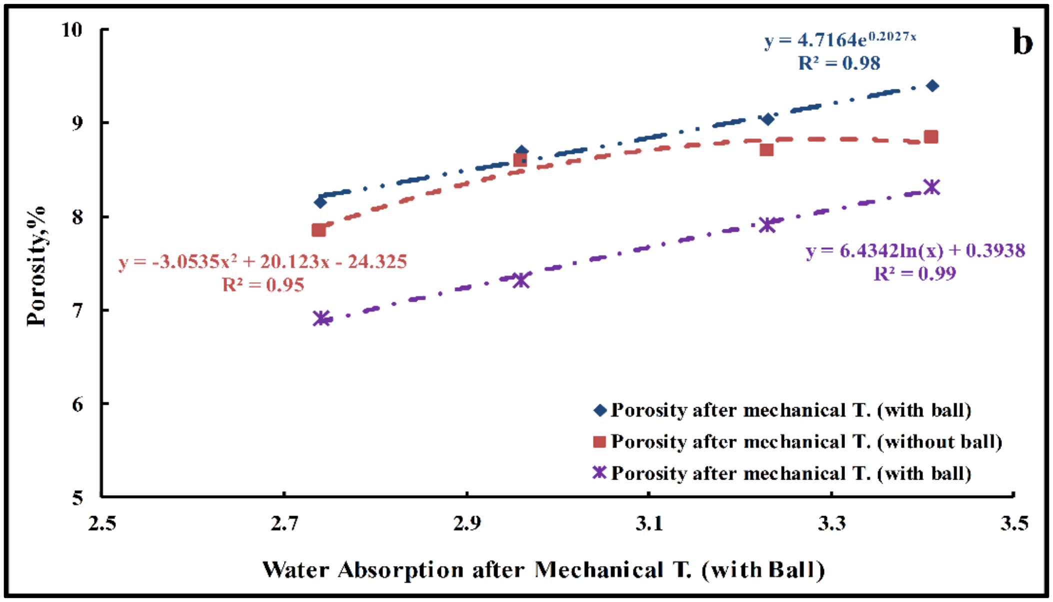


Figure 5.8: Relation between porosity and water absorption through the combination of heat treatment and various mechanical techniques: (a) without ball, (b) with ball (Al-Bayati et al., 2016 b).

5.4 Influence of Combination on Relation between Physical and Mechanical Properties

5.4.1 Relation between Water Absorption and Mechanical Properties

The relation between water absorption and mechanical property; namely, adhered mortar loss for CRCA#2 is graphically plotted in Figure 5.9. As can be seen, similar behavior is observed for various cases. Therefore, the findings indicate a relation between water absorption and adhered mortar loss. It is also observed that there is a significant difference in water absorption values between the cases with and without mechanical treatment as shown in Figure 5.9 (a). This indicates the influence of mechanical treatment. However, a slight difference is noticeable between the different cases of mechanical treatment techniques.

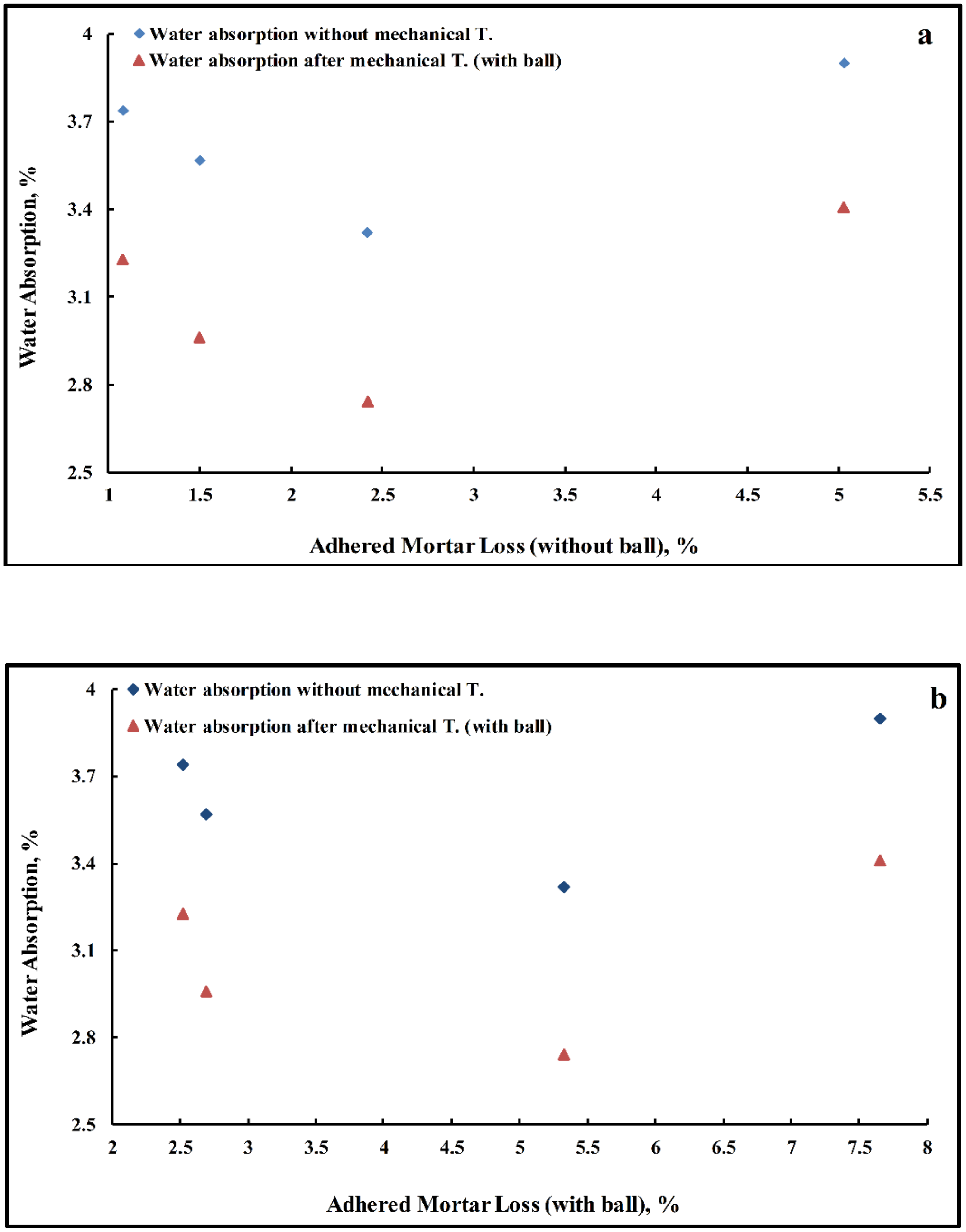


Figure 5.9: Relation between water absorption and adhered mortar loss through the combination of heat treatment and various mechanical techniques: (a) without balls, (b) with balls.

5.4.2 Relation between Porosity and Mechanical Properties

The relationship between a physical property, namely; porosity and two different mechanical properties in terms of abrasion loss and adhered mortar loss for CRCA#2 is analyzed in Figures 5.11 and 5.12. The obtained findings revealed that a significant relationship is registered between porosity and the mentioned mechanical characteristics as shown by the considerable correlations obtained. Nonlinear equations are obtained that evidently describe the behavior of these relations. It is notable that a second order equation reflects the behaviour of the relation of various characteristics after using different techniques including no combination method, combination with mechanical treatment without balls and combination with mechanical treatment with balls.

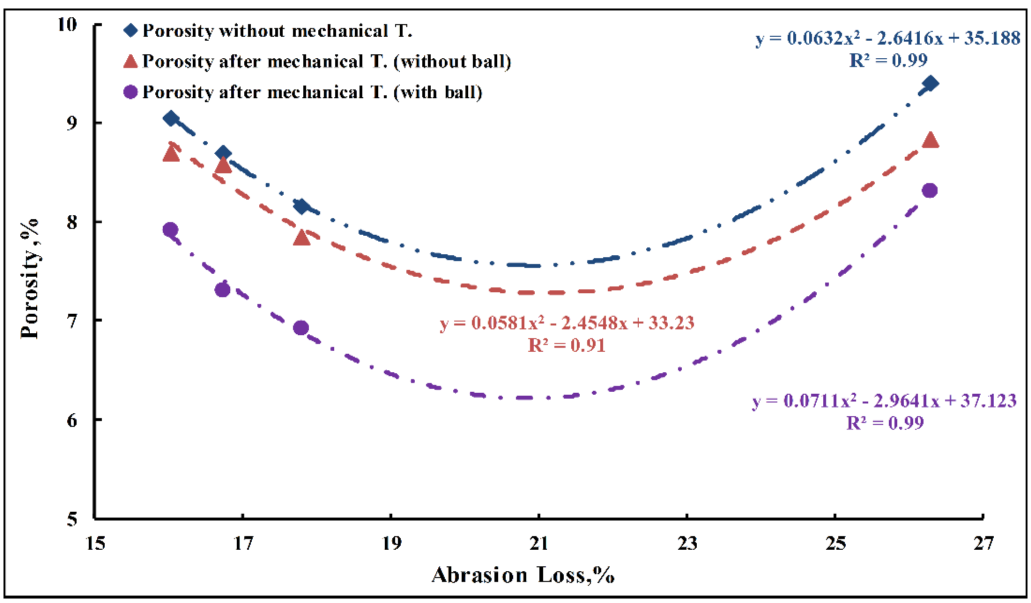
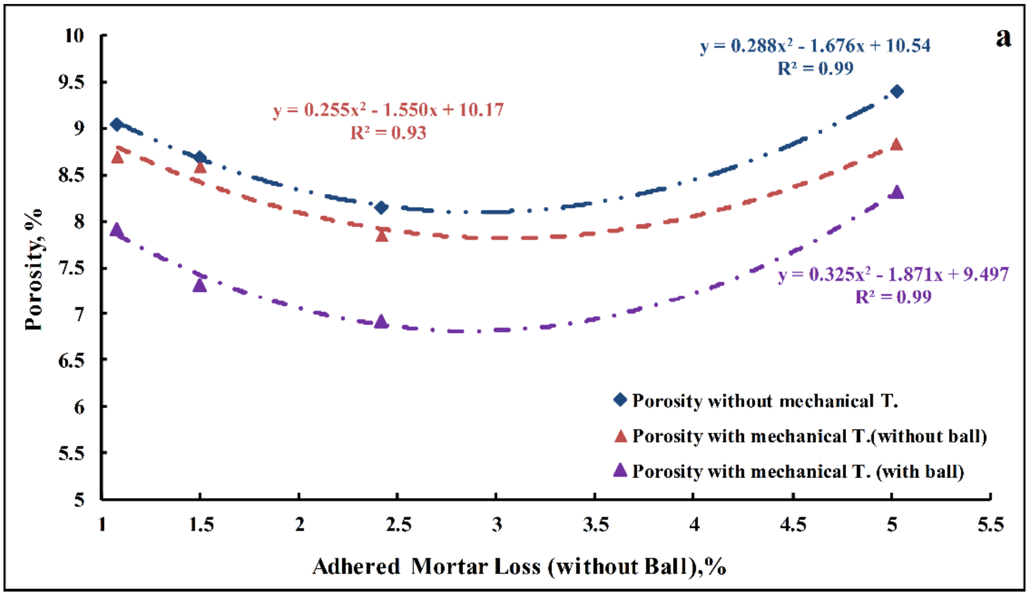


Figure 5.9: Relation between porosity and abrasion loss through the combination of heat treatment and various mechanical techniques (Al-Bayati et al., 2016 b).



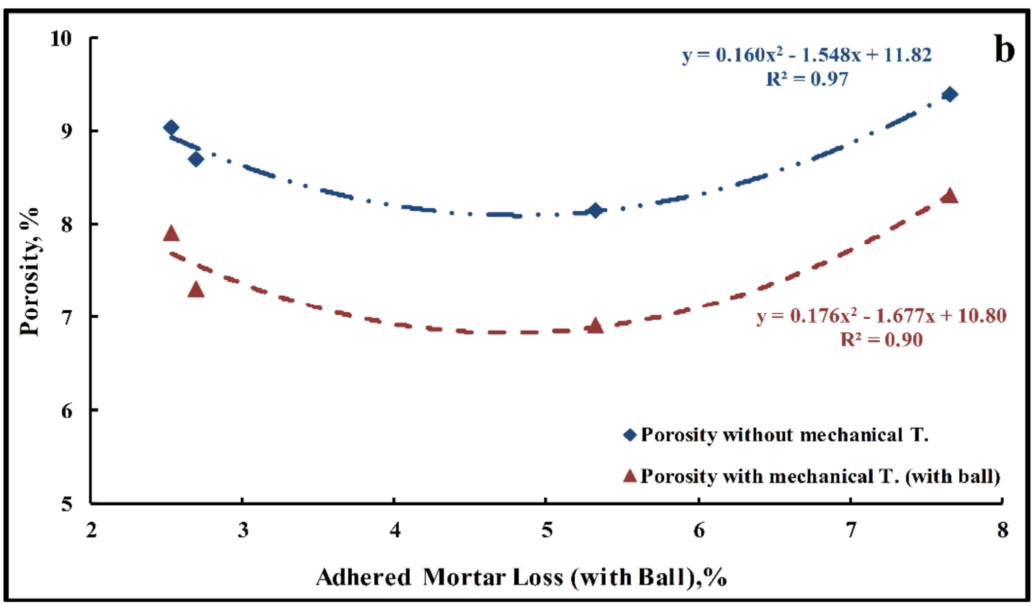


Figure 5.10: Relation between porosity and adhered mortar loss through the combination of heat treatment and mechanical techniques: (a) without balls, (b) with balls (Al-Bayati et al., 2016 b).

5.5 Selection Criteria of Best Treatment Methods

After a comprehensive study related to enhancing different properties of CRCA by applying different treatments, different conditions, and various combination techniques, the following can be stated:

- The use of heat treatment is a highly successful technique for improving various characteristics of CRCA when the method is performed at temperatures between 300 °C to 350 °C. However, the heat treatment has significant negative effects on the characteristics of CRCA at high temperatures.
- The utilization of acid treatment at a low concentration is a highly effective technique for enhancing CRCA properties. Nevertheless, because of the corrosive impacts of acids, the degree of CRCA improvement is strongly related to the type of acid used. It is demonstrated that the application of acetic acid treatment has a greater influence on the enhancement of CRCA characteristics compared to the effect of HCl acid. In addition, the use of acetic acid is safe and preferable due to the high corrosive impacts of HCl acid on some aggregate surfaces. De Juan & Gutiérrez (2009) stated that HCl treatment should not be applied with RCA types that originally consisted of limestone aggregates because of negative acidic attacks to the surface of this aggregate type.
- The application of mechanical treatment is effective and highly successful for obtaining a significant improvement in different CRCA properties. However, the use of mechanical method with steel balls for enhancing CRCA characteristics appears to be more effective than the technique without steel balls.

Based on the above, the use of heat treatment at 300 °C and pre-soaking with weak acid treatment are chosen to be used with short mechanical treatment with balls to apply a combination technique that achieves desirable improvements in CRCA properties.

5.6 Main Properties of Treated CRCA

After the application of a combination approach using various treatment methods, the obtained findings of the main properties of CRCA are summarized in Table 5-4. It is important to mention that the findings indicate two different stages of treatment for CRCA.

At the first stage, the CRCA treatment involved the application of two different approaches: the pre-soaking in the weak acid solution, $C_2H_4O_2$, and heat treatment. The second stage included the utilization of short mechanical treatment with steel ball using the Micro-Deval device. As different treatment techniques were used, the comparison with the untreated CRCA appears to be quite reasonable to obtain an equitable evaluation for those treatment methods.

As shown in Table 5-4, a significant improvement for both CRCA types is registered due to the impact of treatment methods. However, the effects of different treatment approaches on CRCA characteristics seem to be different. In terms of the properties of BRD and water absorption, a considerable improvement was obtained for both properties under the influence of the treatment techniques. After the combination of heat treatment at 300 °C and short mechanical treatment, the water absorption of CRCA#1 and CRCA#2 were lowered from 5.91 to 4.13 and 3.74% to 2.88%, respectively. This treatment approach leads to a reduction of 30% and 23.0% for CRCA#1 and CRCA#2 respectively in this important characteristic. Meanwhile, it is observed that the water absorption of CRCA was considerably reduced from 5.91 to 4.581 and 3.74% to 2.36% for CRCA#1 and CRCA#2 respectively, due to the influence of the integration of two treatments: pre-soaking with weak acid solution and short mechanical method. Due to the application of this approach, a significant reduction of 22.5% and 37% is recorded for the water absorption for CRCA#1 and CRCA#2 respectively, resulting in the best performance between the different combination approaches.
Simultaneously, a highly notable enhancement to the BRD characteristic is obtained for both types of combinations. However, it is important to mention that the use of the combination of pre-soaking method and short mechanical treatment appears to be more effective for improving this property in terms of CRCA#2. Meanwhile, the combination of heat method and short mechanical treatment appears to be more effective for improving this property in terms of CRCA#1. From the perspective of porosity, the experimental findings demonstrated a considerable improvement in this property due to the application of the different treatment techniques. There is a significant reduction, approximately 26%, and 20.9%, in the porosity of CRCA#1 and CRCA#2 respectively, after applying the combination of heat treatment at

300°C and short mechanical treatment method. The combination of pre-soaking method and the same mechanical treatment leads to a substantial decrease in the porosity value. By achieving an approximate reduction of 19.4% and 33.5% for CRCA#1 and CRCA#2 respectively, the use of this combination approach is highly successful in improving the porosity of CRCA#2. Meanwhile, the combination of heat treatment followed by short mechanical treatment appears to be highly effective for CRCA#1 improvement.

Table 5-4: Main Characteristics of Treated CRCA after Criterions Selection

Type of CRCA / Type of property	Untreated CRCA		CRCA after heat & Sh.M.T.*		CRCA after soaking in $C_2H_4O_2$ solution & Sh.M.T.*	
	CRCA#1	CRCA#2	CRCA#1	CRCA#2	CRCA#1	CRCA#2
Bulk Relative Density (BRD)	2.295	2.421	2.447	2.486	2.386	2.551
Absorption, %	5.91	3.74	4.125	2.879	4.581	2.36
Porosity, %	13.56	9.05	10.092	7.16	10.93	6.02

Sh.M.T.* = Short mechanical treatment.

5.7 Summary of This Chapter

This chapter focused on the evaluation of the effect of the combination of different treatment methods on enhancing the physical and mechanical properties of two different CRCA types. The major findings of this chapter are summarized in the following points:

- The application of the combination of different treatments is a highly successful technique for enhancing the physical and mechanical properties of CRCA compared with separate (single) treatments.
- For CRCA#1, the combination of thermal heating at 350 °C and short mechanical treatment (without steel balls) exhibits the best performance by reducing the water absorption by 27.4%. Using weak acid treatment followed by short mechanical treatment also appears to decrease water absorption efficiently (20.6%). The reduction of water

absorption is 16.4% for an integrated treatment between the strong acid and same mechanical process compared to untreated CRCA#1.

- For CRCA#2, the combination of acetic acid treatment and short mechanical method with steel balls exhibits the best performance by reducing the water absorption by 36.9%. This was followed by integration of thermal treatment at 350 °C and short mechanical treatment with steel balls by 26.7%, then the combination of a strong acid and the same mechanical process by 23%, compared to untreated CRCA#2.
- There is a considerable reduction in the porosity of CRCA with increasing temperatures that range between (20 °C-250 °C) for both types of mechanical treatment (with and without steel balls). However, a significant decrease is observed between 250 °C and 350 °C, recording the best performance for mechanical treatment with balls.
- The outcomes also indicated that there is a negative impact on the porosity for heat treatment with and without the combination of treatments at elevated temperatures ranging between (350 °C-750 °C).
- There is a significant improvement in the porosity of different CRCA types through a combination of different acid treatments and various mechanical methods. However, the findings show that the type of applied mechanical method has a high impact on the porosity of CRCA due to a high variance in the results.
- The porosity decreased by 18.4% and 12.1% for CRCA#1 and CRCA#2 respectively due to the combination of weak acid treatment and mechanical treatment without steel balls. A good improvement is obtained when CRCA was treated with strong acid followed by the same mechanical treatment with reduction values of 14% and 11% for CRCA#1 and CRCA#2, respectively. This indicated that weak acid appears to be highly influential and more preferable than strong acid due to various concerns related to acid attacks on aggregate surfaces.
- For CRCA#2, the obtained results showed that the combination of strong acid treatment and short mechanical treatment with steel ball results in a 34.1% reduction of porosity while the combination of weak acid and the same mechanical procedure led to a 20.9%

reduction of porosity. Thus, acid treatment with strong acid appears to be more effective than weak acid for enhancing the porosity of CRCA using this type of mechanical method.

- The findings indicate a strong relationship between physical properties, namely, water absorption and porosity as well as various mechanical characteristics: abrasion loss and adhered mortar loss due to obtaining high regression values.

CHAPTER 6

INFLUENCE OF TREATMENT METHODS ON SURFACE CHARACTERIZATION OF CRCA

In this chapter, the obtained findings of CRCA#1 have been published in the Construction and Building Materials Journal (Al-Bayati et al., 2016).

6.1 Influence of Treatments on Surface Morphology

6.1.1 Surface Morphology of Untreated CRCA

The surface morphology and texture of treated and untreated CRCA#1 are shown in Figures 6.1 to 6.5. According to magnified perspectives in Figure 6.1, the morphology of untreated CRCA#1 was rough; an irregular with a high porous structure. It was observed that adhered mortar was widely spread at different thicknesses causing surface heterogeneity. Therefore, the high magnification image clearly indicated the presence of many various voids and particles without specific shape and size. This explains the higher water absorption and lower density for untreated CRCA#1. These results confirm laboratory test findings, which found that the untreated CRCA has a high-water absorption and low density as shown in Table 4-1.

6.1.2 Influence of Treatments on Surface Morphology of CRCA

Compared with untreated CRCA#1, it was noted that there is a considerable difference in the degree of roughness of the CRCA surface depending on the treatment method. Roughness disappeared broadly from CRCA#1 surface due to the acid treatment (Figures 6.4 to 6.5), as acidic solutions attack the surface and dissolve adhered mortar. Hence, this method can be an effective way for adhered mortar. The SEM images, as shown in Figures 6.2 and 6.3, indicated successful heat treatment at 350 °C because of the small remaining amounts of mortar, whereas there is a large area of mortar on the surface at 250 °C. This outcome confirms the laboratory test results presented in Figure 4.7 and Table 4-1.

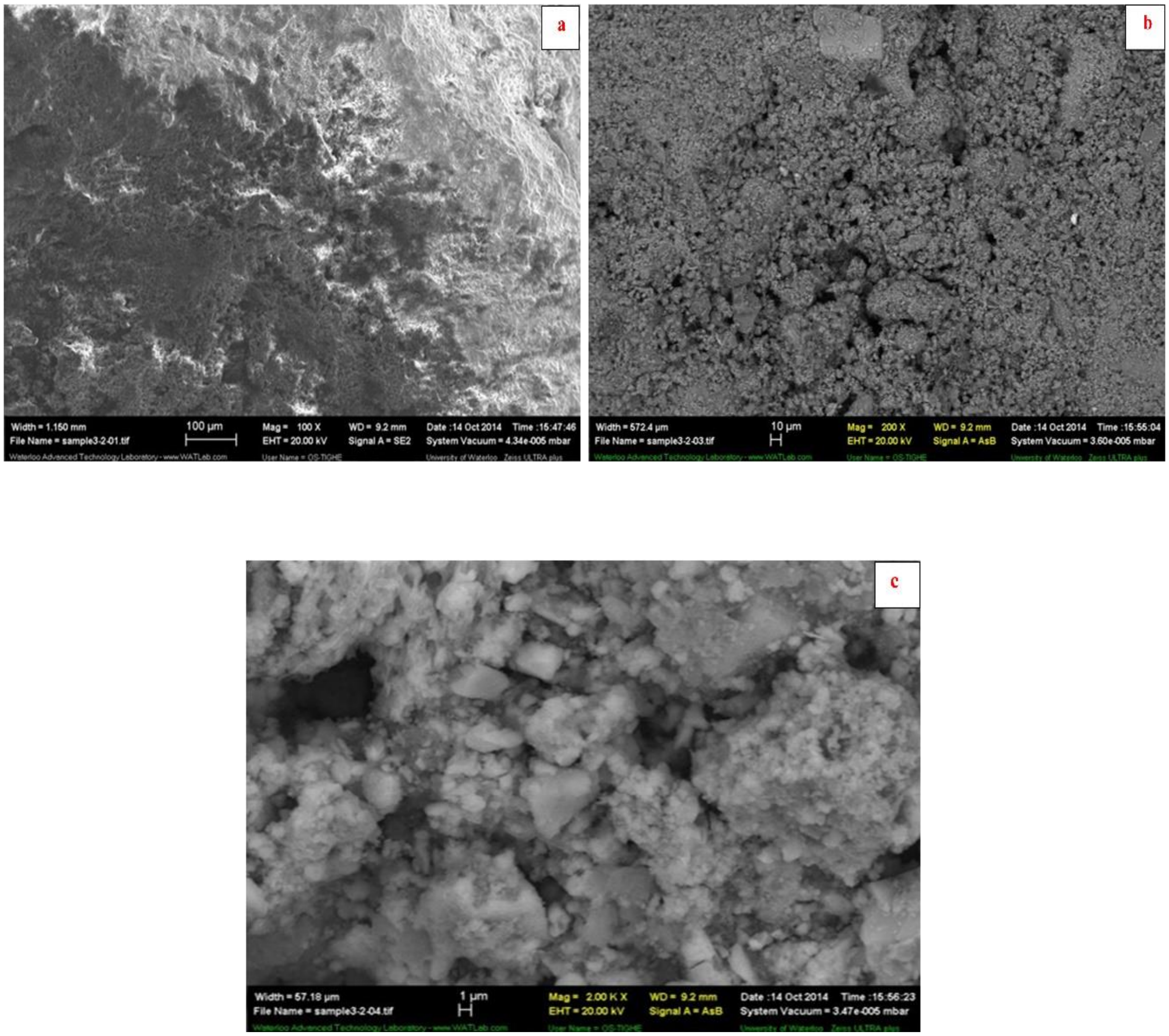


Figure 6.1: SEM for untreated CRCA#1 (a: 100X, b: 200X, c: 2000X).

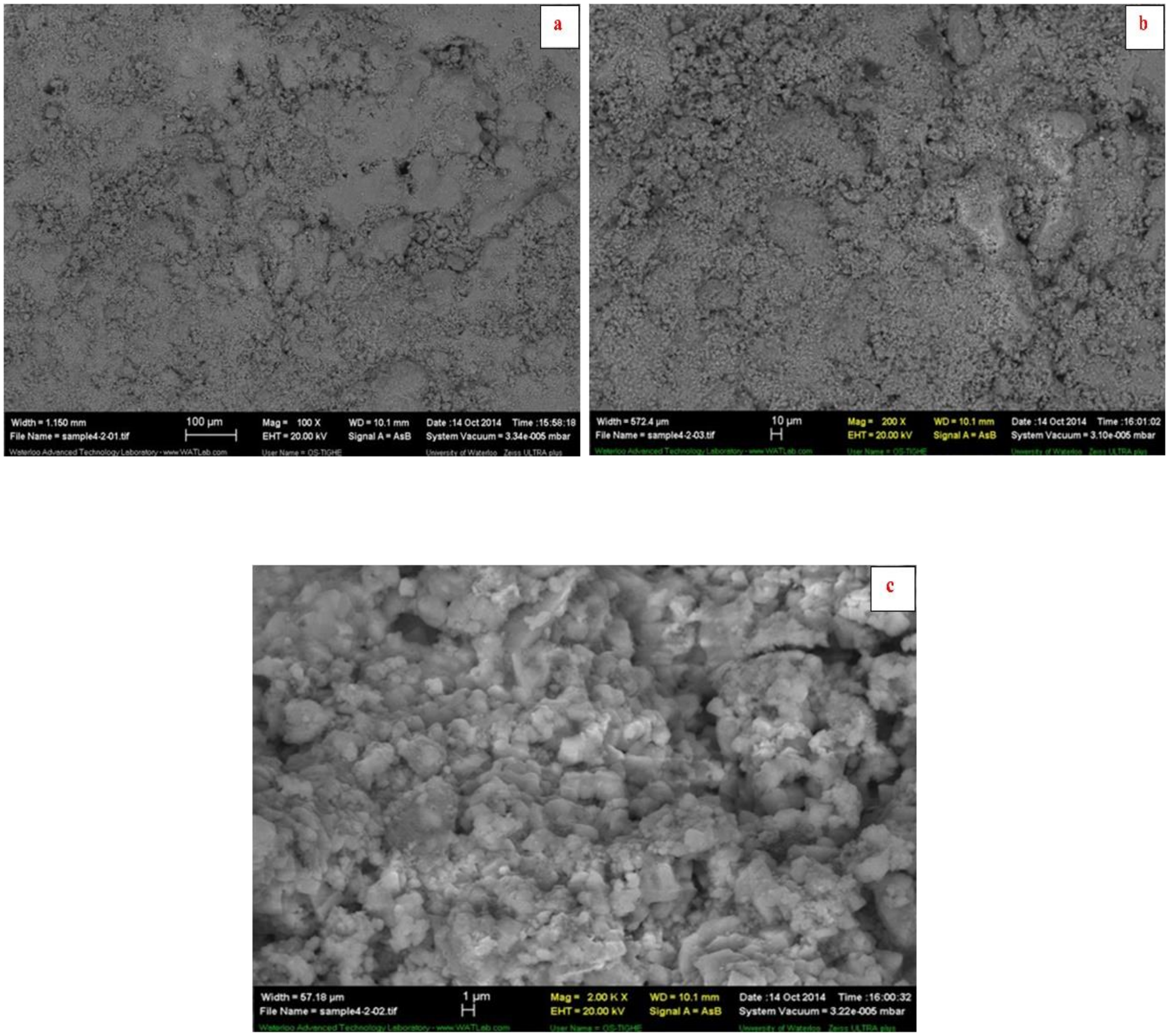


Figure 6.2: SEM for CRCA#1 with heat treatment at 250 °C (a: 100X, b: 200X, c: 2000X).

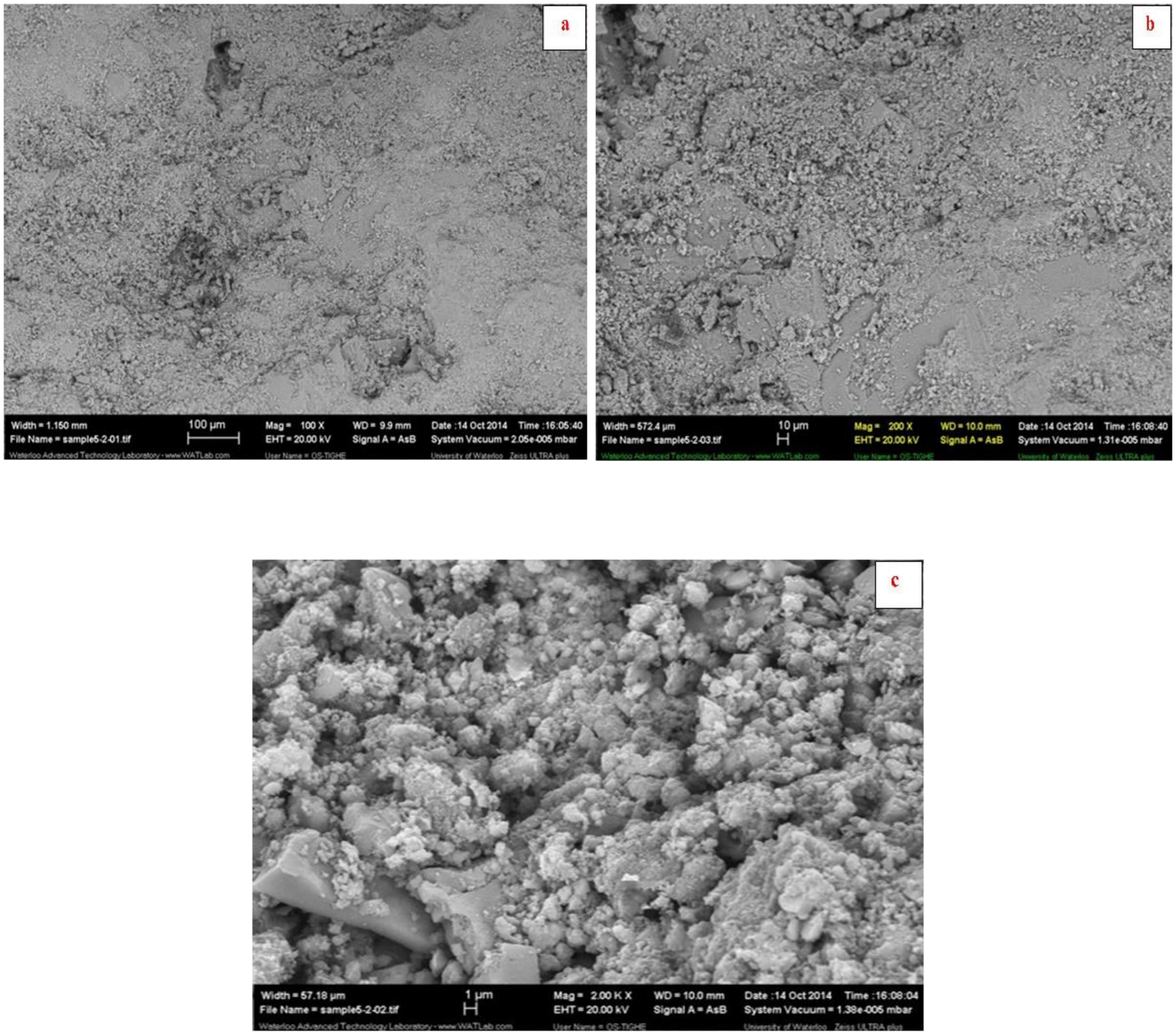


Figure 6.3: SEM for CRCA#1 with heat treatment at 350 °C (a: 100X, b: 200X, c: 2000X).

6.1.3 Influence of Acid Treatment on Surface Morphology of CRCA

It can be seen in the captured images (Figures 6.4 & 6.5) that there is a significant damage on the CRCA surface with HCl treatment. However, this damage is completely different to the surface treated with acetic acid. This could be explained by two matters: firstly, there is a significant variance of the ability between strong and weak acid to attack the surface adhered mortar and secondly, the surface material type. De Juan & Gutiérrez (2009) mentioned that HCl treatment cannot be used to treat RCA with limestone aggregates due to the adverse acid attacks on this type of aggregates.

As a result, the surface morphology of untreated CRCA was a rough and heterogeneous surface and high porous structure due to various thickness of adhered mortar which includes different voids size. Whereas the treated CRCA surface was more homogeneous and less adhered mortar depending on treatment type. However, there was an obvious damage on CRCA surface due to the impact of strong acid attack.

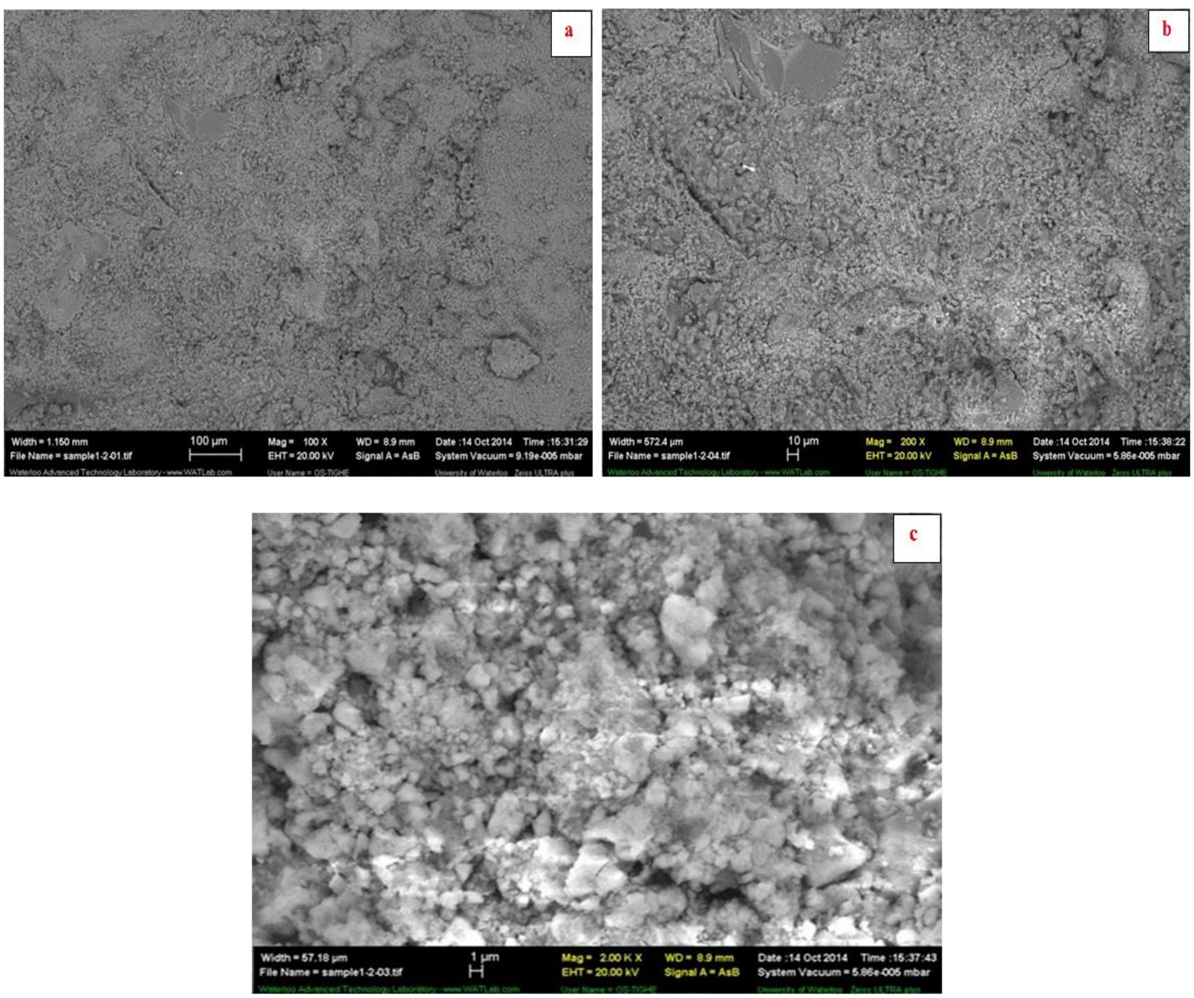


Figure 6.4: SEM for CRCA#1 with $C_2H_4O_2$ acid treatment (a: 100X, b: 200X, c: 2000X).

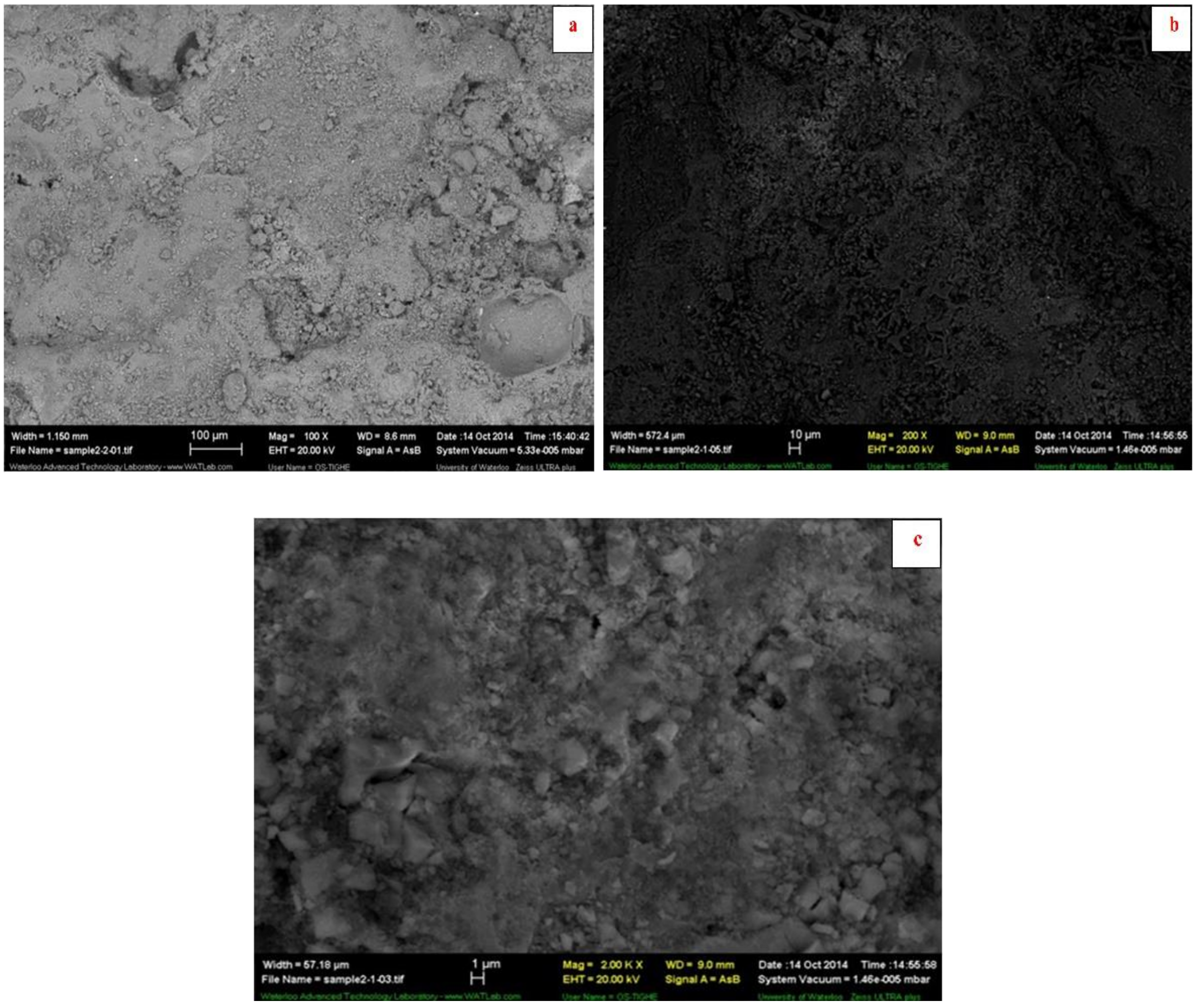
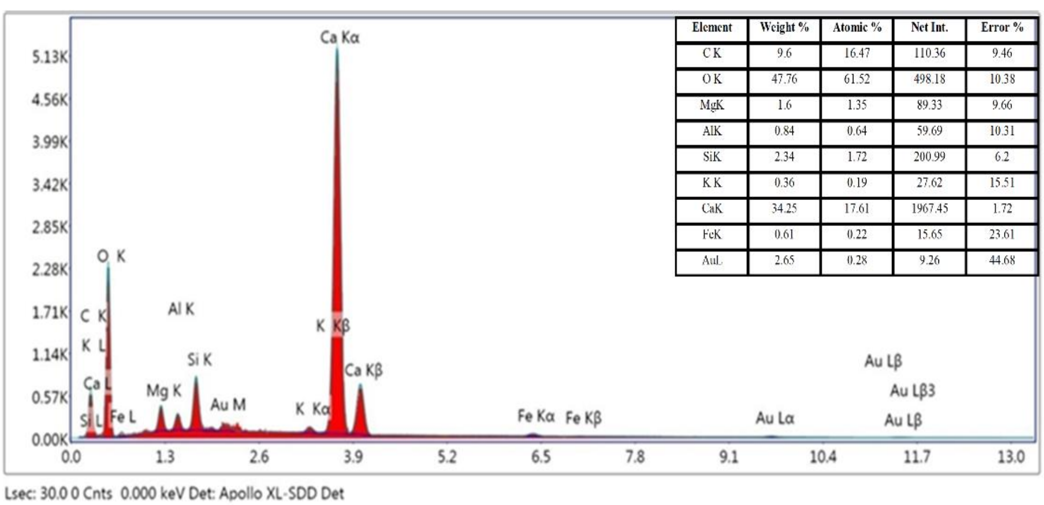


Figure 6.5: SEM for CRCA#1 with HCl acid treatment (a: 100X, b: 200X, c: 2000X).

6.2 Influence of Treatments on Surface Mineralogy

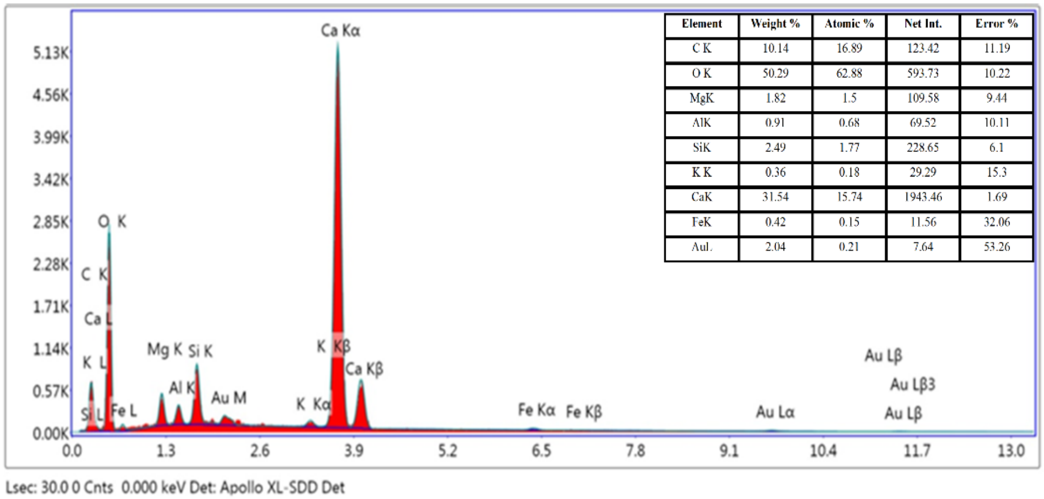
The results of EDAX analysis for untreated CRCA and treated with various methods are given in the Figures 6.6 to 6.10. The findings represent spectrum analysis for chemical and mineral composition of CRCA#1 through EDAX quantification. For untreated CRCA (Figure 6.6), the EDAX analysis clearly showed that the predominant elements are oxygen, calcium, carbon, silicon and magnesium respectively whereas aluminum, iron and potassium were also revealed in trace quantities.

Interestingly, oxygen is the highest weight percentage in chemical composition and there are large amounts of carbon in CRCA#1. It is well-known that oxygen atoms correlate with other atoms, especially metals, within a solid material to form metal oxides such as aluminum oxide (alumina), silicon oxide (silica) and others. Moreover, there is no free oxygen within a solid material because it normally has a gas state when liberated. Therefore, there is a considerable difference between the chemical compositions observed after different treatments, which include atoms of elements and a table, which include compounds such as alumina and silica. This also explains the higher carbon percentage, which refers to the existence of calcium carbonate (limestone) indicating aggregate type. As a consequence, it was clearly understandable that chemical and mineral composition of the CRCA surface through EDAX analysis is mainly categorized into two groups predominant and trace elements. However, there is still a need to further tests such as XRD for more beneficial categorization.



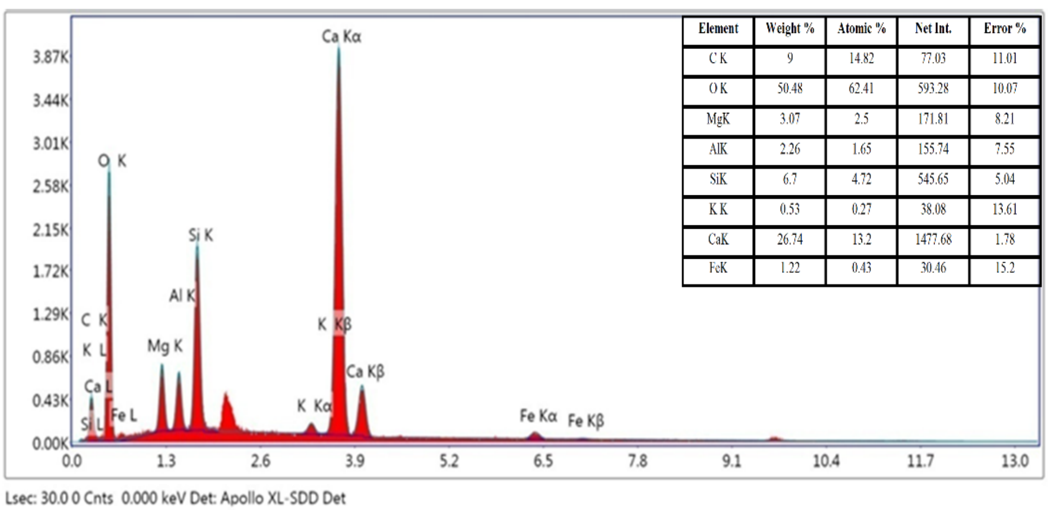
Element	Weight %	Atomic %	Net Int.	Error %
C K	9.6	16.47	110.36	9.46
O K	47.76	61.52	498.18	10.38
MgK	1.6	1.35	89.33	9.66
AlK	0.84	0.64	59.69	10.31
SiK	2.34	1.72	200.99	6.2
K K	0.36	0.19	27.62	15.51
CaK	34.25	17.61	1967.45	1.72
FeK	0.61	0.22	15.65	23.61
AuL	2.65	0.28	9.26	44.68

Figure 6.6: EDAX analysis for untreated CRCA#1.



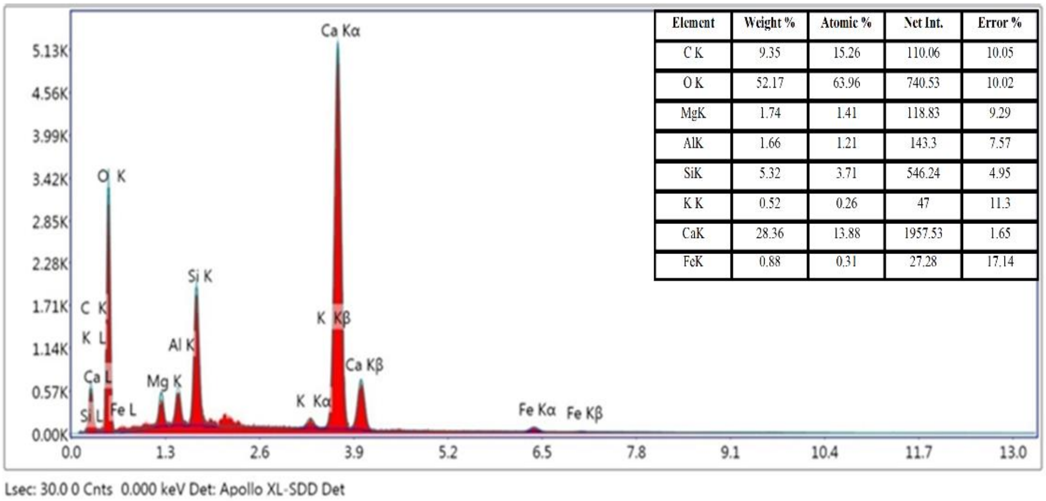
Element	Weight %	Atomic %	Net Int.	Error %
C K	10.14	16.89	123.42	11.19
O K	50.29	62.88	593.73	10.22
MgK	1.82	1.5	109.58	9.44
AlK	0.91	0.68	69.52	10.11
SiK	2.49	1.77	228.65	6.1
K K	0.36	0.18	29.29	15.3
CaK	31.54	15.74	1943.46	1.69
FeK	0.42	0.15	11.56	32.06
AuL	2.04	0.21	7.64	53.26

Figure 6.7: EDAX analysis for CRCA#1 with heat treatment at 250 °C.



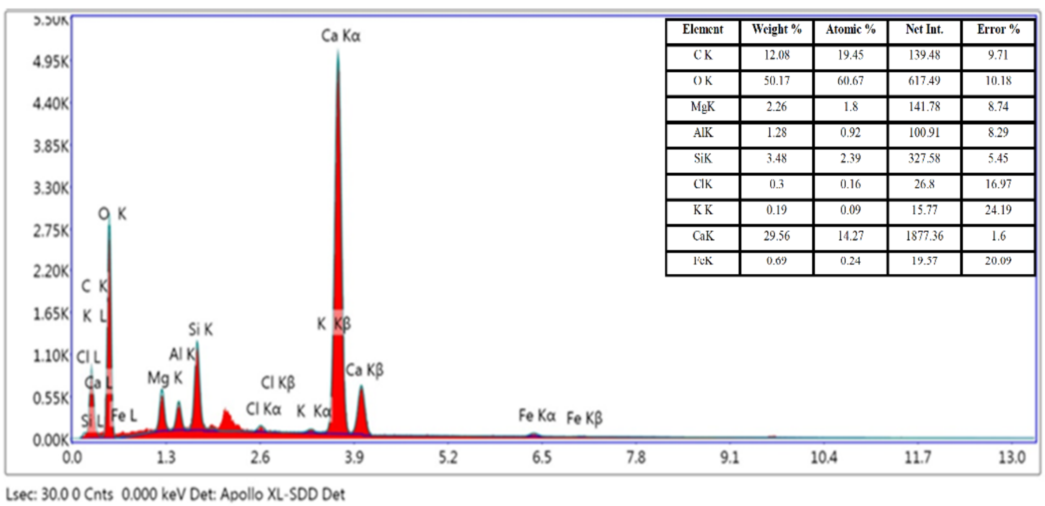
Element	Weight %	Atomic %	Net Int.	Error %
C K	9	14.82	77.03	11.01
O K	50.48	62.41	593.28	10.07
MgK	3.07	2.5	171.81	8.21
AlK	2.26	1.65	155.74	7.55
SiK	6.7	4.72	545.65	5.04
K K	0.53	0.27	38.08	13.61
CaK	26.74	13.2	1477.68	1.78
FeK	1.22	0.43	30.46	15.2

Figure 6.8: EDAX analysis for CRCA#1 with heat treatment at 350 °C.



Element	Weight %	Atomic %	Net Int.	Error %
C K	9.35	15.26	110.06	10.05
O K	52.17	63.96	740.53	10.02
MgK	1.74	1.41	118.83	9.29
AlK	1.66	1.21	143.3	7.57
SiK	5.32	3.71	546.24	4.95
K K	0.52	0.26	47	11.3
CaK	28.36	13.88	1957.53	1.65
FeK	0.88	0.31	27.28	17.14

Figure 6.9: EDAX analysis for CRCA#1 with $C_2H_4O_2$ acid treatment.



Element	Weight %	Atomic %	Net Int.	Error %
C K	12.08	19.45	139.48	9.71
O K	50.17	60.67	617.49	10.18
MgK	2.26	1.8	141.78	8.74
AlK	1.28	0.92	100.91	8.29
SiK	3.48	2.39	327.58	5.45
ClK	0.3	0.16	26.8	16.97
K K	0.19	0.09	15.77	24.19
CaK	29.56	14.27	1877.36	1.6
FeK	0.69	0.24	19.57	20.09

Figure 6.10: EDAX analysis for CRCA#1 with HCl acid treatment.

6.3 Calcium to Silicon (Ca/Si) Ratio

As indicated in the literature (Jawahar et al., 2013), CSH is the predominant product to hydration of cementitious materials in the concrete during curing period. The reactions that include hydration process of the cement paste in concrete substantially consist of the reaction between Tricalcium silicate and Dicalcium silicate, which are known as Alite and Belite, respectively, and water. The products of these reactions are mainly including CSH and CH, which is also known as Portlandite, as shown in the following equations:

$$2Ca_3SiO_5 + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \ldots\ldots\ldots\ldots \text{(6-1)}$$

$$2Ca_2SiO_4 + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 \ldots\ldots\ldots\ldots \text{(6-2)}$$

There are also other important reactions including the pozzolanic reaction:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{+2} + H_2SiO_4^{-2} + 2H_2O \rightarrow CaH_2SiO_4.2H_2O \ldots\ldots \text{(6-3)}$$

Therefore, it is clear that the atomic (Ca/Si) ratio of CSH in cement paste is changeable, and depends on the water to binder ratio, type of the binder and curing period (Jawahar et al., 2013). The average atomic ratios Ca/Si and (Al+Fe)/Ca of CRCA for different treatment types calculated from EDAX outcomes are plotted in Figures 6.11 to 6.13.

6.3.1 Behaviour of Ca/Si through Heat Treatment

The EDAX analysis demonstrated that there was a highly significant reduction in the Ca/Si ratio with the rising temperatures during heat treatment, as shown in Figure 6.11. A noticeable decrease was observed in the temperatures range between 250-350 °C, where the percentage of calcium atoms have decreased, and silicon atoms have increased. The high Ca/Si ratio (Figures 6.11 & 6.12) and low (Al + Fe)/Ca ratio (Figure 6.13) for untreated CRCA surface at room temperature (20 °C) indicated that the CRCA surface was highly porous and rich in CH crystals. Whereas the surface was comparatively poor in CSH and Tricalcium aluminate hydrate (CAH) but even lower in calcium sulfoaluminate hydrate (AFt) (ettringite). These outcomes were confirmed by Trägárdh's categorization of hydrate regions that are rich in CH crystals (Erdem et al., 2012) and agreed with the research results that found that the increased CH during the hydration process causes an increase in the Ca/Si ratio (Jawahar et al., 2013). In addition, it was similar to Erdem’s study findings except for a high presence of ettringite due to sulfate (Erdem et al., 2012). This can be explained by the increase of CH crystals, which is mainly attributed to the chemical reaction between high quantities of the main component of cement (anhydrous calcium oxide (CaO), with water. The reaction is explained by the following:

$$CaO + H_2O \rightarrow Ca(OH)_2\ (portlandite\ or\ CH)\ )\ldots\ldots\ldots\ldots\ldots\ldots\ (6\text{-}4)$$

As well as the calcium silicate reactions (equations 6-1 & 6-2) that normally produce CH.

Whereas, the CH crystals may dissolve in the pore liquid as an ions Ca^{+2} + $2OH^{-}$, the CSH is not soluble. With an exceedingly alkali concentration, the presence of ions Na^{+} and K^{+} leads to calcium ions becoming extremely insoluble, especially if the pH of pore fluids nearby reach or exceed 12.4, which is almost the highest obtainable boundary for solving the CH at 20 °C (Bazant & Steffens, 2000). Therefore, the CH crystals may accumulate in the ITZ and the pores of the attached mortar.

The rising temperature works to remove water molecules from hydrous compounds within a dehydration process that leads to form new hydrated compounds and to increase CSH formation. The continuously rising temperatures have great influence on the compound type that results from the dehydration process. Thermal gravimetric investigations for RCA provided further details about the relationship between rising temperatures at different ranges and losing weight due to water removal. The vaporized water at a temperature range lower than 105 °C related to the mass loss and can perhaps lead to poorly formed CSH. The water loss at temperatures between 105 °C and 200 °C is results from the dissociation of water, which is linked with compounds such as lower temperature CSH and ettringite. Whereas, the dissociation of correlated water molecules to well-formed hydrated compounds such as CSH and CAH is the reason of the loss in the temperatures between 200 °C-420 °C (Zhang et al., 2015; El-Hassan et al., 2013). Therefore, the significant difference between poorly formed CSH at temperatures range up to 200 °C and well hydrated CSH and CAH at temperatures between 200 °C-420 °C could explain the large decrease of the Ca/Si ratio between 250 °C-350 °C compared to a slight reduction at range between 20 °C-250 °C.

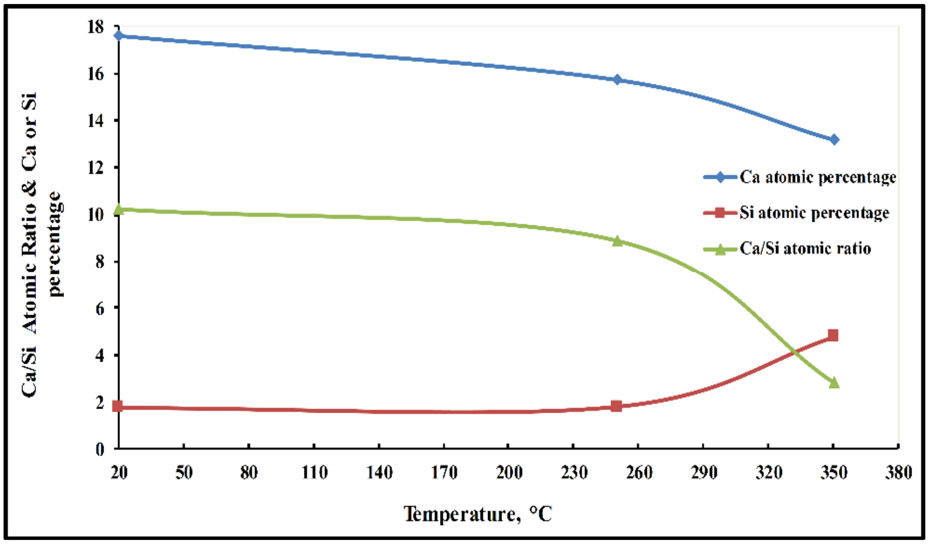


Figure 6.11: Behaviour Ca & Si atoms and Ca/Si atomic ratio for heat treatment.

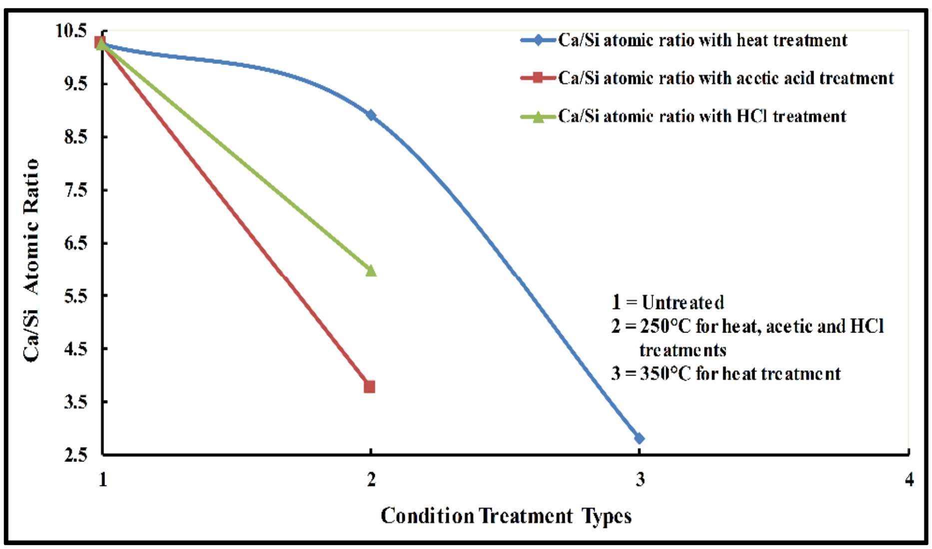


Figure 6.12: Ca/Si atomic ratio for different treatment types.

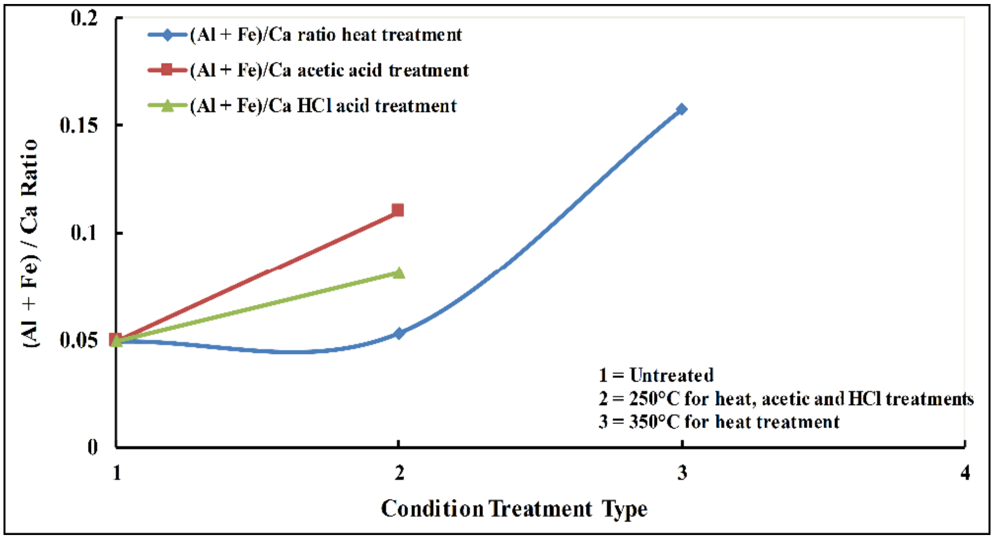


Figure 6.13: (Al+Fe)/Ca ratio for different treatment types.

The lowering of the Ca/Si ratio is mainly attributed to a high increase of CSH production and considerable consumption to CH at the same time. The reason for the significant decrease of CH is the new hydrous compounds due to increasing temperatures, especially CSH, which could promote activity to form siliceous and, siliceous and aluminous materials behave as a pozzolans. These pozzolans (Kong et al., 2010; Jawahar et al., 2013) can consume accumulated CH in the pores to produce CSH and decrease the Ca/Si ratio according to equation (6-3). As a result, the intermixed materials on the CRCA surface are predominantly CSH, and comparatively lower ettringite and AFm due to the slight increase (Al + Fe)/Ca ratio but fewer CH crystals. The obtained results agreed with research findings by Erdem et al. (2012) and almost accepted Trägårdh's categorization of hydrate regions that are rich in CSH (Erdem et al., 2012).

6.3.2 Behaviour of Ca/Si through Acid Treatment

The EDAX analysis also demonstrated that there was significantly lower Ca/Si ratio for both HCl and acetic acid treatment but less than that of the heat treatment. The explanation of acidic influence on the Ca/Si ratio could be briefly summarized as below:

The first case basically includes CRCA#1 immersion in 0.1 M of an aqueous solution of HCl. Molecules of CSH are complicated compounds and are exhibit difficult solubility behaviour due to the large number of hydrated CSH compounds. CH crystal is classified as a solid material that is only slightly soluble in water at room temperature, but the saturated solution of CH can clearly categorize it as a strong base solution due to high liberation of OH- ions. HCl is a strong acid and very soluble in water which results in total dissociation in water. In addition, the presence of positive ions such as Na^+ and K^+ is high. A large number of CSH compounds; a complex equilibrium of CaO-SiO_2-H_2O and variable value of pH are the mainly attributed factors that influence on the equilibrium.

$$Ca(OH)_{2(S)} \leftrightarrow Ca^{+2}_{(aq)} + 2OH^{-}_{(aq)} \ldots\ldots\ldots\ldots.. \text{(6-5)}$$

$$HCl + H_2O \rightarrow H_3O^{+} + Cl^{-} \ldots\ldots\ldots\ldots\ldots\ldots \text{(6-6)}$$

Therefore, the simplification of a very complicated system is reasonable. Because of the large numbers and highly complicated solubility of CSH, there is no focus on the solubility influence of CSH in an equilibrium state because there is a need to specifically additional detailed study which is located far outside the scope of this study. Therefore, the ionic equilibrium could be classified as a type of strong acid and strong base. The concentration of H^+ ions for this equilibrium is (0.1 M) due to total dissociation of strong HCl acid. The concentration of OH^- ions is (0.025 M) calculated from the pH of a saturation solution of CH which is (12.4) (Bazant & Steffens, 2000). The concentration also can be calculated from the equilibrium constant which is also called the solubility product for CH at 20 °C. This significant difference between these ions promotes the forward direction of CH to dissociate more OH^- until reaching equilibrium which means more CH consumption and lowering the Ca/Si ratio.

$$Ca(OH)_{2(S)} \leftrightarrow Ca^{+2}_{(aq)} + 2OH^{-}_{(aq)} \ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots..\ldots. \text{(6-5)}$$

$$CH_3COOH + H_2O \leftrightarrow H_3O^{+} + CH_3COO^{-} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(6-7)}$$

The CRCA#1 immersion in 0.1 M of an aqueous solution of $C_2H_4O_2$ is the second case. $C_2H_4O_2$ is a weak acid and miscible with water, which leads to lower release of H^+ ions.

With the same simplification, the ionic equilibrium can be classified as a type of buffer solution that includes weak acid and conjugate base which is slightly different from the normal conjugate base. The pH value of this type of solution represents a crucial point, which can be numerically calculated. The simple calculations indicated that the pH value of the solution reached 6 which means a high release of OH^- ions compared with 12.4 for CH saturation solution. This leads to a significant increase in CH consumption, which results in a lower Ca/Si ratio as compared to the HCl case.

6.4 Influence of Treatments on Surface Microstructure of CRCA

As it was mentioned earlier, the graphs (Figures 6.11 to 6.13) revealed that there is a significant reduction in the Ca/Si ratio for all treatment types. The lowering of the Ca/Si ratio considerably contributes to improve microstructure of CRCA in different ways:

- The large formation of new products due to pozzolanic reaction could fill the pores and cover the surface of ITZ. This mainly contributes to improving microstructure through increasing the strength of this region, which is classified as a weak area (Kong et al., 2010). This explanation is the major reason behind the idea of addition of pozzolanic materials such as fly ash and silica fume to enhance RCA properties. These materials can largely transform CH crystals that accumulated on the surface or within the pores to new products, especially CSH, resulting in considerable lowering of the Ca/Si ratio and noticeable increase in strength and durability of RCA (Kong et al., 2010). The experimental results of improved durability in terms of resistance to freezing and thawing and abrasion loss obviously indicate to this type of microstructure enhancement. Additionally, it is generally accepted that there is an inverse relationship between the strength and porosity for a porous material (Lian et al., 2011). The obtained results of porosity reduction with acidic and heat treatment at lower temperatures strongly refer to improved strength of CRCA.

- Another way to possibly increase the strength of the surface is through the increase of the concentrations of silicate ions in ITZ area. The graphs (Figures. 6.11-6.12) of the Ca/Si ratio clearly indicated that there is an important increase of silicate ions, which successfully confirm this approach for all treatment types at different percentages. This also refers to pozzolanic effect because these materials are a siliceous or aluminosiliceous compounds that effectively work to enhance strength and microstructure improvement (Kong et al., 2010; Jawahar et al., 2013).

- Also, the new products significantly participate to make the surface more homogenous through lowering heterogeneity. This conclusion is confirmed by the observations of SEM images that revealed the surface with different types of treatment becoming more homogeneous than the original state. The outcome was also similar regarding the relationship between lowering of the Ca/Si ratio and surface homogeneity (Erdem et al., 2012).
- Further benefit of accumulated new products is that the surface treatment could possibly increase the density of the ITZ surface, resulting in another type of improvement. For this study, the results of density after various treatments and porosity strongly confirm this conclusion.

As a result, there is a substantial improvement to the microstructural level of the CRCA#1 surface. This improvement mainly consists of the increase in the following properties: increase density, increase surface homogeneity and reduce Ca/Si ratio. Additionally, there is a strong potential to increase strength of CRCA in different ways, however there is still a need to strength test in order to confirm this increase.

6.5 Relationship between Mineralogical and Mechanical properties

The relationship between mineralogical properties in terms of Ca/Si ratio and durable and mechanical properties namely abrasion loss and adhered mortar loss are shown in Figures. 6.14 and 6.15. As can be seen, linear equations are obtained that evidently describe conduct of these properties. A considerable correlation completely demonstrates an existence of a strong connection between Ca/Si and two different durable and mechanical properties through heat treatment.

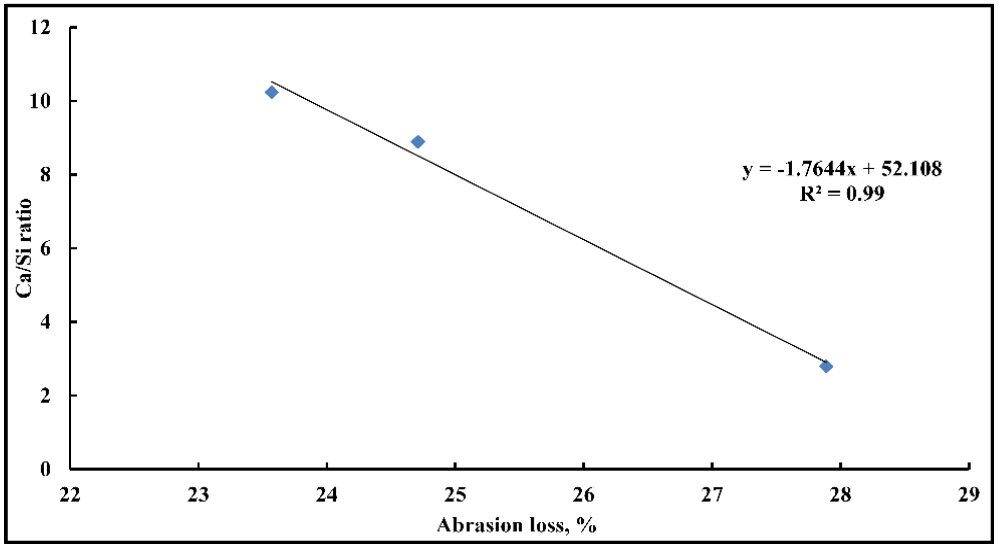


Figure 6.14: Relationship between Ca/Si and abrasion loss for CRCA#1 through heat treatment.

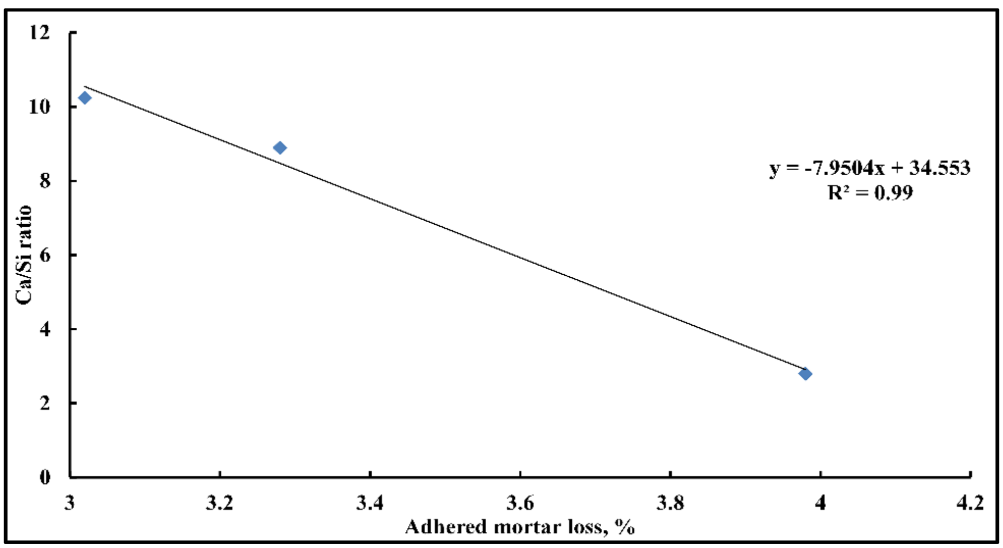


Figure 6.15: Relationship between Ca/Si and mortar loss for CRCA#1 through heat treatment.

6.6 Summary of This Chapter

This chapter concentrated on examining the influence of different treatments on enhancing the morphological and mineralogical properties of CRCA under the effect of different types of treatment methods. Based on the experimental results, the main points of this chapter can be summarized as in the following:

- It is demonstrated that the morphology of untreated CRCA has a rough and irregular surface with a highly porous structure. It was also observed that adhered mortar is widespread on the CRCA surface at different thicknesses, causing surface heterogeneity.
- Compared with untreated CRCA, a large microstructural enhancement was obtained due to the utilization of different treatment methods. The degree of roughness of the CRCA surface is lowered depending on the type of treatment method used.
- From the captured images, it was noted that there is significant damage on the CRCA surface with HCl treatment. However, this damage is completely different compared to the surface treated with acetic acid treatment.
- The obtained findings showed that the untreated CRCA surface is highly porous and rich in CH crystals, whereas the surface is comparatively poor in C-S-H and C-A-H but even lower in AFt (ettringite).
- The results of EDAX analysis demonstrated that there is a significant reduction in the Ca/Si ratio with the application of different treatments. However, decreasing the Ca/Si ratio depends on the type of applied treatment method. The lowering of the Ca/Si ratio considerably contributes to improving the microstructure of CRCA.
- There is a considerable improvement to the surface microstructure of CRCA. This improvement mainly consists of increased density, increased surface homogeneity and reduced Ca/Si ratio. Additionally, there is a strong potential to increase the strength of CRCA in different ways; however, there is still a need to apply strength tests to confirm this increase.

CHAPTER 7

INFLUENCE OF TREATMENT METHODS ON MICROSTRUCTURE PROPERTIES OF CRCA

In this chapter, the obtained findings of CRCA#1 have been published in the Construction and Building Materials Journal (Al-Bayati et al., 2016). The outcomes of CRCA#2 have been presented at the Transportation Association of Canada (TAC) Conference (Al-Batayti et al., 2016). In addition, the results of CRCA#2 has also been submitted to the International Journal of Pavement Engineering.

7.1 Pore Size of Mortar Surface

Pore size behavior of CRCA#2 is presented in Figure 7.1 and Table 7-1 based on the captured images of SEM test in Figures 7.2 to 7.7. The obtained outcomes of heat treatment clearly indicate that there is a dramatic decrease in pore size through a temperature range of (0-350 °C). By contrast, the pore size is sharply increased within a temperature range of (350-500 °C), resulting in a considerable negative effect of higher temperatures on pore size of the mortar surface. More specifically, it is highly interesting to note that the pore size through heat treatment at 500 °C is increased three times compared with pore size of untreated CRCA. The obtained results also demonstrated that a successful acid treatment is registered for both types; strong and weak acid for decreasing pore size of CRCA. However, the treatment using strong acid seems to be more successful based on the laboratory results.

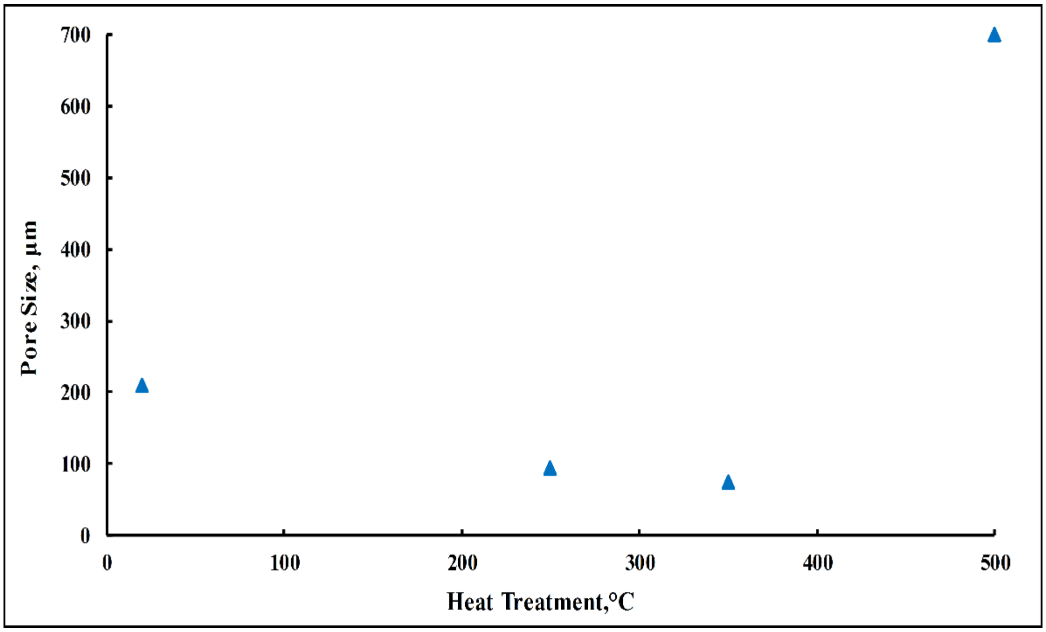


Figure 7.1: Behavior of pore size of mortar surface for CRCA#2 through heat treatment.

Table 7-1: Pore Size of Mortar Surface for CRCA#2 after Acid Treatments

CRCA Treatment/ Property	Pore size (µm)
CRCA untreated	208.9
CRCA soaking in HCl	139.9
CRCA soaking in C2H4O2	156.1

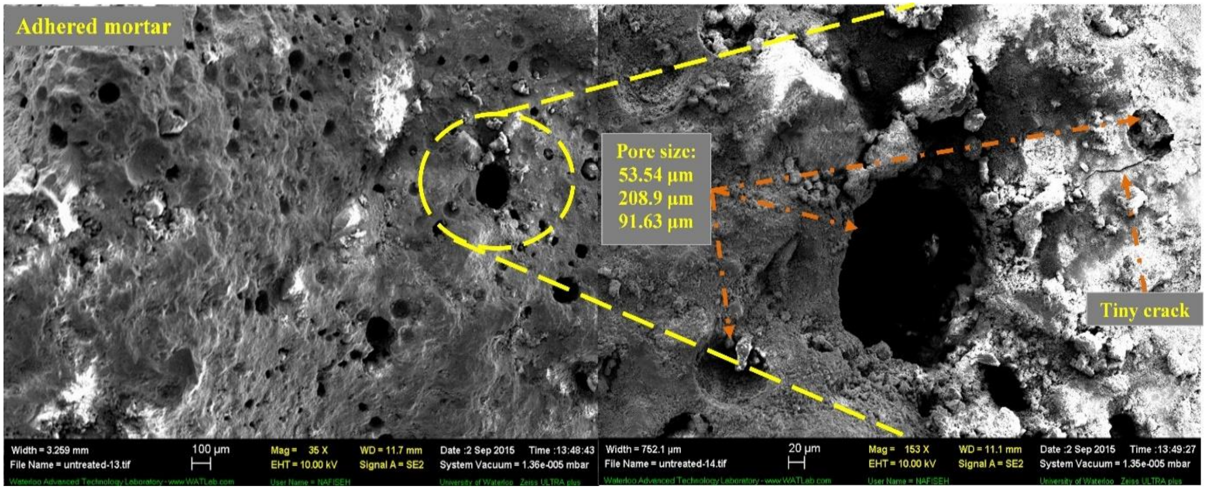


Figure 7.2: Pore size of mortar surface for untreated CRCA#2.

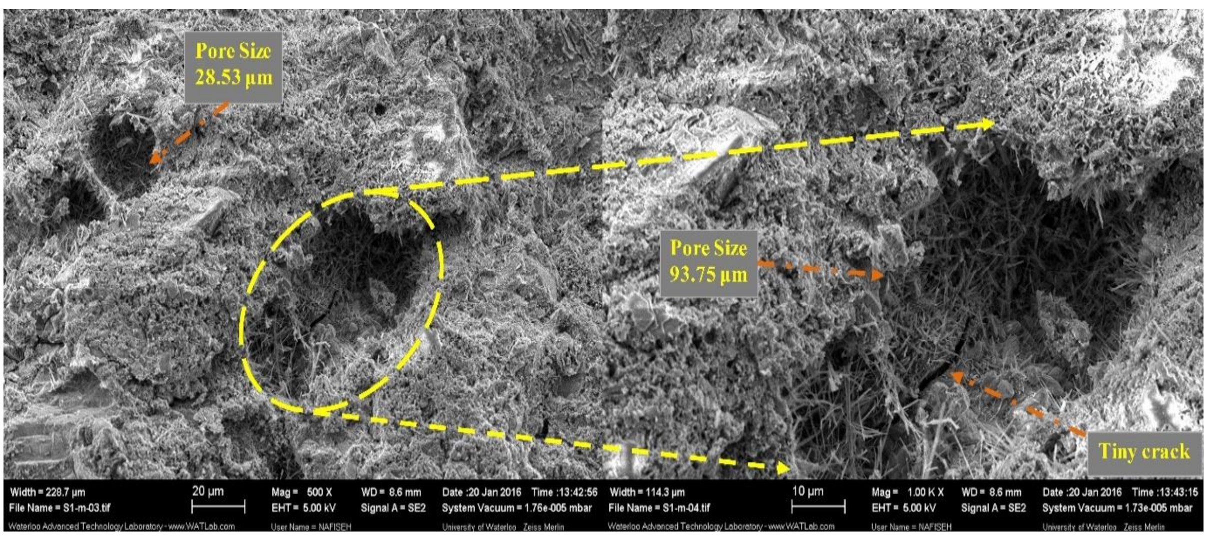


Figure 7.3: Pore size of mortar surface for CRCA#2 through heat treatment at 250 °C.

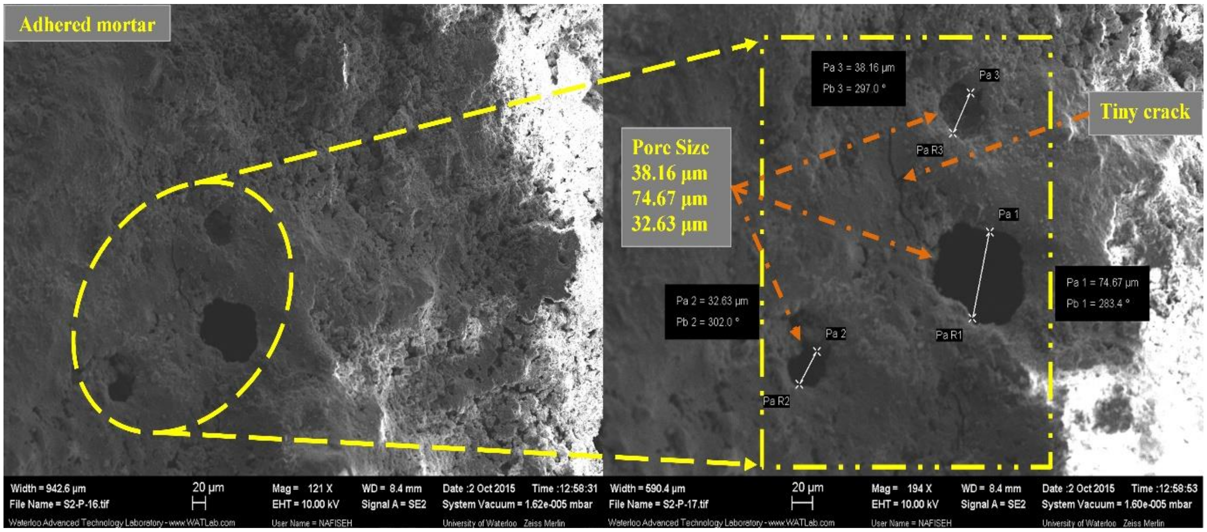


Figure 7.4: Pore size of mortar surface for CRCA#2 through heat treatment at 350 °C.

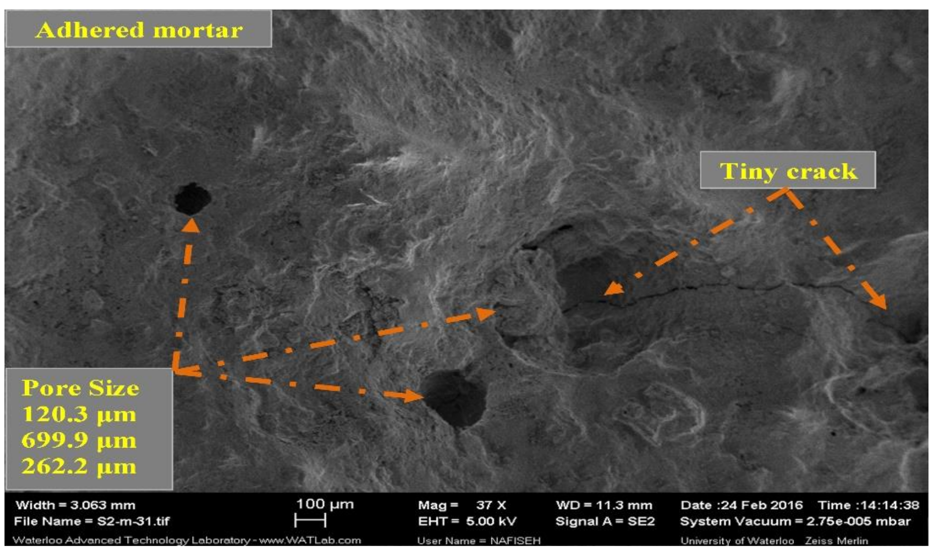


Figure 7.5: Pore size of mortar surface for CRCA#2 through heat treatment at 500 °C.

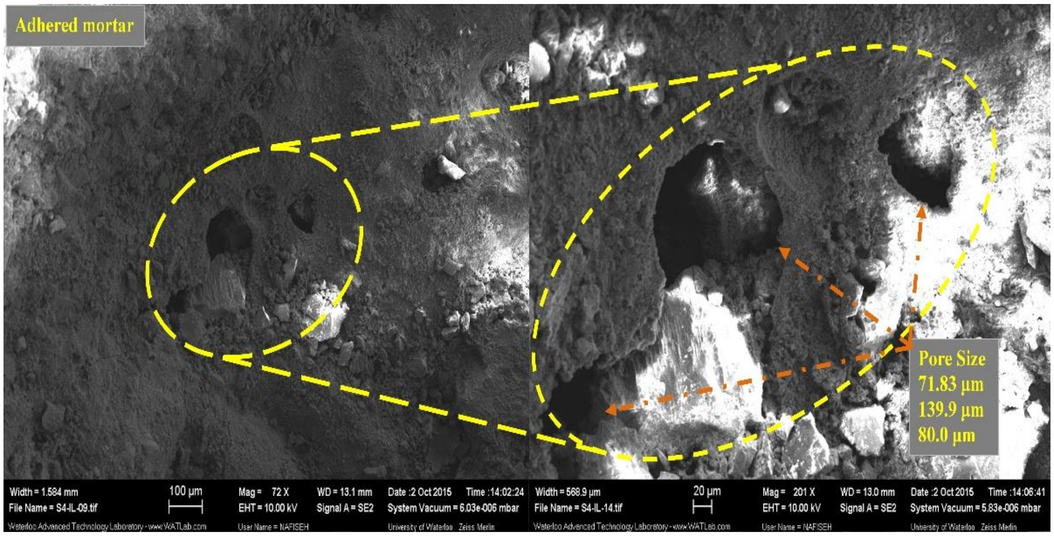


Figure 7.6: Pore size of mortar surface to CRCA#2 through HCl treatment.

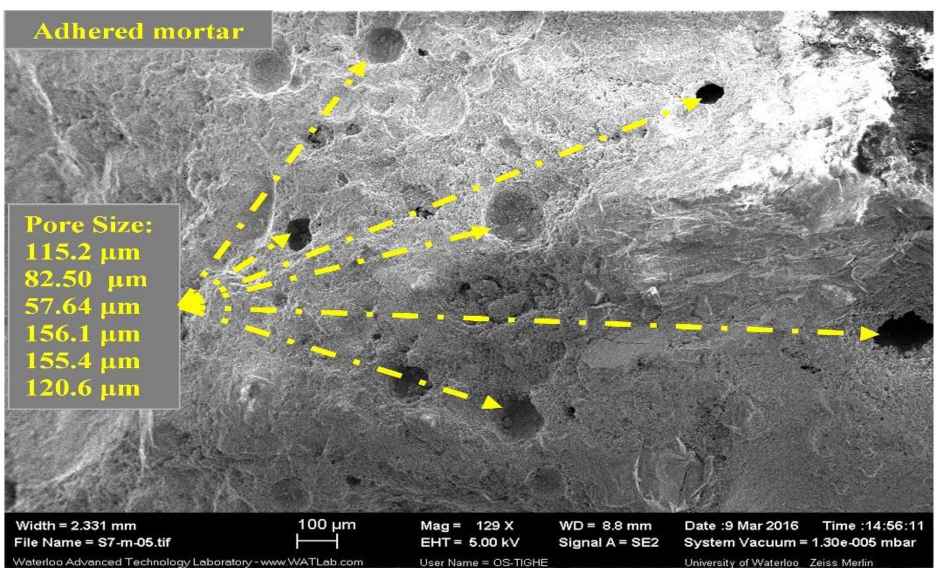
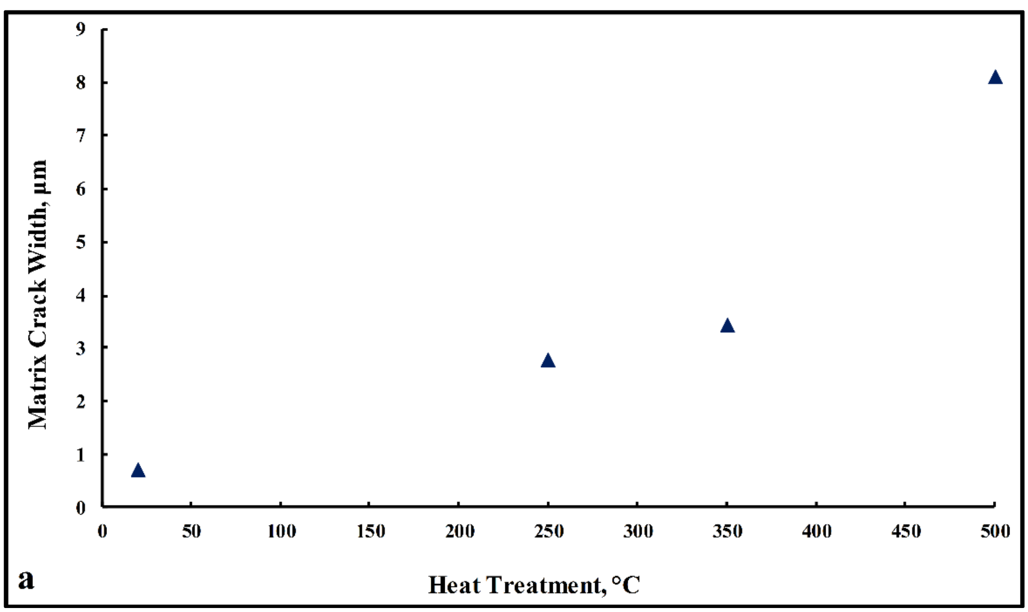


Figure 7.7: Pore size of mortar surface for CRCA#2 through $C_2H_4O_2$ treatment.

7.2 Width and Length of Matrix Cracks

Properties of matrix cracks including width and length, and behavior of cracks on mortar surface of CRCA#2 for various treatment types, are demonstrated in Figure 7.8 (a & b) and Table 7-2. Whereas, the SEM images of matrix cracks are given in Figures 7.9 to 7.14. It is shown that there is a negative influence of heat treatment on properties of matrix cracks; width and length on the mortar surface. The width and length of matrix cracks are gradually increased within the temperature range of (0-350 °C), whereas the properties of cracks, width and length, are sharply increased through rising temperatures to 500 °C resulting in a considerable impact for heat treatment at higher temperatures. The obtained outcomes also revealed that the behavior of both properties exhibit as a polynomial equation and strongly correlate with heat treatment due to high regression. Table 7-2 displays properties of matrix cracks including width and length using acid treatment. The obtained results indicated that there is a negative effect for both types of acid treatment on properties of matrix cracks through increasing width and length compared with the same properties of matrix cracks for untreated CRCA#2. It is concluded that the influence of both acid treatments is similar to impact of heat treatment within temperature range (0-350 °C).



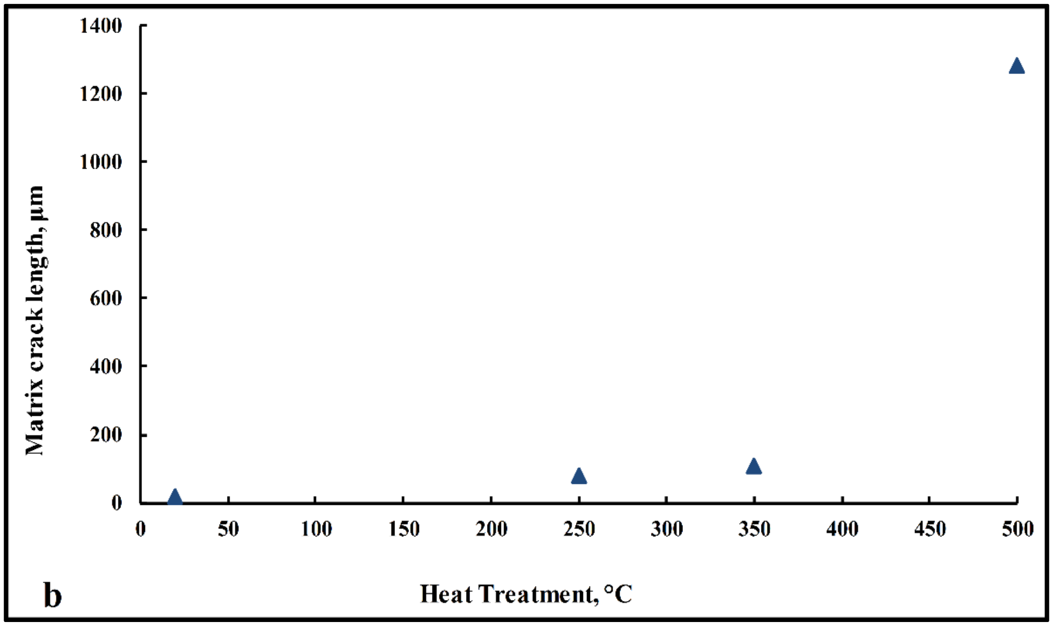


Figure 7.8: Behavior of matrix cracks properties through heat treatment: (a) Width of crack, (b) Length of crack.

Table 7-2: Matrix (Macro) Crack Width and Length of Mortar Surface After Acid Treatments

CRCA Treatment/ Property	Macro crack width (µm)	Macro crack length (µm)
CRCA untreated	0.70	20
CRCA soaking in HCl	2.68	35
CRCA soaking in $C_2H_4O_2$	4.54	123

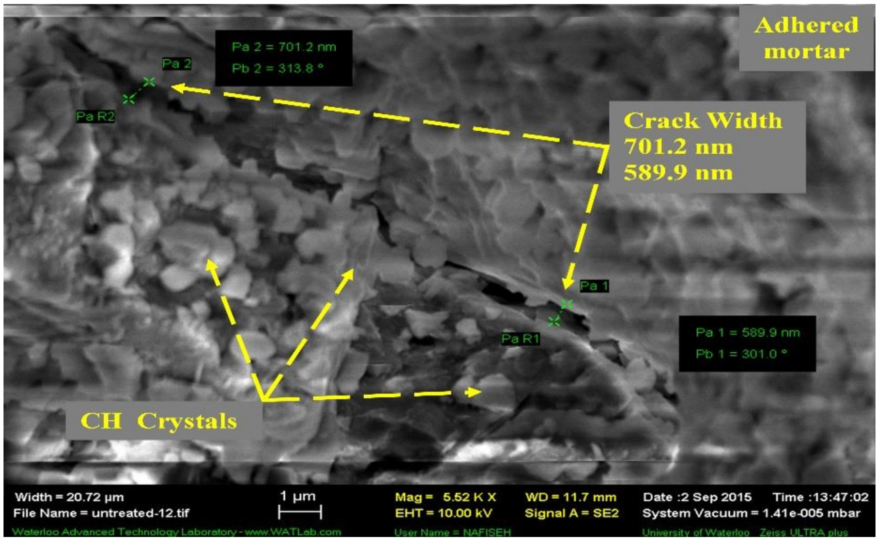


Figure 7.9: Matrix cracks of mortar surface for untreated CRCA#2.

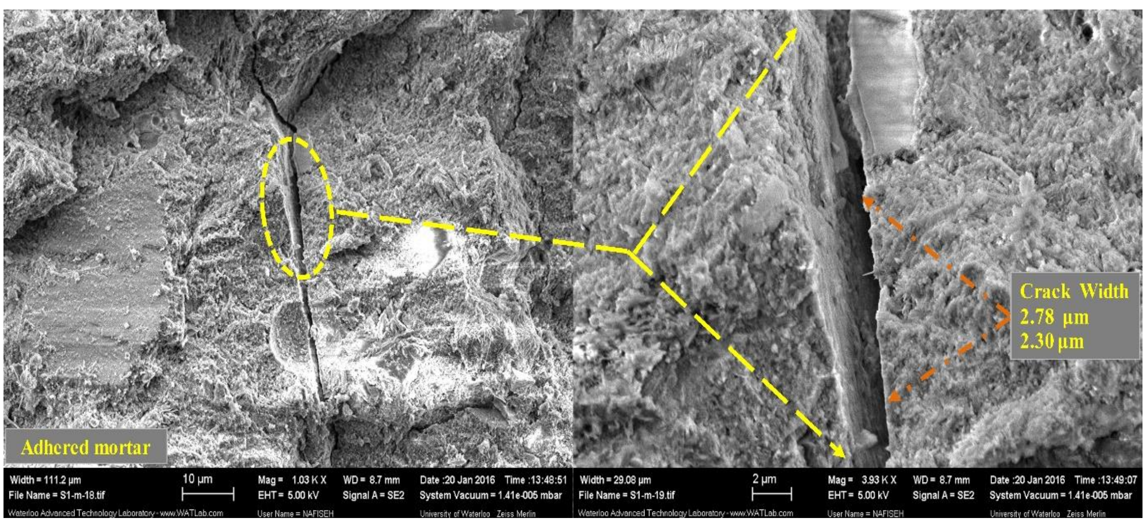


Figure 7.10: Matrix cracks of mortar surface for CRCA#2 through heat treatment at 250 °C.

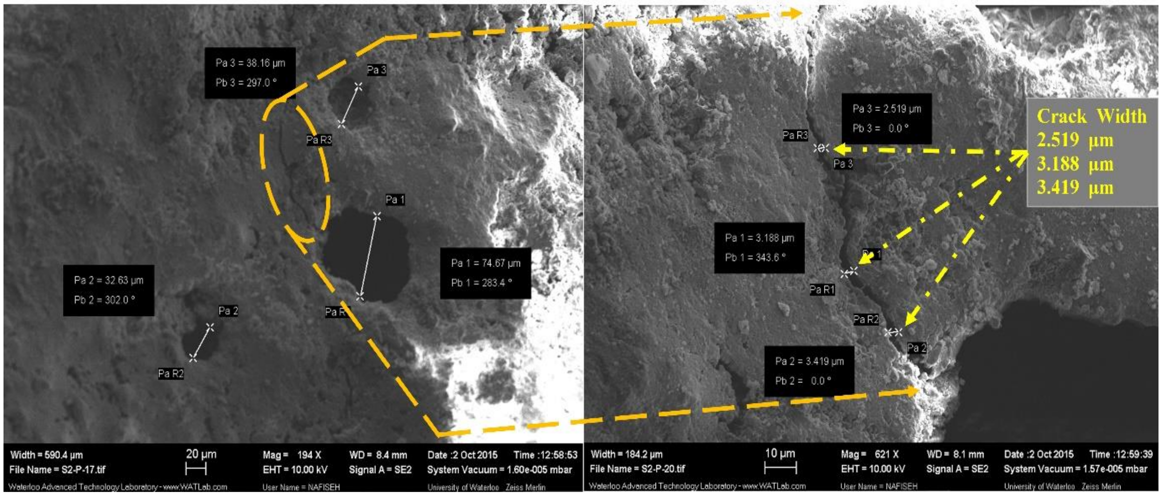


Figure 7.11: Matrix cracks of mortar surface for CRCA#2 through heat treatment at 350 °C.

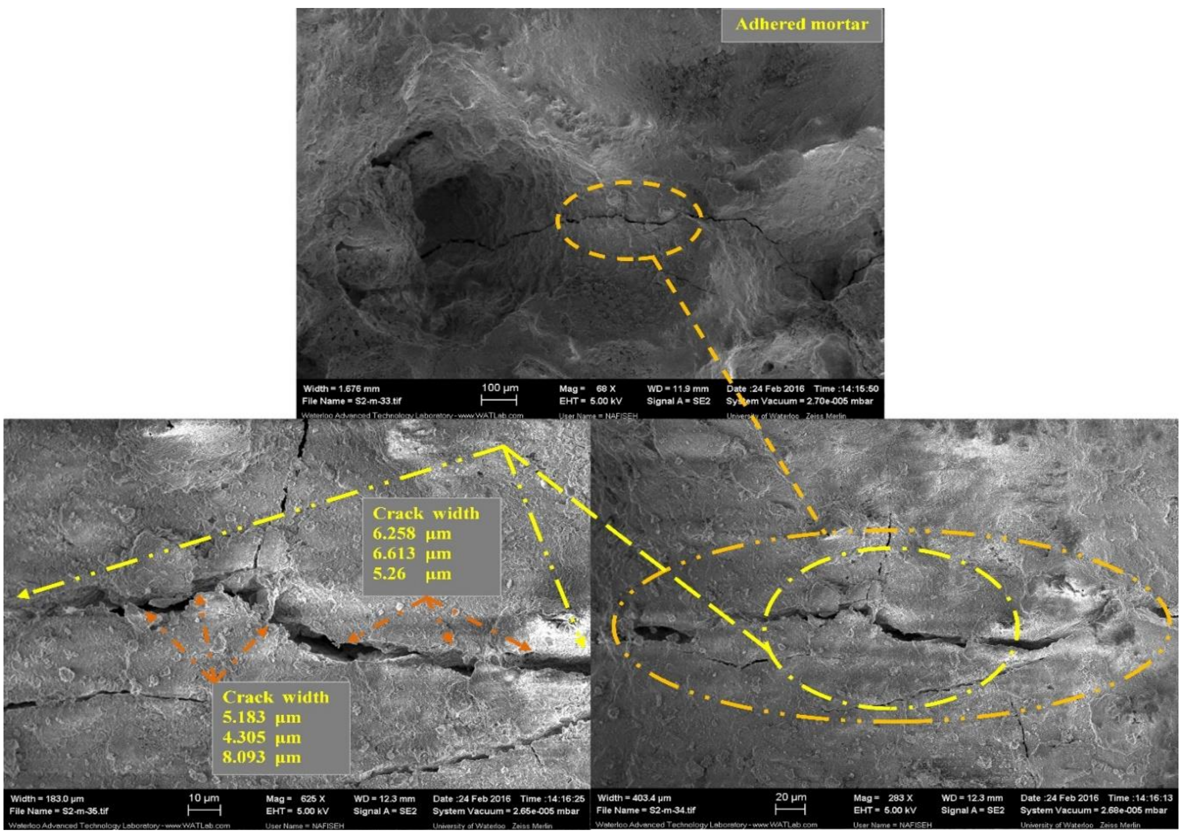


Figure 7.12: Matrix cracks of mortar surface for CRCA#2 through heat treatment at 500 °C.

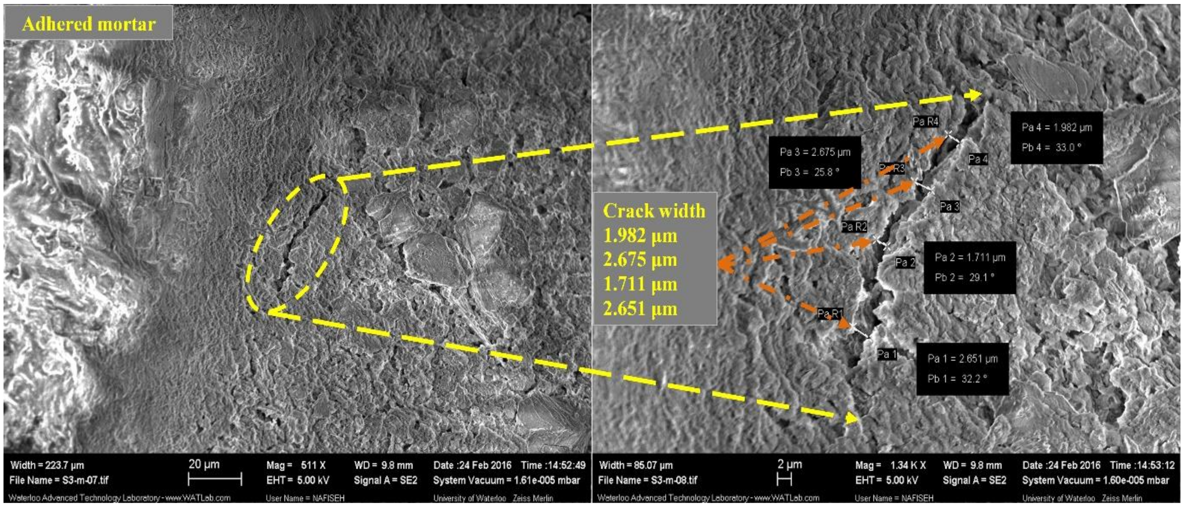


Figure 7.13: Matrix cracks of mortar surface for CRCA#2 after HCl treatment.

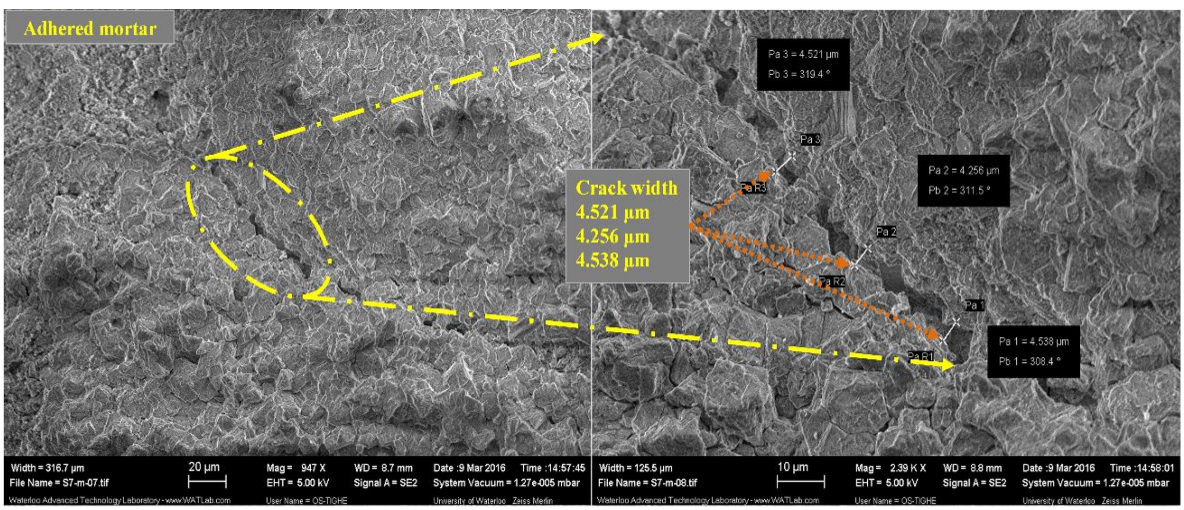


Figure 7.14: Matrix cracks of mortar surface for CRCA#2 after $C_2H_4O_2$ treatment.

7.3 Matrix (Macro) Cracks Density

The obtained results of crack density and the relationship between crack density and properties of matrix cracks including width and length are presented in Figures 7.15 and 7.16. The outcomes demonstrate that crack density is slightly raised in a temperature range of (0-350 °C), whereas crack density is dramatically increased at a higher temperature range of

(350 °C -500 °C). However, the overall behavior shows a strong relationship between the crack density and heat treatment.

The outcomes also demonstrate that properties of matrix cracks including width and length are significantly related to crack density. As crack density increases, both matrix crack properties, width, and length are increased. However, a significant difference in behavior is noticeable between the two properties. It can be concluded that crack density and matrix crack properties, width and length, are strongly related to the used heat treatment.

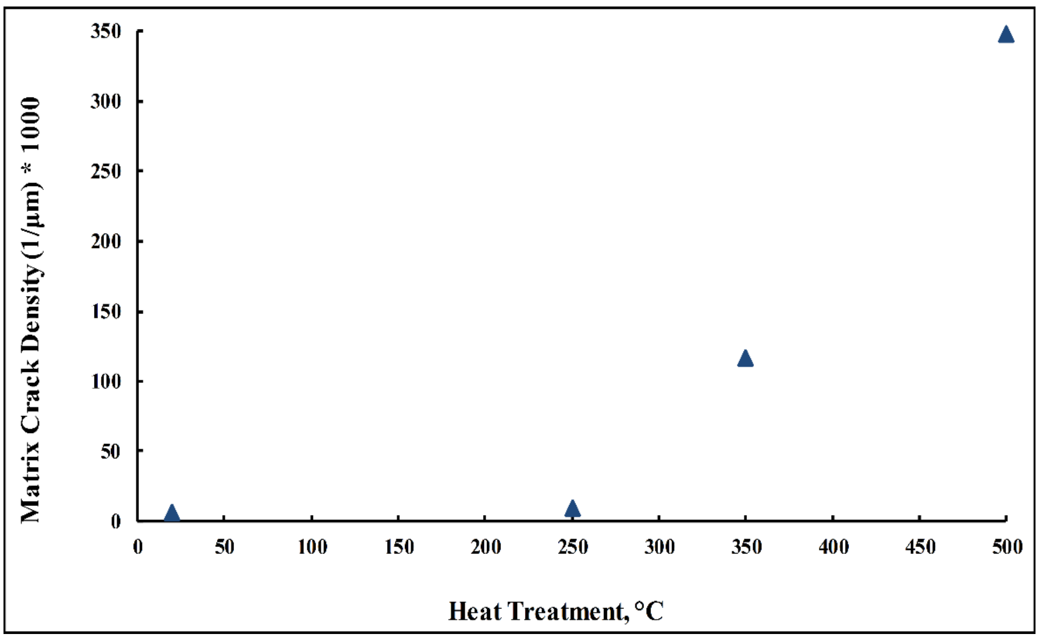


Figure 7.15: Behavior of matrix cracks density for CRCA#2 through heat treatment.

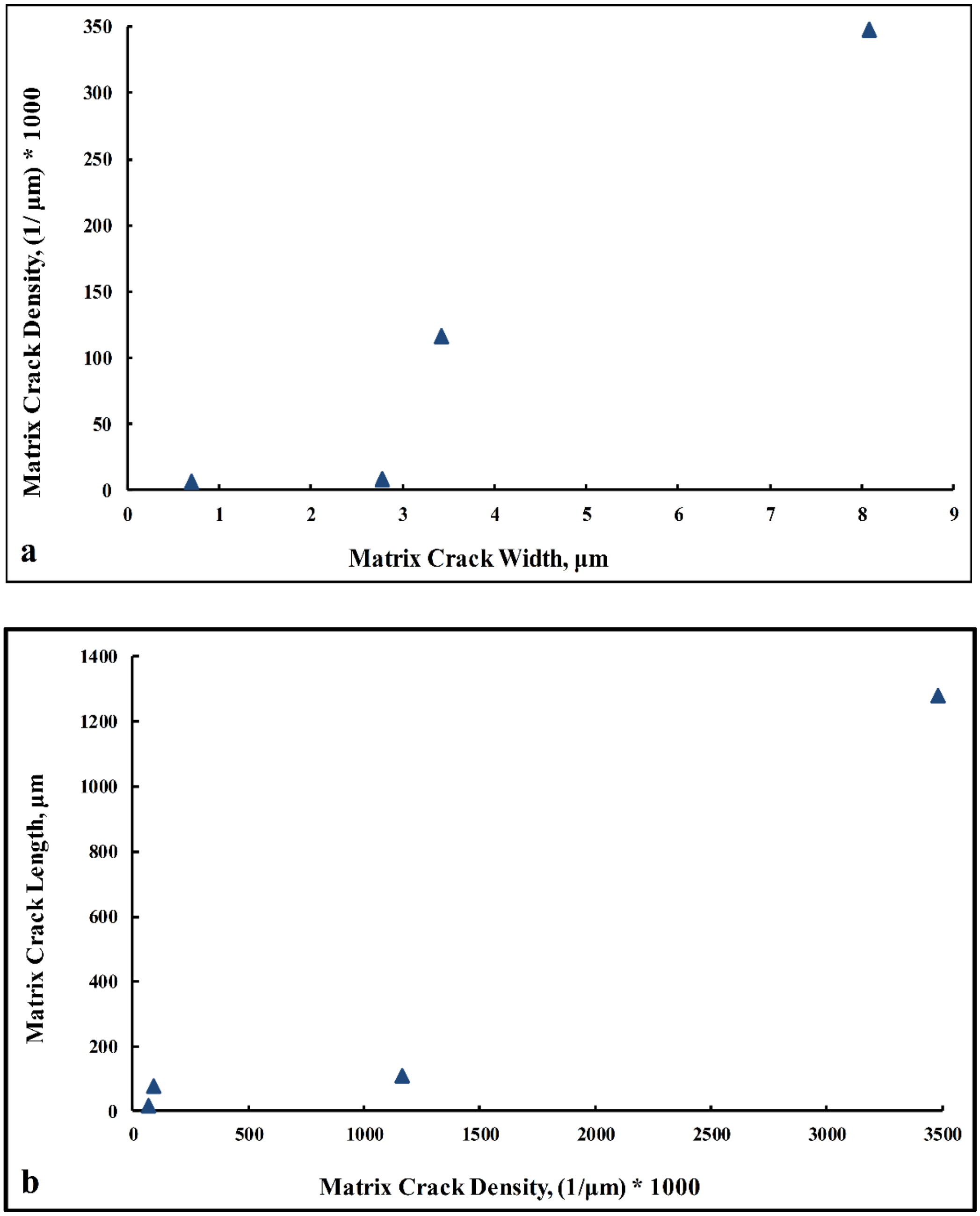


Figure 7.16: Relationship between matrix cracks density and cracks properties for CRCA#2: (a) Width of crack, (b) Length of crack.

7.4 Summary of This Chapter

This chapter investigated the impact of different treatment methods on various microstructure properties of CRCA such as pore size and matrix cracks and their properties (e.g. width and length). Based on the obtained results, the major points of this chapter are summarized as follows:

- The findings revealed that there is a positive impact of the heat treatment at temperatures up 350 °C on the reduction of pore size, whereas a negative impact is observed at high temperatures ranging between 350 °C and 500 °C.
- The results demonstrated that a successful acid treatment is registered for both acid types on decreasing the pore size of the CRCA surface. However, the utilization of strong acid seems to be more effective than weak acid depending on the captured images.
- There is a negative influence for the heat treatment on the properties of matrix cracks: width and length on the mortar surface.
- The crack density on the mortar side is highly related to the properties of matrix cracks including width and length.

CHAPTER 8
EFFECT OF DIFFERENT TREATMENT METHODS ON THE INTERFACIAL TRANSITION ZONE MICROSTRUCTURE TO COARSE RECYCLED CONCRETE AGGREGATE

In this chapter, the outcomes of CRCA#2 have been presented at the Transportation Association of Canada (TAC) Conference (Al-Batayti et al., 2016).

8.1 Introduction

In this chapter, the effect of various treatment methods on the ITZ microstructure is examined. To assess the influence of different treatments, ITZ microcracks are evaluated. Behaviour of ITZ microcracks and their properties, length and width, under the influence of the treatments are also explored. In this chapter, an approach is followed to evaluate ITZ improvement. The mentioned approach mainly consists of general assessment using the Ca/Si ratio as an indicator for ITZ improvement. This ratio is evaluated for both sides of the ITZ zone, aggregate and mortar surface. In addition, intermix phases; namely, CSH, CH, AFM, for both sides of the ITZ zone are investigated to assess the transformation of different phases under the impact of various treatments using certain criteria. Such transformation is used as a further index for measuring ITZ improvement.

8.2 Influence of Treatment Types on ITZ Microcracks (Interface Gap)

The differences between the microstructure of ITZs for untreated and treated CRCA were studied using the images indicated in Figures 8.1 to 8.6. The magnified perspectives shown in Figure 8.1 show the captured image of untreated CRCA with a microcrack interface (gap interface) between the aggregate and attached mortar. It is demonstrated that the microcrack width is not uniform in the ITZ microstructure as it was reported by previous investigations

(Jawahar et al., 2013). Instead, the maximum width of the microcrack is 129.7μm, which represents between 2-3 times the usual thickness of ITZ for a concrete or recycled concrete material. The size of the microcrack can be responsible for increasing ITZ porosity, decreasing interface bonding and making this area weaker than the surface of both mortar and aggregate. Therefore, this observation will be very helpful to understand ITZ properties and it should be considered through investigation of strength of recycled concrete. However, there is no mention about this observation in the literature related to concrete and recycled concrete according to the best of the authors' knowledge.

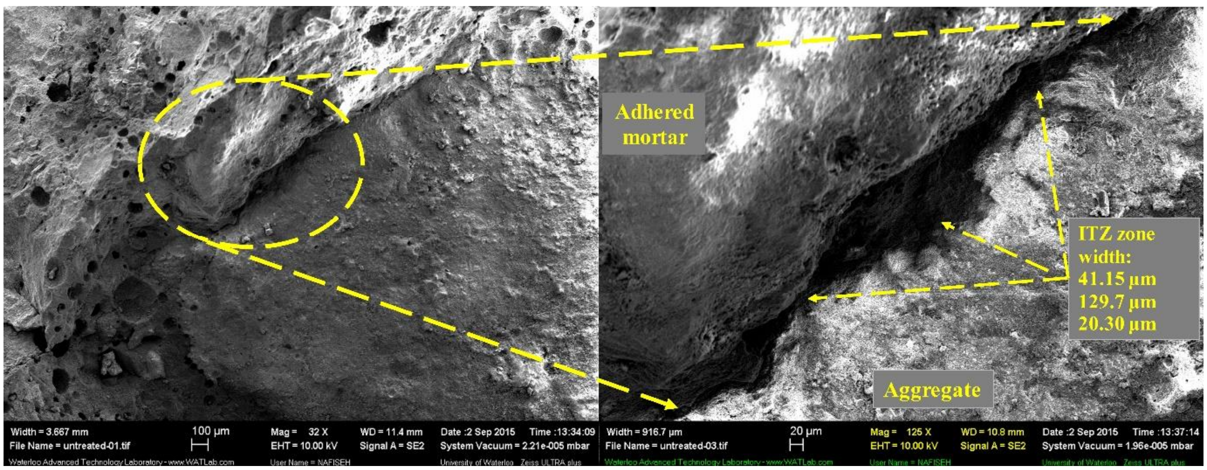


Figure 8.1: ITZ microcrack width to untreated CRCA#2.

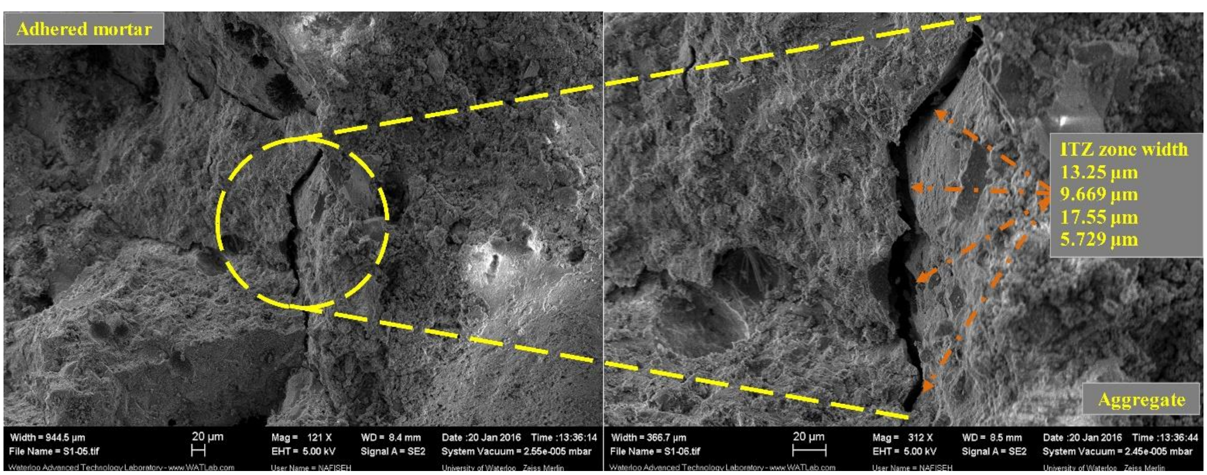


Figure 8.2: ITZ microcrack width to CRCA#2 through heat treatment at 250 °C.

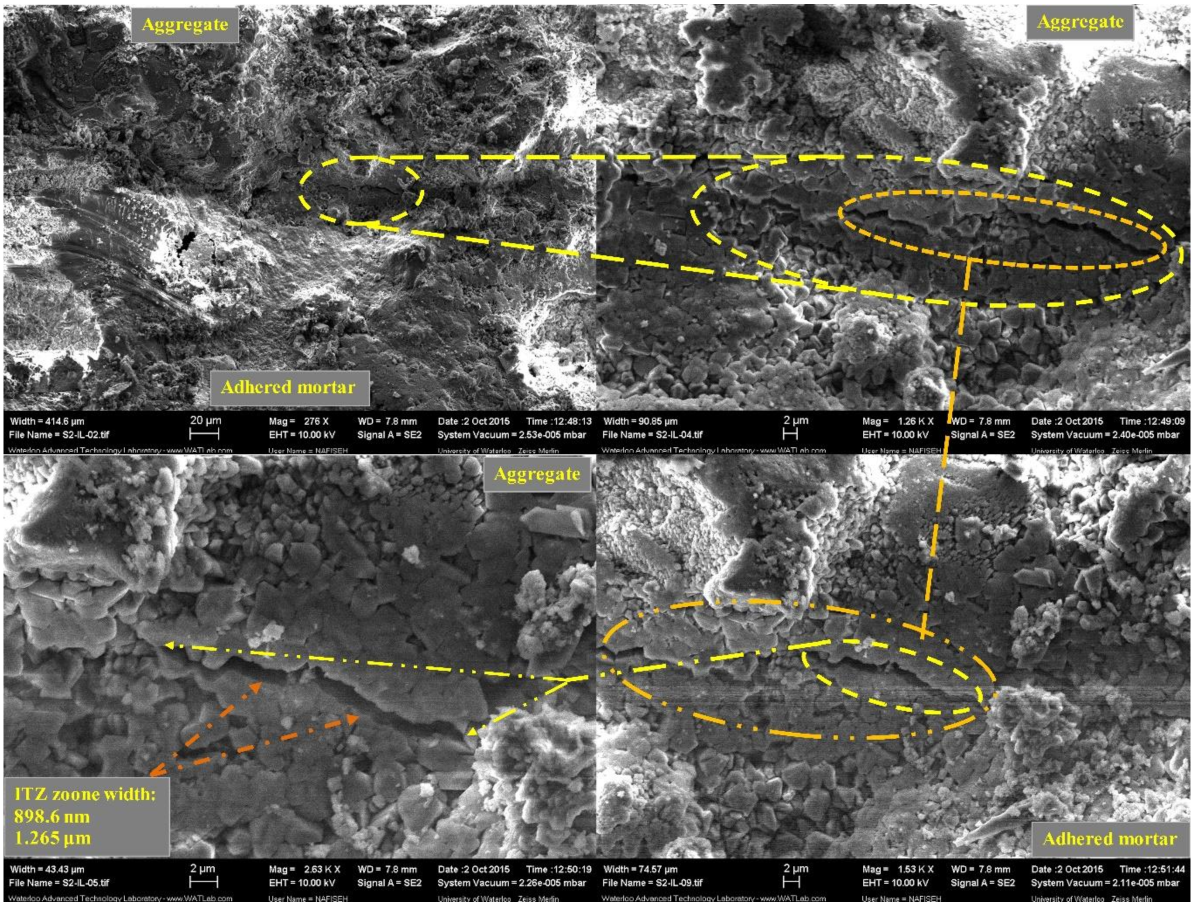


Figure 8.3: ITZ microcrack width to CRCA through heat treatment at 350 °C.

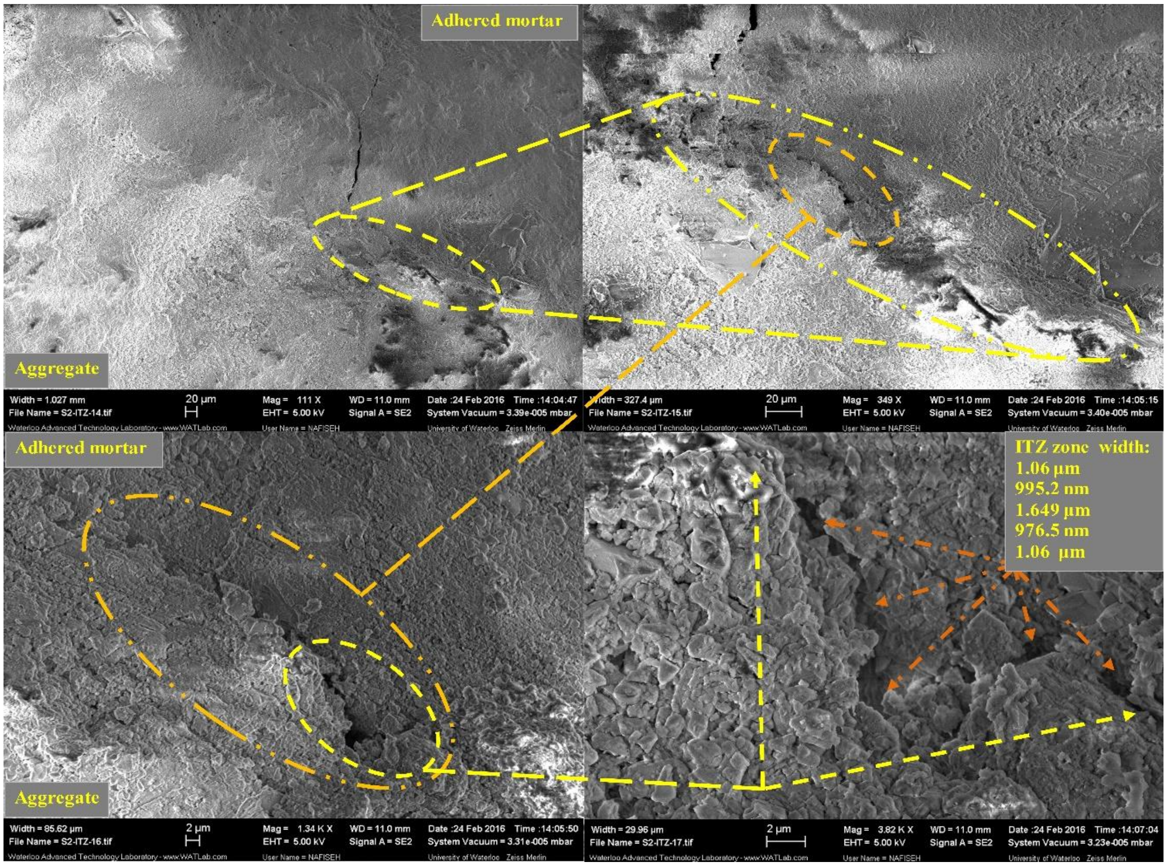


Figure 8.4: ITZ microcrack width to CRCA through heat treatment at 500 °C.

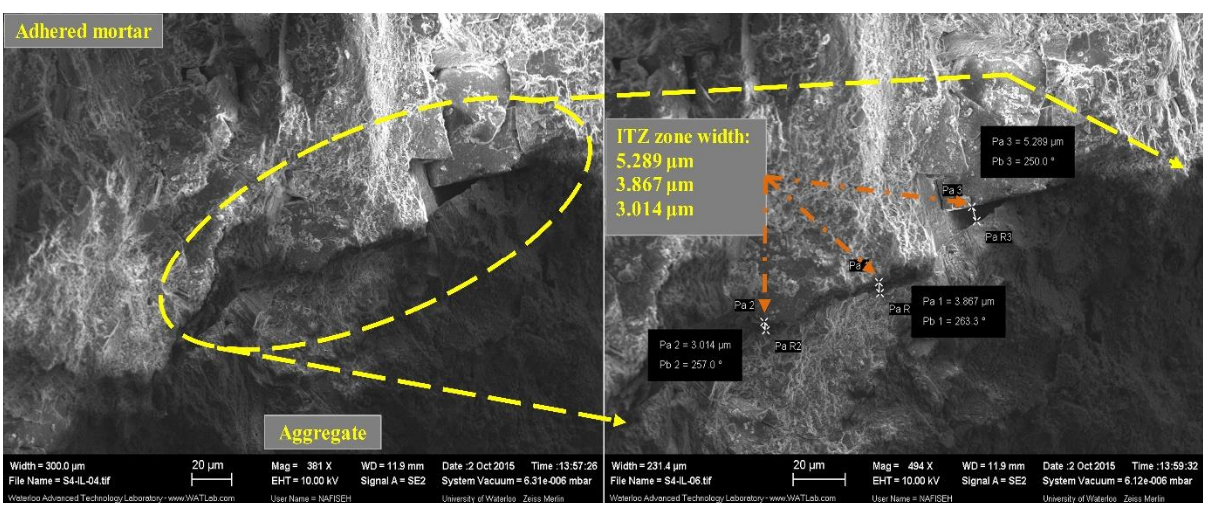


Figure 8.5: ITZ microcrack width to CRCA#2 through acidic treatment with HCl.

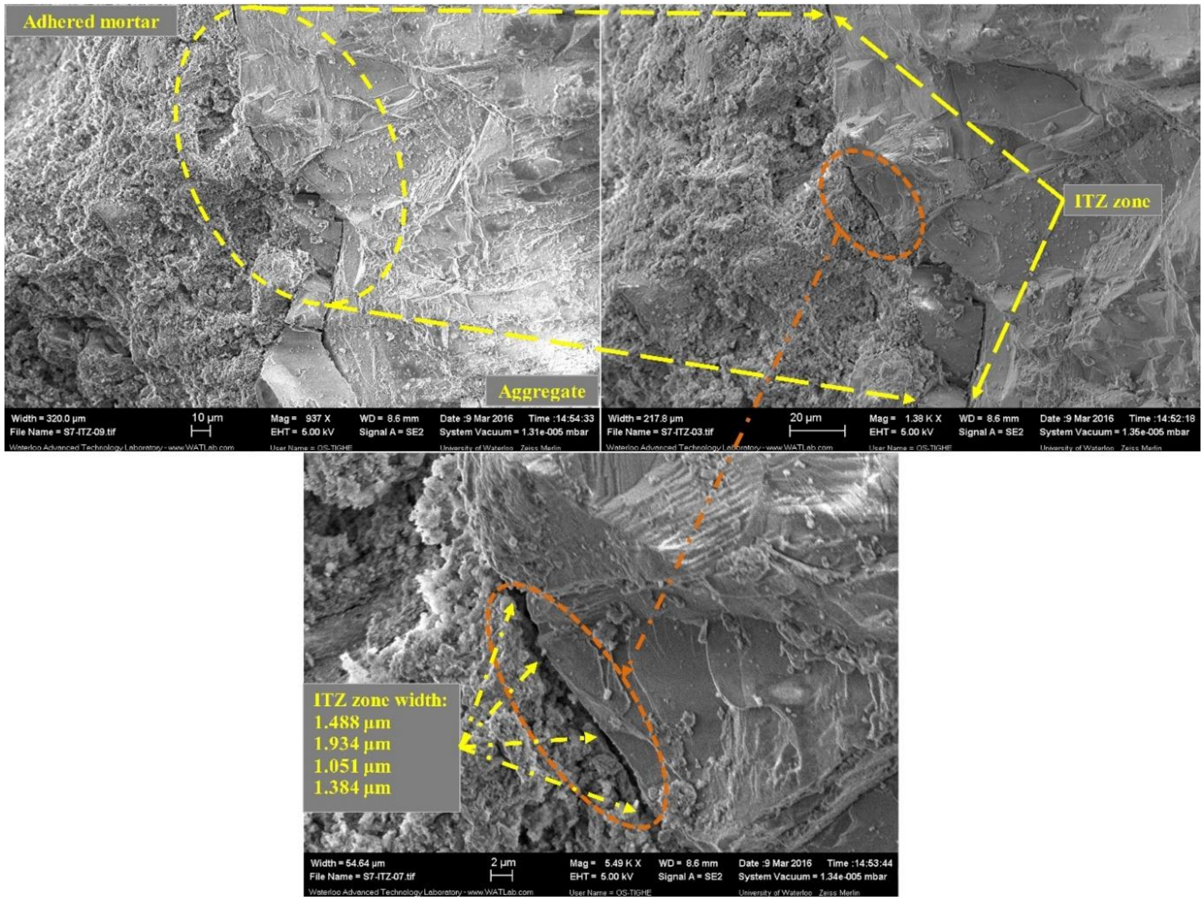


Figure 8.6: ITZ microcrack width to CRCA#2 through acidic treatment with $C_2H_4O_2$.

In order to understand behavior of the width and length of microcracks in the ITZ, the maximum width and length of microcracks for acid treatment types are tabulated in Table 8-1. The obtained results of heat treatment under different conditions are graphically analyzed in Figure 8.7. Overall, it is clearly noticeable that there is a considerable reduction in width and length of microcracks resulting in a significant improvement to the ITZ. This is mainly attributed to a large accumulation of CSH particles, which result from various reactions as in the following equations:

$$2C3S\ (Alite)+6H \rightarrow (C-S-H)\ +3CH(Portlandite) \text{ ………… } (8.1)$$

$$2C2S\ (Belite)+4H \rightarrow (C-S-H)\ +CH(Portlandite) \text{ ……..…. } (8.2)$$

$$CH(Portlandite)+SH \rightarrow (C-S-H) \text{ ……………………. } (8.3)$$

Table 8-1: Microcrack Width and Length in ITZ Zone before and after Acid Treatments

CRCA Treatment/ Property	Micro crack width (μm)	Micro crack length (μm)
CRCA untreated	129.70	780.0
CRCA soaking in HCl	4.06	209.1
CRCA soaking in $C_2H_4O_2$	1.46	28.8

The aged CRCA has been exposed to concrete hydration components. The reaction of conversion of CH crystals that are accumulated on the CRCA surface to CSH particles is becoming a main source for producing CSH particles. This is achieved under pozzolanic action which transforms the amounts of CH crystals into CSH particles by the pozzolanic reaction (equation 8.3). The accumulated CSH particles fill the microcracks due to their small size compared with CH crystals resulting in microcrack improvement and ITZ densification.

As can be seen in Figure 8.7, there is an inverse relationship between the microcrack width and length, and increasing temperatures. The microcrack width and length are sharply decreased through heat treatment between (0-500 °C). It is interesting to note that there is a slight increase, which can be negligible, to microcrack width at 500 °C compared with heat treatment at 350 °C. This means there is little impact of heat treatment type at high temperatures on microcrack width. However, heat treatment has a negative influence on other surface properties of aggregate and mortar as will be discussed later in this investigation. Therefore, it can be concluded that there is a strong relationship between heat treatment and microcrack width and length through this kind of treatment. From Table 8-1, the obtained results also revealed that acid treatment for both strong and weak acid is highly successful to lowering width and length of microcracks in the ITZ. However, treatment using weak acid seems to be more effective than strong acid due to a slight difference in obtained outcomes for both types of treatment compared with microcrack properties of untreated CRCA.

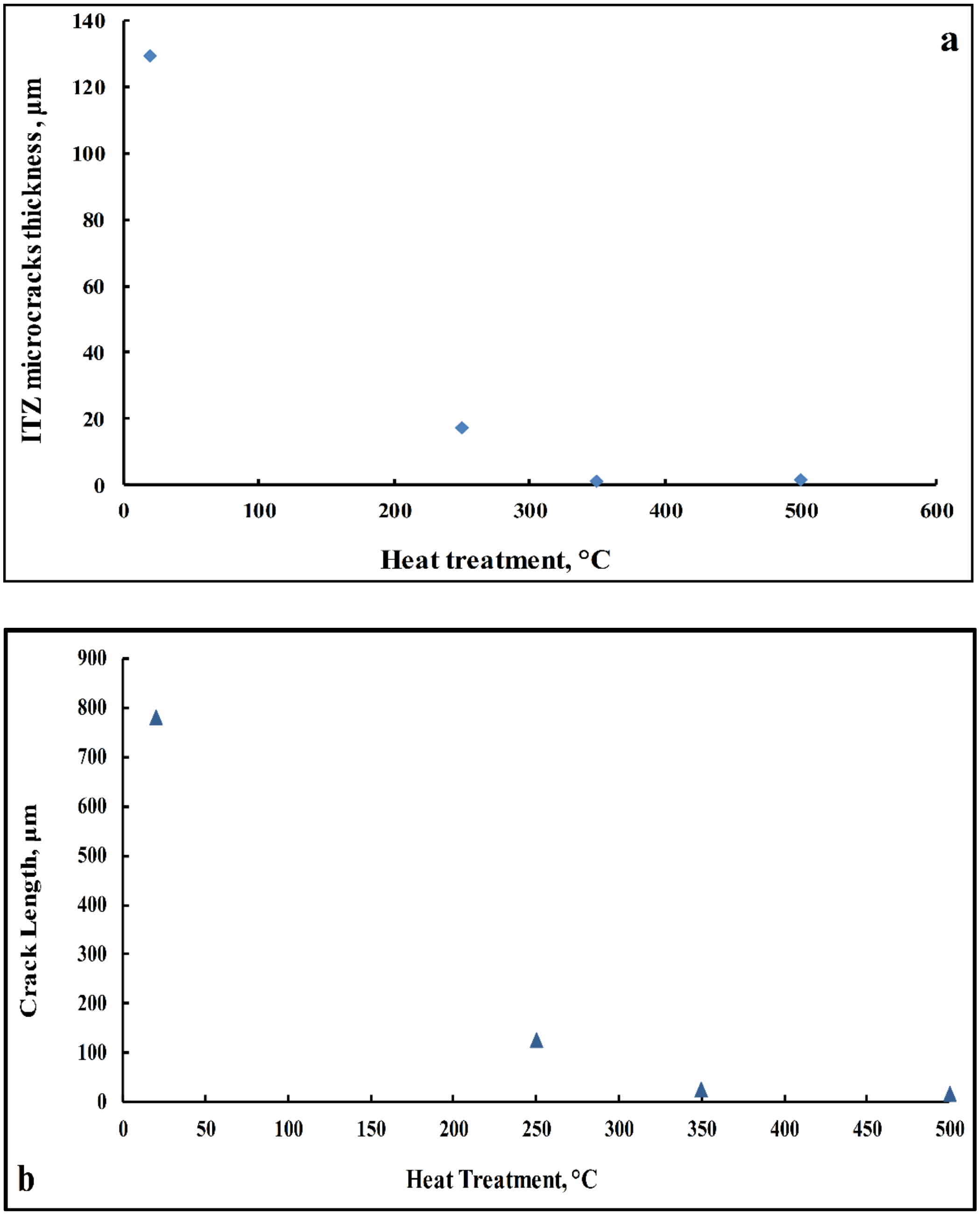


Figure 8.7: Behavior of ITZ microcrack through heat treatment: (a) width, (b) length.

8.3 Elemental Composition Behavior on Both Sides of ITZ

Figures 8.8 (a & b) present the atomic percentages of calcium (Ca), silicon (Si) and Ca/Si ratio from the outcomes of EDAX analysis (Appendix A), which was conducted on both sides of the ITZ; mortar side and aggregate side, were interpreted as a schematic diagram. The analysis of untreated CRCA revealed that there is a significant difference in Ca atoms between the mortar and the aggregate side indicating a higher percentage of CH particles on the mortar side that is mainly responsible for high porosity in the ITZ. From the obtained results of heat treatment at 250 °C, it is concluded that a considerable decrease of Ca atoms with a high increase of Si atoms resulted in a significant enhancement for the ITZ for the mortar side as compared with the aggregate surface. It is notable that a reduction in the Ca/Si ratio is observed, indicating a significant transformation of the CSH phase which is substantially responsible for ITZ improvement.

The outcomes of acid treatments showed that HCl treatment seems to be more effective than acetic acid in terms of Ca atom behavior for both sides of aggregate and mortar indicating a high degree of transformation to CH crystals. Additionally, it is interesting to note that a high increase in Si atoms is registered through acetic acid treatment compared with HCl acid for the aggregate side, whereas HCl acid treatment is more effective for increasing Si atoms for the mortar side than acetic acid. This could be explained by two factors: firstly, there is a significant variance in the ability of strong and weak acids to attack the surface adhered mortar, and secondly, the surface material type. De Juan & Gutiérrez mentioned that HCl treatment cannot be used to treat RCA with limestone aggregates due to the adverse acid attacks on this type of aggregate. Moreover, the obtained results demonstrated that there is a considerable reduction of Ca/Si ratio for the aggregate side using acetic acid treatment as compared to HCl acid treatment, whereas HCl acid seems to be more successful for lowering the Ca/Si ratio on the mortar side, resulting in a significant transformation of CSH phase.

The atomic Ca/Si ratios on both sides of the ITZ measured by SEM coupled with EDAX are plotted in Figure 8.9. It is shown that a significant difference was observed in the behavior of atomic Ca/Si ratio between aggregate and the mortar side of the ITZ. For a temperature range between 20 °C-350 °C, the atomic Ca/Si ratio of the mortar side was sharply decreased, whereas it was registered that there is a slight decrease to the same ratio on the aggregate side of the ITZ. It is also demonstrated that heat treatment at higher temperatures between (350 °C -500 °C) has a negative influence on atomic Ca/Si ratio for both aggregate and the mortar side of the ITZ. However, the Ca/Si ratio on the mortar side is significantly affected by higher temperatures through increase of the Ca/Si ratio compared with the aggregate side which is only slightly influenced by the same conditions. The significant regression clearly indicates that the behavior of the atomic Ca/Si ratio on both sides of the ITZ and heat treatment are considerably related.

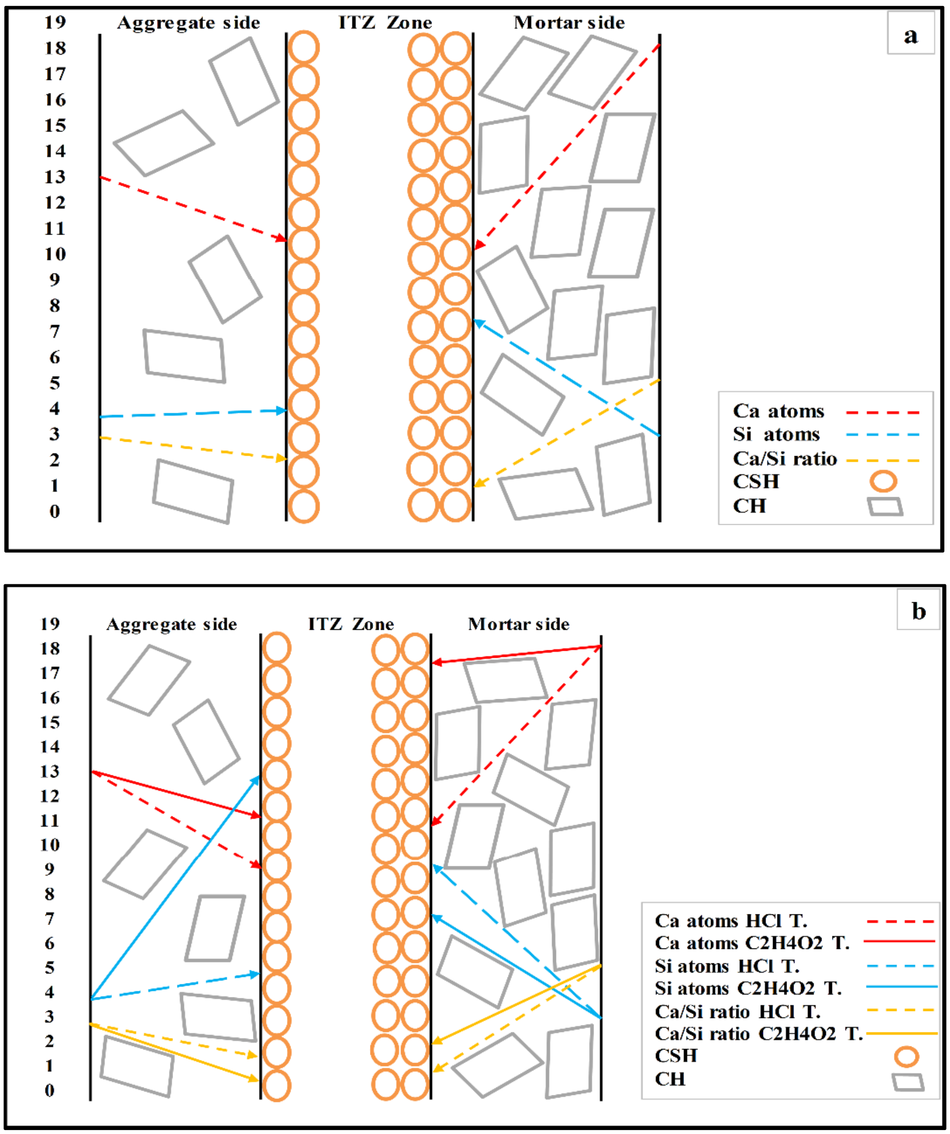


Figure 8.8: Schematic diagram of ITZ zone: (a) heat treatment at 250°C, (b) acid treatments.

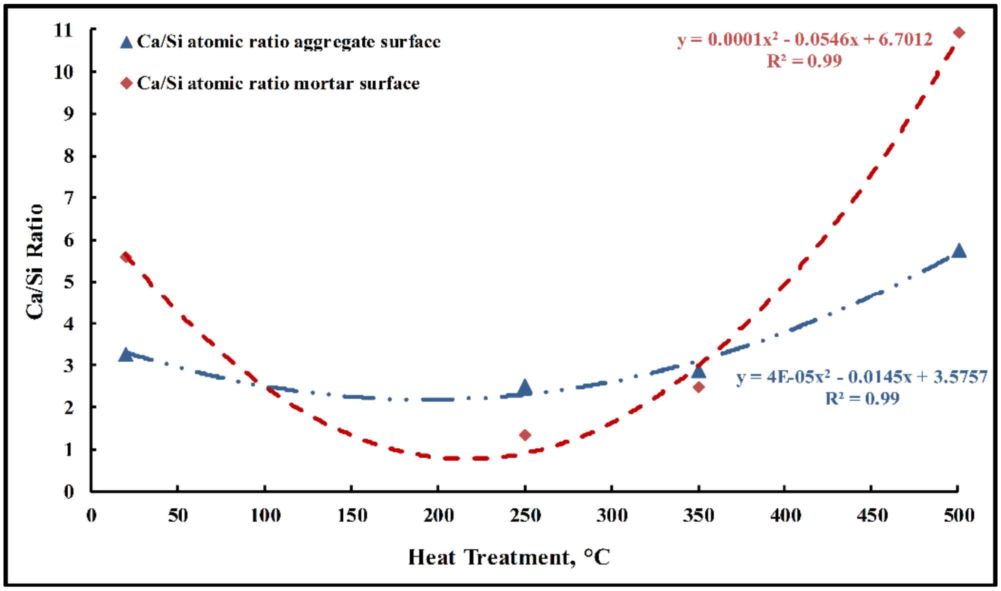


Figure 8.9: Behaviour of Ca/Si atomic ratio for aggregate and mortar surface through heat treatment.

8.4 Intermix Phases Behavior on Both Sides of ITZ

Figure 8.10 represents the modification of intermix phases on both sides of the ITZ; aggregate and mortar side through different treatment types. Generally, it is thoroughly noticeable that the obtained results of the Ca/Si and the (Al + Fe)/Ca ratios reflect broad transformations of intermix phases on both sides of the ITZ. However, substantial improvement of transformation to CSH phase was registered for various treatment types. For untreated CRCA, the ratios of Ca/Si and (AL+Fe)/Ca indicate that the intermixed material on the surface of mortar and the aggregate side of the ITZ consists of different phases. As clearly shown, the position of the intermix phase is located in a transition area, which means, there is no certain predominant material among various phases for both surfaces of aggregate and mortar. Nevertheless, a significant difference was observed regarding the Ca/Si ratio which refers to the existence of a large variation between constituent materials of the two surfaces. For heat treatment type, it is revealed that the best performance of transformation to CSH phase is recorded at 250 °C recording Ca/Si ratio valued 2.5 for aggregate side of ITZ, whereas the mortar side enhancement through CSH transformation at 350 °C exhibits as an optimum behavior with 2.46 of Ca/Si ratio. It is interesting to note that the Ca/Si ratio at 250 °C was significantly lowered to 1.34 compared with the value at 350 °C. This can be explained by the possibility of secondary ettringite formation due to a high percentage of (Al+Fe/Ca) (ratio 0.46). Erdem et al. supposed that the release of sulfate or a high amount of Al, Fe and S may promote ettringite recrystallization. Therefore, there is deviation from the CSH to AFM phase though lowering Ca/Si ratio. The obtained results of heat treatment at 500 °C clearly present a negative impact of high temperature on transformation to the CH phase due to a considerable increase in Ca atoms compared with untreated CRCA for both sides of the ITZ; aggregate and mortar. It could be expected that material decomposition occurred at higher temperatures. Thermal Gravimetric Analysis (TGA) provided more details about the mass loss and chemical breakdown of compounds such as H_2O and CO_2 due to exposure to different temperatures. TGA studies indicated that the mass loss between 105 °C-200 °C is related to vaporized water in pores and poorly hydrated CSH, whereas loss is correlated with water dissociation from well hydrated CSH between 200 °C-420 °C. $Ca(OH)_2$ decomposes between temperatures 420 °C-550 °C, whereas poor and well crystalline $CaCO_3$ molecules dissociate to release CO_2 between 550 °C-720 °C and 720 °C-950 °C, respectively. However, these temperature ranges are slightly different due to many factors such as aggregate type and chemical composition.

The outcomes of acid treatment indicated that there is a significant difference in CSH transformation between the aggregate and mortar sides of the ITZ for HCl acid treatment though approximate closer values Ca/Si ratios 1.84 and 1.17 respectively were recorded. The obtained results of acetic acid treatment revealed that there is a considerable difference between the aggregate and mortar side (0.88) and (2.32) resulting in significant phase transformation.

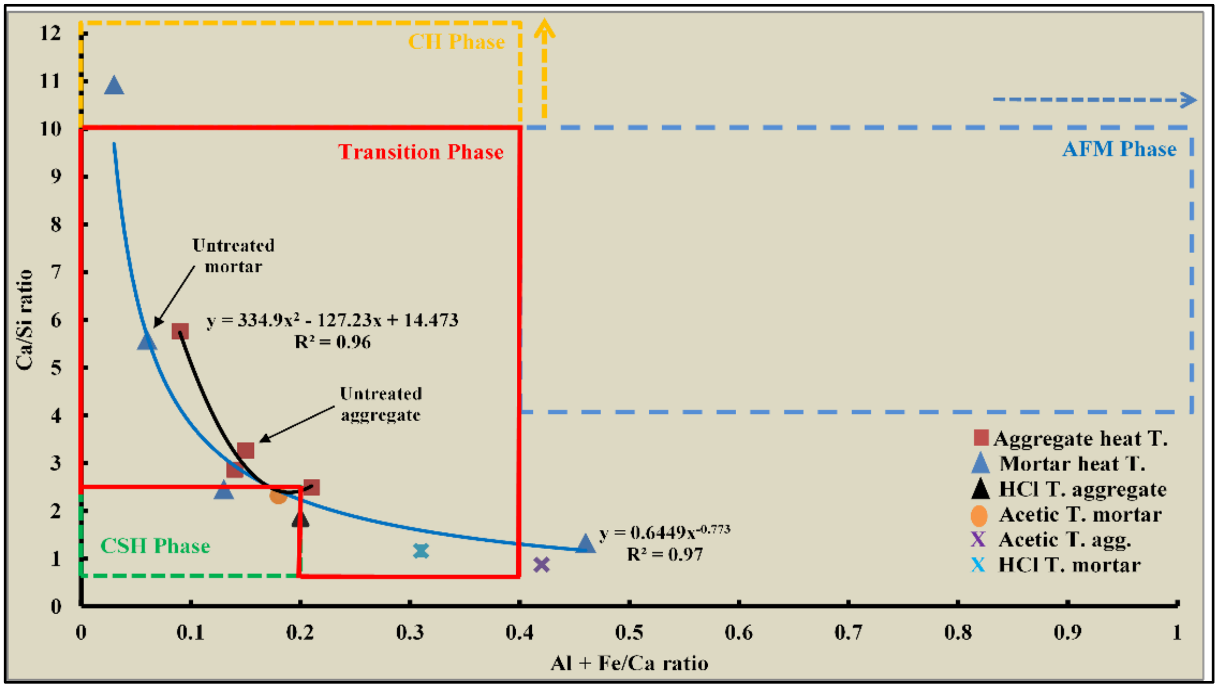


Figure 8.10: Intermix phases to mortar and aggregate of CRCA through heat treatment.

8.5 Summary of This Chapter

This chapter explored the effect of different treatment types on the ITZ zone. Depending on the obtained findings, the key points of this chapter are summarized as follows:

- The obtained results revealed that the use of heat treatment is highly successful in improving the properties of ITZ microcracks, including the width and length of microcracks.
- Heat treatment at 250 °C exhibited the best performance by highly decreasing the Ca/Si ratio resulting in a significant improvement for the aggregate side, whereas the optimum behavior for mortar side improvement is recorded at 350 °C. However, there is a negative impact for heat treatment at higher temperatures between (350-500 °C) on the atomic Ca/Si ratio for both the aggregate and mortar side of the ITZ region.
- A successful treatment is recorded for both acid types in lowering the width and length of ITZ microcracks. However, the weak acid treatment seems to be more effective in improving the

mortar side of ITZ, whereas the strong acid is more successful in enhancing the aggregate side of ITZ region.

- It is observed that the best performance of transformation to the CSH phase was at 250 °C for the aggregate side of the ITZ, whereas the mortar side improvement through CSH transformation is recorded at 350 °C as an optimal behaviour.
- It is concluded that the application of acetic acid treatment is more successful for CSH transformation for the mortar side of the ITZ, whereas HCl acid treatment appears to be highly successful in CSH transformation on the aggregate side of the ITZ.

CHAPTER 9

EVALUATION OF ITZ IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE

In this chapter, the obtained findings of CRCA#2 has been submitted to Journal of Materials in Civil Engineering.

In this chapter, the influence of different treatments on the ITZ improvement of CRCA in terms of CSH compounds: tobermorite/jennite is evaluated. The approach is targeted to assess ITZ improvement. The targeted approach basically consists of the use of two different assessment types. The first part of the targeted approach, which includes a general evaluation, is used for ITZ improvement using the surface morphology of the ITZ zone as an indicator for assessing the mentioned improvement. Additionally, the Ca/Si ratio is also evaluated as a further index for measuring the general evaluation of ITZ improvement. To obtain a more reliable evaluation, a particular assessment for ITZ improvement is performed by evaluating the main CSH compounds: tobermorite and jennite. Compared to untreated CRCA, the impact of different treatments on the behaviour of these compounds is assessed.

9.1 SEM Observations of ITZ Microstructure

To investigate the surface morphology and texture, different series of SEM micrograph of the ITZ between the adhered mortar and aggregate surface for untreated and treated CRCA were analyzed using the images indicated in Figures 9.1 to 9.6.

9.1.1 Microstructure of ITZ for Untreated CRCA

Figure 9-1 presents the SEM micrograph of the ITZ between the aggregate surface and the adhered mortar for untreated CRCA. From the captured image, the surface morphology of aggregate was clearly uniform, and its structure was very different from that of the adhered mortar paste. In contrast, it is observed that the morphology of adhered mortar paste was rough; it was irregular with a high porous structure, resulting in surface heterogeneity. The high magnification image clearly indicated the presence of many various voids and particles without specific shape and size. This explains the higher water absorption and lower density for untreated CRCA. These results confirm laboratory test findings, which found that the untreated CRCA has a high water absorption and relatively low density. It is noteworthy that a specific borderline between the aggregate surface and adhered mortar paste was clearly visible, creating the ITZ region.

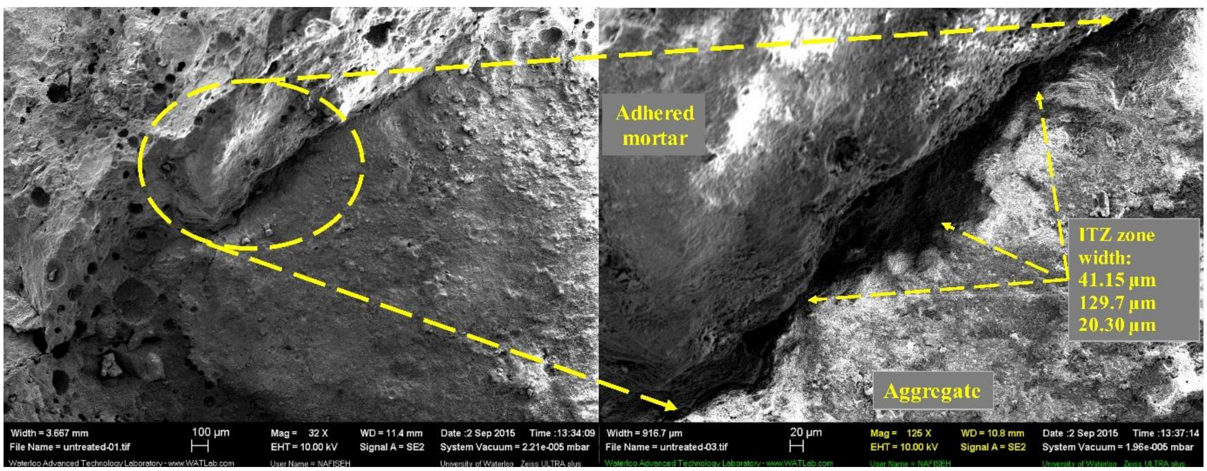


Figure 9.1: ITZ region of untreated CRCA.

9.1.2 Microstructure of ITZ for Treated CRCA with Heat Treatment

The SEM micrographs of the ITZ between the aggregate surface and the adhered mortar for treated CRCA with heat treatment at temperatures 250 °C, 350 °C and 500 °C are shown in Figures 9.2 to 9.4, respectively. The overall analysis of the surface morphologies for treated CRCA with heat treatment demonstrated that a modification of ITZ is successfully performed at various temperatures. However, the presence of the significant microstructure characteristics due to the temperature variations of the heat treatment can be observed in the following points:

- Due to accumulated particles densely packed together, a dense ITZ is clearly visible for treated CRCA at temperatures of 250°C, 350°C, resulting in a high heterogeneity and rough ITZ region. This could be mainly attributed to a large accumulation of CSH particles, which result from various reactions as in the equations (6.1-6.3). Because of completion of the service life and concrete components hydration for CRCA, the reaction of conversion of CH crystals that are accumulated on the CRCA surface to CSH particles seems to be the main source for producing CSH particles. This is fundamentally achieved under pozzolanic action which transforms the amounts of CH crystals into CSH particles by the pozzolanic reaction (equation 6.3). This approach has been widely approved by numerous investigations till and has become commonly agree upon; therefore, the addition of pozzalanic materials including fly ash and silica fume is seen as a highly successful method for enhancing microstructure, especially the ITZ region of RCA. The accumulated CSH particles can easily fill pores and microcracks within the ITZ region due to their small size compared with CH crystals, which lead to improvement and ITZ densification.
- It is worth noting that there is a considerable decrease in the degree of roughness of the ITZ region surface depending on the treatment temperature. Roughness disappeared broadly from the ITZ region and the surface totally differs from other moderate treatment temperatures due to the exposure to the high temperature of heat treatment at 500 °C as can be seen in Figure 9.4. This means that CSH particles are highly influenced by heat treatment type at high temperatures. Additionally, it is interesting to note that there was a crack with 30-40 µm length and 3-6 µm width found in the mortar surface perpendicular to the ITZ region, indicating a negative influence of the heat treatment at high temperatures on the mortar properties. This observation is similar to the findings of a previous study (Li et al., 2009).
- Though heat treatment at different temperatures was registered as a successful approach for improving the ITZ region, various pores, tiny cracks and ITZ microcrack for treatment at 250 °C and diverse pores on the mortar surface for treatment at 350 °C is still noticeable on CRCA surface.

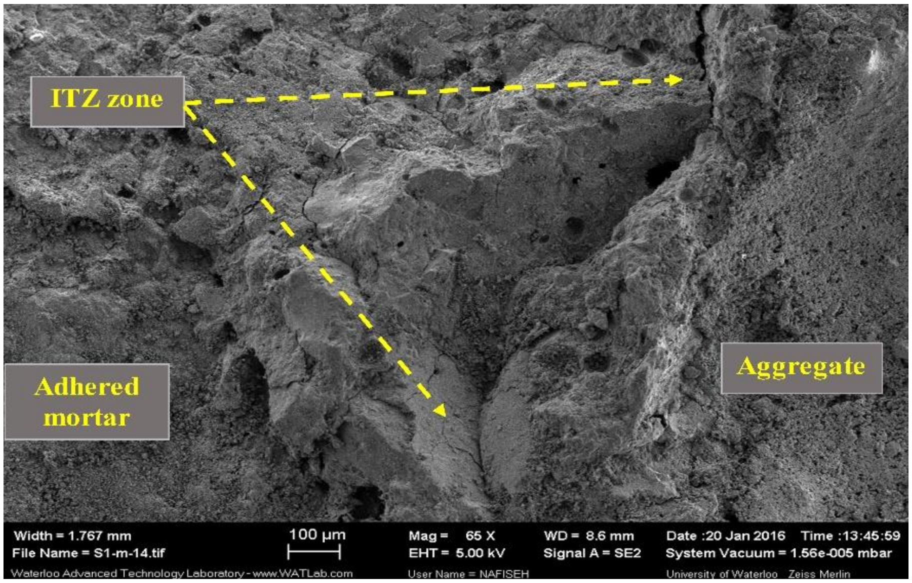


Figure 9.2: ITZ region of CRCA with heat treatment at 250 °C.

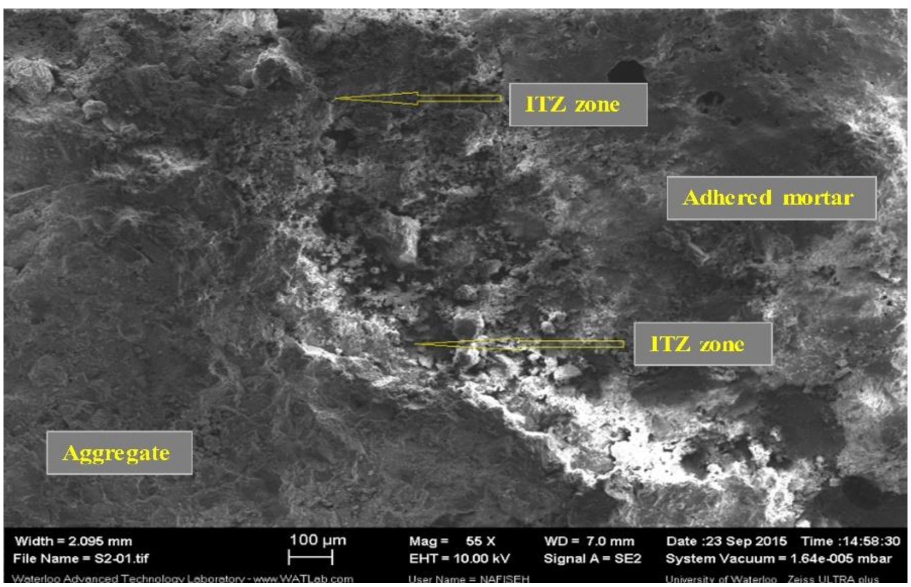


Figure 9.3: ITZ region of CRCA with heat treatment at 350 °C.

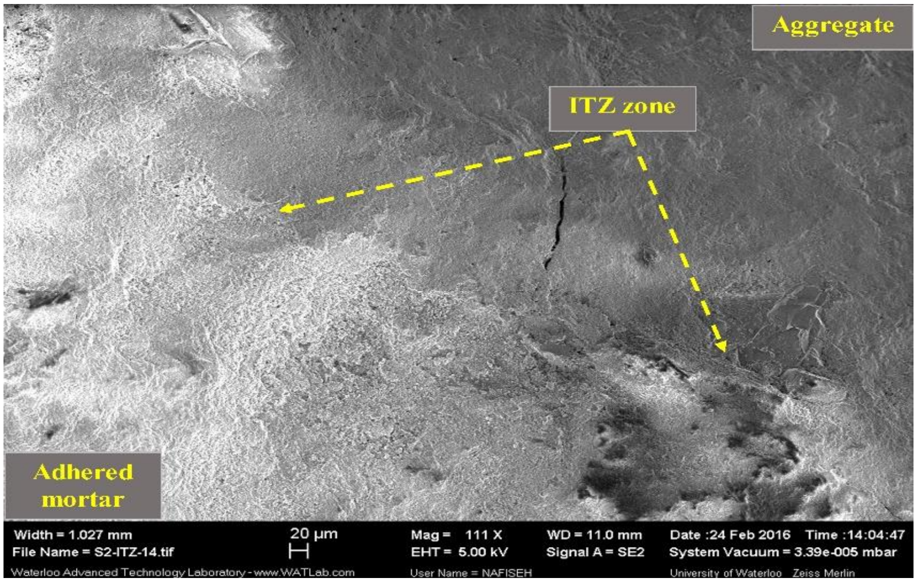


Figure 9.4: ITZ region of CRCA with heat treatment at 500 °C.

9.1.3 Microstructure of ITZ for Treated CRCA with Acid Treatment

The SEM micrographs of the ITZ between the aggregate surface and the adhered mortar for treated CRCA with acid treatment are presented in Figures 9.5 and 9.6. According to magnified perspectives, the obtained SEM images revealed that acid treatment for both strong and weak acid is highly successful for enhancing the ITZ region. It is interesting to note that the ITZ borderline between the aggregate surface and adhered mortar paste was highly homogenous, uniform, and clearly visible without accumulated CSH particles for treated CRCA with acetic (weak) acid whereas, the ITZ borderline of treated CRCA with HCl (strong) acid was less homogenous and relatively non-uniform. Directly next to the ITZ borderline, small amounts of irregular CSH particles randomly cover the adhered mortar surface for treated CRCA with acetic acid, whereas a non-uniform, highly cracked and porous mortar surface represent the main characteristics of the surface morphology of treated CRCA with HCl acid. Therefore, a significant difference in the degree of roughness of the CRCA surface was observed depending on treatment acid type as acidic solutions attack the surface and dissolve adhered mortar, and in this way, this method can be an effective method of adhered mortar removal. It is important to note that there was no impact of the acidic attack regarding aggregate surface for both strong and weak acid treatment, indicating to the type of aggregate that appears to be unaffected by acidic treatment. It was observed in a previous study that there is significant damage on the CRCA surface with HCl treatment compared to the surface treated with acetic acid. This could be explained by two factors; firstly, there is a significant variance in the ability between strong and weak acid to attack the surface adhered mortar and secondly, the surface material type. De Juan & Gutiérrez (2009) mentioned that HCl treatment cannot be used to treat RCA with limestone aggregates due to the adverse acid attacks on this type of aggregates.

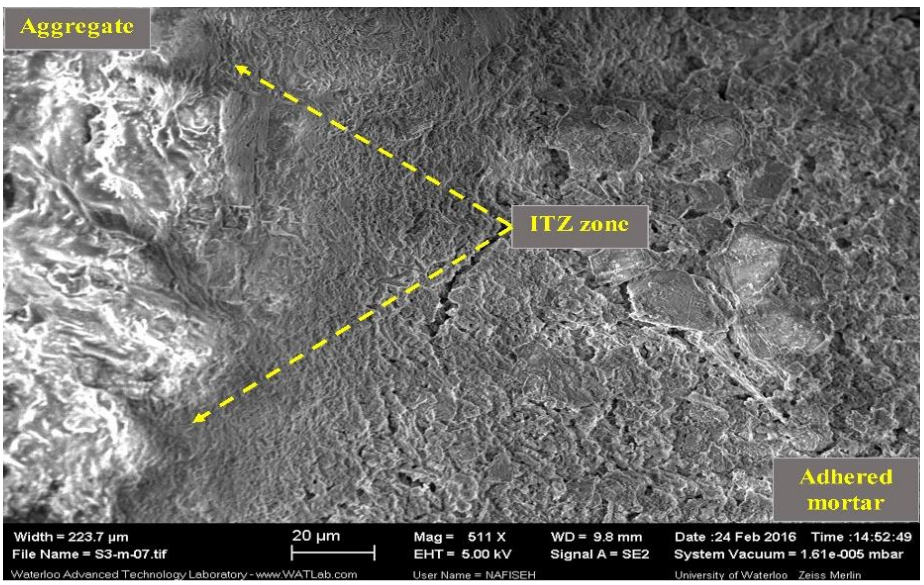


Figure 9.5: ITZ region of CRCA with HCl acid treatment.

9.2 Chemical Composition Analysis for ITZ Region

The results of EDAX analysis with regards to the ITZ region for untreated CRCA and treated with various methods are shown in the Figures 9.9 to 9.14. The findings represent spectrum analysis for chemical and mineral composition of CRCA through EDAX quantification.

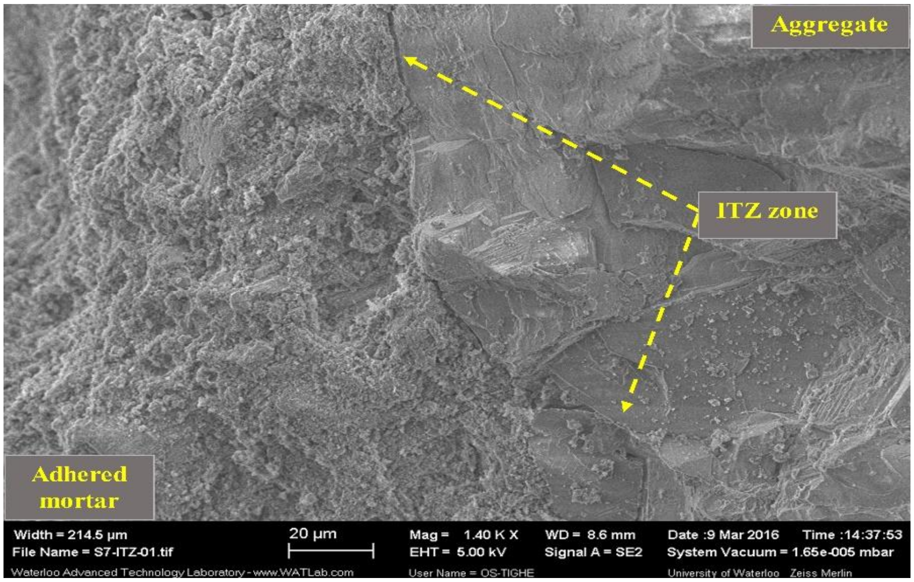


Figure 9.6: ITZ region of CRCA with acetic acid treatment.

9.2.1 Calcium to Silicon (Ca/Si) Atomic Ratio

The EDAX analysis demonstrated that there was a highly significant reduction in the Ca/Si ratio with the rising temperatures during heat treatment, as shown in Figure 9.7. A noticeable decrease was observed in the temperature range between 20 °C and 250 °C. The rising temperature works to remove water molecules from hydrous compounds within a dehydration process that leads to the formation of new hydrated compounds and increased CSH formation. The continuously rising temperatures have a significant influence on the compound type that results from the dehydration process. The findings of TGA analysis for RCA investigations provided further details about the relationship between rising temperatures at different ranges and loss of weight due to water removal. The vaporized water at a temperature range lower than 105 °C is related to the mass loss and can perhaps lead to poorly formed CSH. The water loss at temperatures between 105 °C and 200 °C results from the dissociation of water, which is linked with compounds such as lower temperature CSH and ettringite, whereas the dissociation of correlated water molecules to well-formed hydrated compounds such as CSH and CAH is the reason for the loss when temperatures between 200 °C and 420 °C (Zega & Di Maio, 2009; El-Hassan et al., 2013;

Zhang et al., 2015). Aggregate and RCA type and chemical composition seem to be acceptable factors that influence the behaviour of Ca/Si reduction through the heat treatment method. The lowering of the Ca/Si ratio is mainly attributed to a high increase of CSH production and considerable consumption of CH at the same time. The reason for the significant decrease of CH is the new hydrous compounds due to increasing temperatures, especially CSH, which could promote activity to form siliceous and, siliceous and aluminous materials which behave as pozzolans. These pozzolans (Kong et al., 2010; Jawahar et al., 2013) can consume accumulated CH in the pores to produce CSH and decrease the Ca/Si ratio according to the pozzolanic reaction as previously stated in equation (6-3).

The obtained results from EDAX analysis also revealed that a significant increase in Ca/Si the ratio is noticeably observed in the temperature range between 250 °C and 500 °C, indicating a significant impact of heat treatment approach at high temperatures on the Ca/Si ratio. Due to exposure to high temperatures, material decomposition and mass loss that include a chemical breakdown of compounds such as H_2O and CO_2 are generally obtained. TGA studies for RCA indicated that the mass loss is correlated with water dissociation from well-hydrated CSH between 200 °C and 420 °C. $Ca(OH)_2$ decomposes between temperatures 420 °C-550 °C, whereas poor and well crystalline $CaCO_3$ molecules dissociate to release CO_2 between 550 °C-720 °C and 720 °C-950 °C, respectively (El-Hassan et al., 2013; Zhang et al., 2015). However, these ranges of temperatures are slightly different due to many factors such as aggregate type and chemical composition.

The values of Ca/Si ratios of CRCA through acid treatment are provided in Table 9-1. It is interesting to note that the Ca/Si ratio was significantly lowered for both HCl and acetic acid treatment compared to the heat treatment method. This indicates that a highly successful approach is registered for both acid treatment methods in comparison with the heat treatment technique.

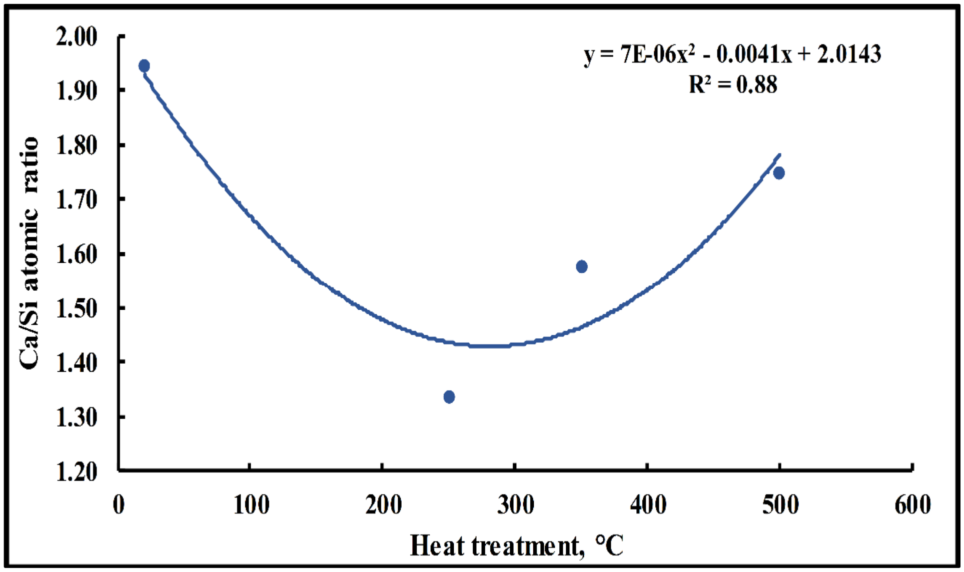


Figure 9.7: Behavior of Ca/Si atomic ratio through heat treatment.

Table 9-1: Ca/Si Atomic Ratio for the ITZ Region through Acid Treatment

CRCA Treatment/ Property	Ca/Si ratio
CRCA untreated	1.95
Treated CRCA with soaking in HCl	0.98
Treated CRCA with soaking in $C_2H_4O_2$	0.71

9.2.2 Aluminum to calcium (Al/Ca) atomic ratio

The behaviour of the Al/Ca atomic ratio from the outcomes of EDAX analysis through heat treatment is plotted in Figure 9.8. It is clearly shown that a significant increase was observed in the Al/Ca atomic ratio through heat treatment. As there is no external source for increasing Al through the heat treatment, the possible explanation for this increase could involve two factors: firstly, there is a possibility of replacement between Al, which can be coming from raw materials or pozzolanic products, and Si in the CSH types. In the second model of CSH, proposed by Richardson and Groves (1992–1993) (Richardson & Groves, 1992; Richardson & Groves, 1993), the tobermorite-jennite model, tobermorite-like structural elements would be intermixed with jennite-like constituents. This model assumes that $Al3^+$ ions replace $Si4^+$ ions at bridging sites only (Richardson, 2004; Richardson, 2008; del Bosque et al., 2014).

The replacement approach is strongly supported by the obtained EDAX data of the weight percentage of Al that remains approximately constant or increased slightly. Secondly, another important issue is that the high amounts of Al may be related to the behavior of the pozzolanic material. It has been previously reported that a different CSH type is formed, such as calcium aluminates hydrate (C_4AH_{13}) with the high amount of Al and lower Ca/Si ratio if there is a pozzolanic material addition including fly ash from coal combustion, ground granulated furnace slags or metakaolin (Goñi et al., 2012). Then, C_4AH_{13} converts to hydrogarnet (C_3AH_6) as is widely agreed. The formation of hydrogarnet for ratios of Al/(Si+Al) in the range of 0.12-0.50 when kaolinite, which is similar to metakaolin, is used as the source of aluminum (Ríos et al., 2009). This approach was targeted to evaluate the obtained data as can be seen in Table 9-2. In Table 9-2, the tabulated data clearly suggest that the occurrence of hydrogarnet is highly probable.

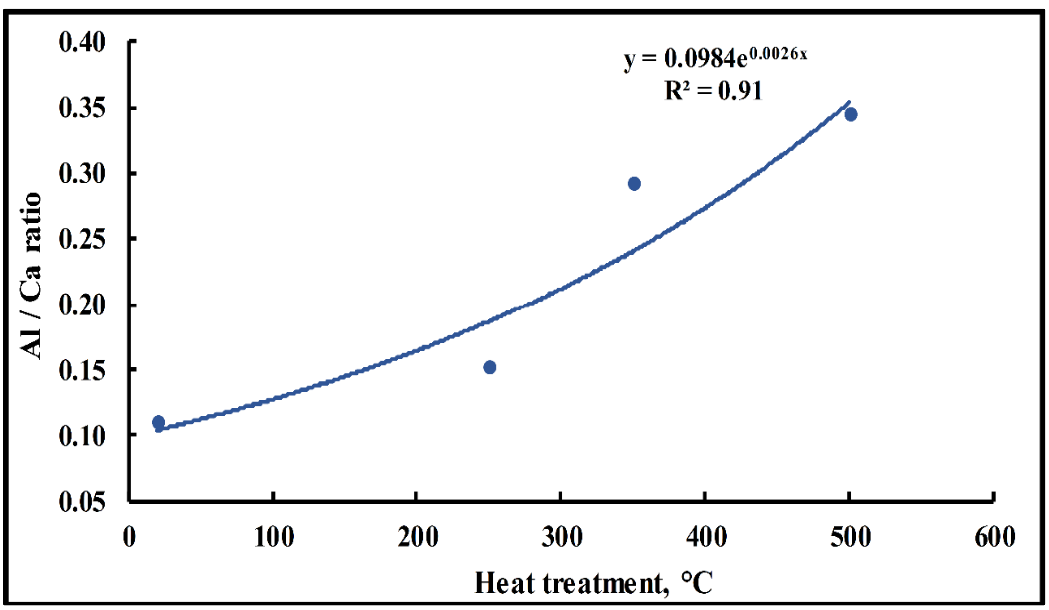


Figure 9.8: Behavior of Al/Ca atomic ratio through heat treatment.

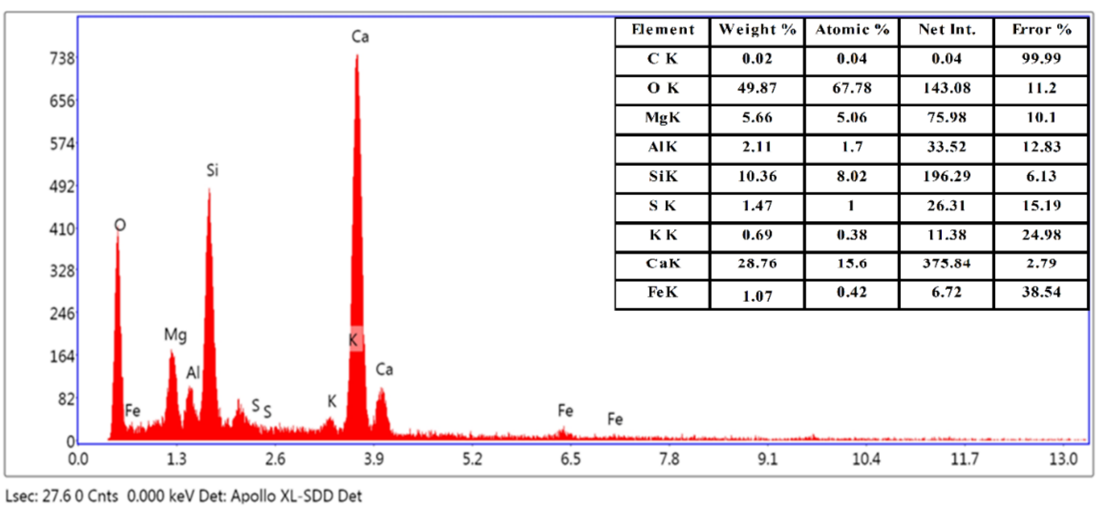
Table 9-2: Al/(Al+Si) Ratio for the ITZ Region through Heat Treatment

CRCA Heat treatment	Al/(Al+Si) ratio
CRCA untreated	0.17
Treated CRCA at 250 ˚C	0.17
Treated CRCA at 350 ˚C	0.31
Treated CRCA at 500 ˚C	0.38

It is interesting to note that a considerable difference in the Al/Ca ratio between the strong acid and the weak acid is observed as can be seen in Table 9-3. From the point of view of chemistry, it seems to be reasonable that the reaction between the Cl^{-} ions and the Al^{+} ions in the aqueous solution is more effective than the reaction between CH3COO¯ (acetate) ions and the Al^{+} ions due to the significant variance in the ability between strong and weak acid to attack the adhered mortar surface. This can lead to a large difference in the percentage of the CAH compounds especially ettringite within the intermix phase.

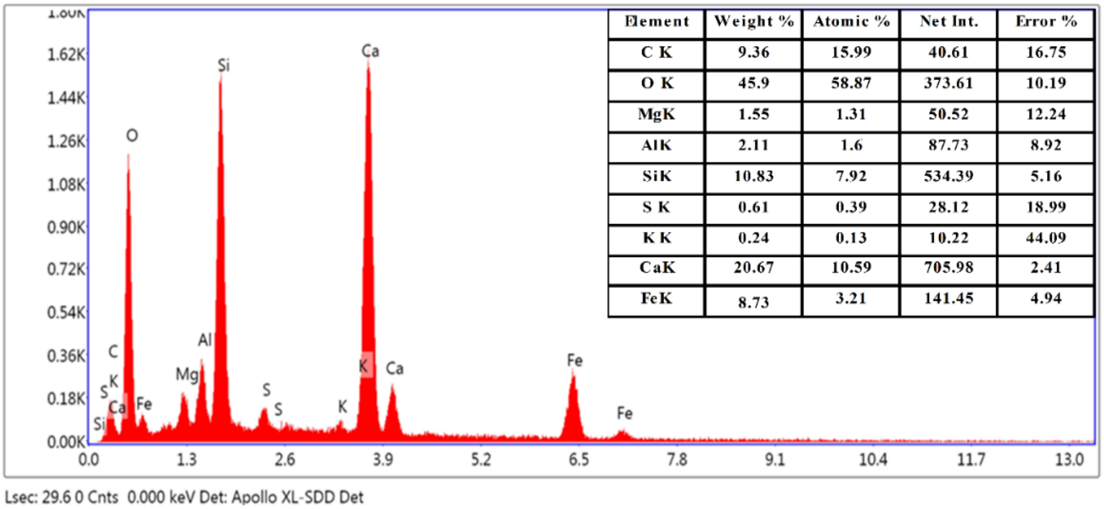
Table 9-3: Al/Ca Atomic Ratio for the ITZ Region through Acid Treatment

CRCA Treatment/ Property	Al/Ca ratio
CRCA untreated	0.11
Treated CRCA with soaking in HCl	1.04
Treated CRCA with soaking in $C_2H_4O_2$	0.21



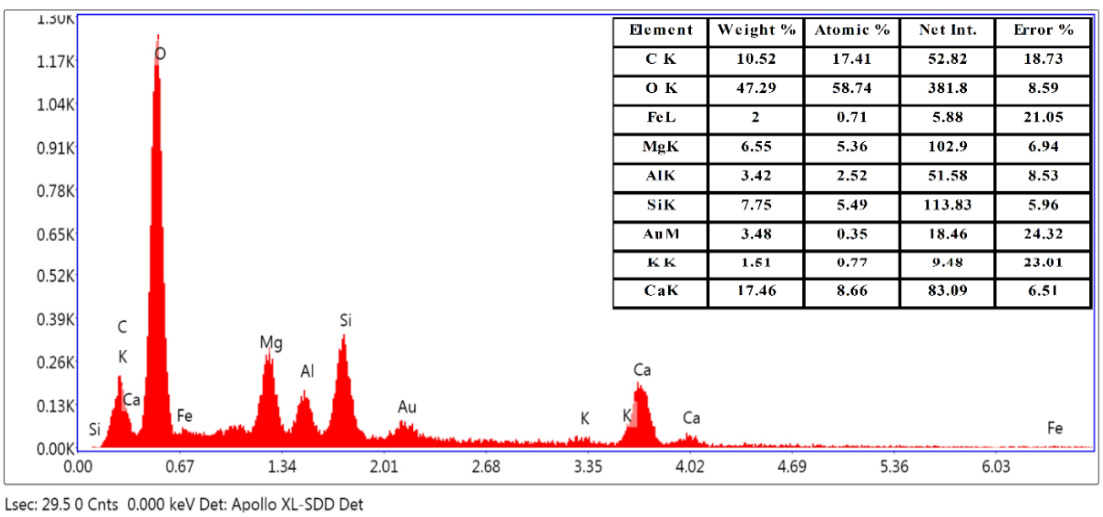
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.02	0.04	0.04	99.99
O K	49.87	67.78	143.08	11.2
MgK	5.66	5.06	75.98	10.1
AlK	2.11	1.7	33.52	12.83
SiK	10.36	8.02	196.29	6.13
S K	1.47	1	26.31	15.19
K K	0.69	0.38	11.38	24.98
CaK	28.76	15.6	375.84	2.79
FeK	1.07	0.42	6.72	38.54

Figure 9.9: EDAX analysis for untreated CRCA.



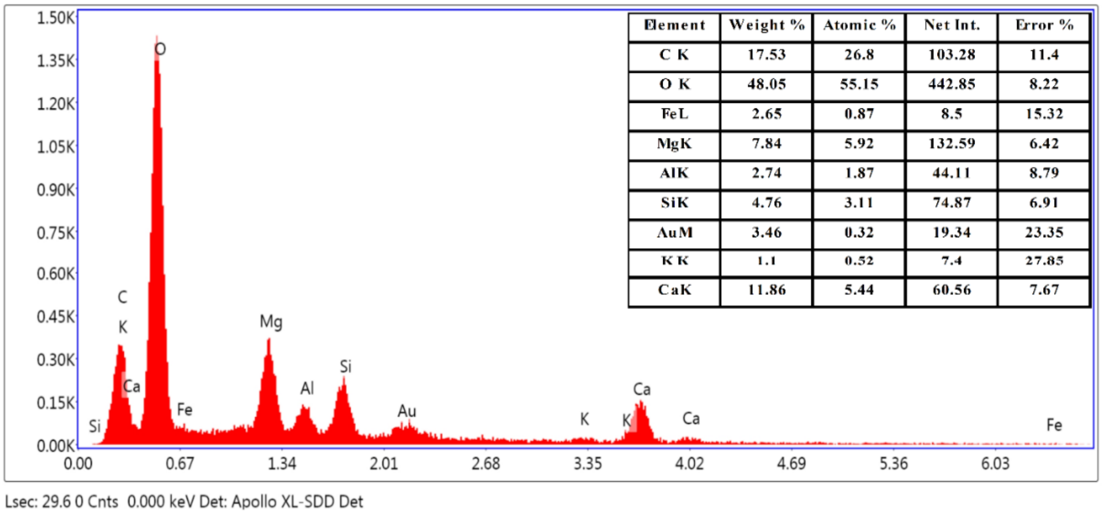
Element	Weight %	Atomic %	Net Int.	Error %
C K	9.36	15.99	40.61	16.75
O K	45.9	58.87	373.61	10.19
MgK	1.55	1.31	50.52	12.24
AlK	2.11	1.6	87.73	8.92
SiK	10.83	7.92	534.39	5.16
S K	0.61	0.39	28.12	18.99
K K	0.24	0.13	10.22	44.09
CaK	20.67	10.59	705.98	2.41
FeK	8.73	3.21	141.45	4.94

Figure 9.10: EDAX analysis for CRCA with heat treatment at 250 °C.



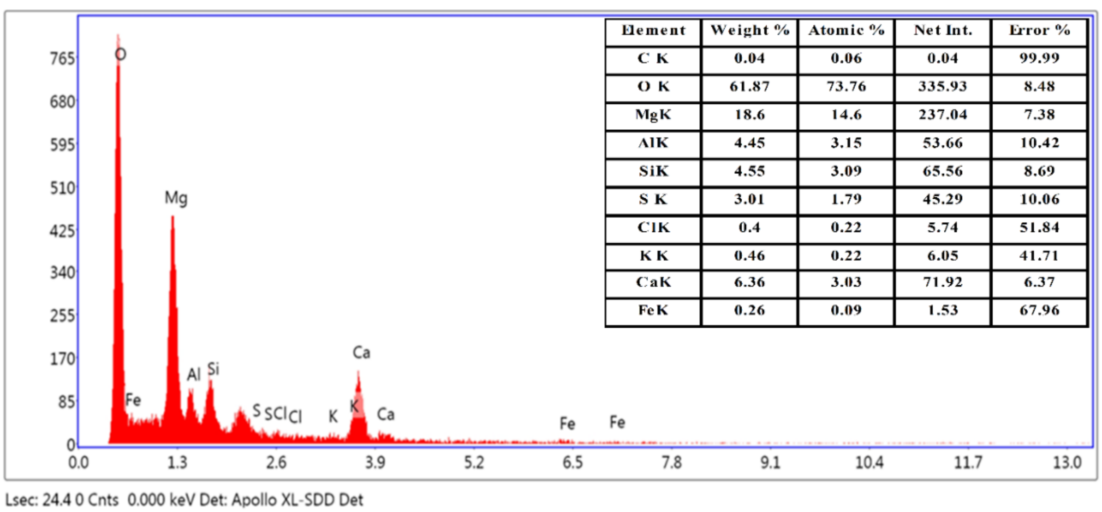
Element	Weight %	Atomic %	Net Int.	Error %
C K	10.52	17.41	52.82	18.73
O K	47.29	58.74	381.8	8.59
FeL	2	0.71	5.88	21.05
MgK	6.55	5.36	102.9	6.94
AlK	3.42	2.52	51.58	8.53
SiK	7.75	5.49	113.83	5.96
AuM	3.48	0.35	18.46	24.32
K K	1.51	0.77	9.48	23.01
CaK	17.46	8.66	83.09	6.51

Figure 9.11: EDAX analysis for CRCA with heat treatment at 350 °C.



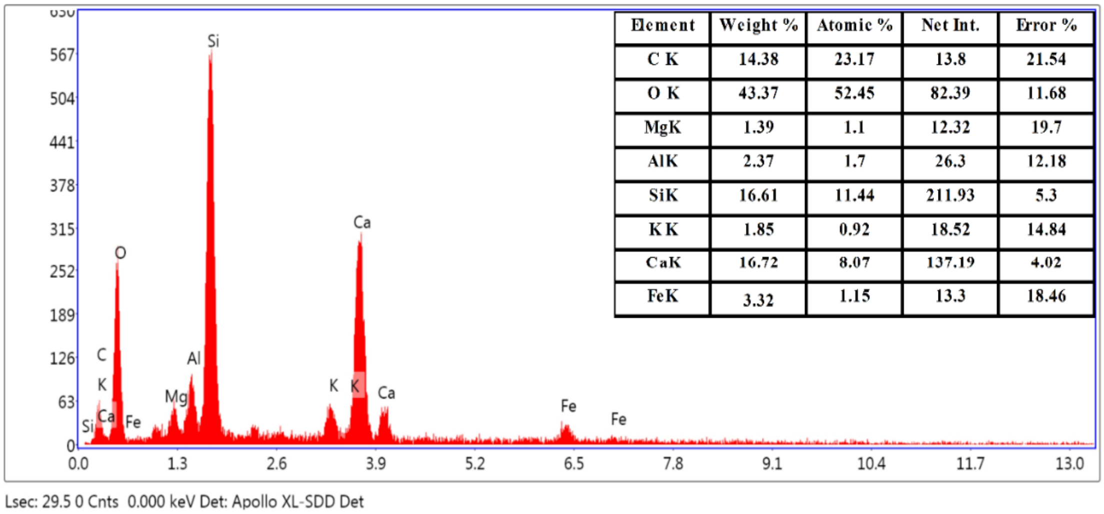
Element	Weight %	Atomic %	Net Int.	Error %
C K	17.53	26.8	103.28	11.4
O K	48.05	55.15	442.85	8.22
FeL	2.65	0.87	8.5	15.32
MgK	7.84	5.92	132.59	6.42
AlK	2.74	1.87	44.11	8.79
SiK	4.76	3.11	74.87	6.91
AuM	3.46	0.32	19.34	23.35
K K	1.1	0.52	7.4	27.85
CaK	11.86	5.44	60.56	7.67

Figure 9.12: EDAX analysis for CRCA with heat treatment at 500 °C.



Element	Weight %	Atomic %	Net Int.	Error %
C K	0.04	0.06	0.04	99.99
O K	61.87	73.76	335.93	8.48
MgK	18.6	14.6	237.04	7.38
AlK	4.45	3.15	53.66	10.42
SiK	4.55	3.09	65.56	8.69
S K	3.01	1.79	45.29	10.06
ClK	0.4	0.22	5.74	51.84
K K	0.46	0.22	6.05	41.71
CaK	6.36	3.03	71.92	6.37
FeK	0.26	0.09	1.53	67.96

Figure 9.13: EDAX analysis for CRCA with HCl acid treatment.



Element	Weight %	Atomic %	Net Int.	Error %
C K	14.38	23.17	13.8	21.54
O K	43.37	52.45	82.39	11.68
MgK	1.39	1.1	12.32	19.7
AlK	2.37	1.7	26.3	12.18
SiK	16.61	11.44	211.93	5.3
K K	1.85	0.92	18.52	14.84
CaK	16.72	8.07	137.19	4.02
FeK	3.32	1.15	13.3	18.46

Figure 9.14: EDAX analysis for CRCA with $C_2H_4O_2$ acid treatment.

9.3 Evaluation of CSH Compounds Using XRD Analysis

The findings of XRD analysis are presented in Figures 9.18 to 9.23.

9.3.1 XRD Analysis for Untreated CRCA

The obtained results indicated that different hydration compounds are found including tobermorite, jennite and ettringite due to the hydration of cement constituents during the life time of the concrete. It is important to note that dolomite percentage was the predominant phase among the different phases, indicating the type of original aggregate. The outcomes of XRD analysis also showed that there are other compounds such as calcium carbonate and silicon oxide.

9.3.2 Behavior of CSH Compounds through Heat Treatment

The behavior of dolomite through heat treatment is presented in Figure 9.15. A high reduction for dolomite percentage was observed through the heat treatment. However, a significant decrease was clearly noticeable between 20 °C-250 °C compared to the range between 250 °C-500 °C. This refers to a thermal dissociation that leads to different compounds including CSH transformation. The obtained outcomes also revealed that the behavior of dolomite exhibit as a power law equation and strongly correlate with heat treatment due to high regression.

The obtained data of the XRD analysis for tobermorite is graphically analyzed in Figure 9.16. In general, the findings revealed that an important increase to the tobermorite percentage was obtained for the heat treatment. However, the maximum percentage of tobermorite was registered at 250 °C, whereas a slight decrease compared to the maximum percentage was noticeable, resulting in a negative influence for the heat treatment at high temperatures on the tobermorite conversion.

Figure 9.17 presents the behavior of jennite through heat treatment. The obtained results demonstrated that a significant decrease to jennite percentage was observed between the temperatures ranging between 20 °C-250 °C. This reduction could be explained by a transformation to another type of CSH, namely tobermorite. From the literature, it is known that CSH jennite type has more water molecules than CSH tobermorite type. With rising temperatures, the possibility of removal of water molecules is highly probable which can lead to a higher tobermorite percentage. This seems to be quite reasonable due to TGA studies that indicate the water molecules removal could be found within the temperature range between 20 °C-250 °C as discussed earlier. On the other hand, this approach can also explain the significant increase to tobermorite percentage within the same temperature range. It is interesting to note that a slight increase was observed to the jennite percentage at high temperatures between 250 °C-500 °C. This increase possibly refers to higher conversion and transformation of dolomite to more CSH compounds including jennite as it was noticeable in the behavior of dolomite within the same range of temperatures.

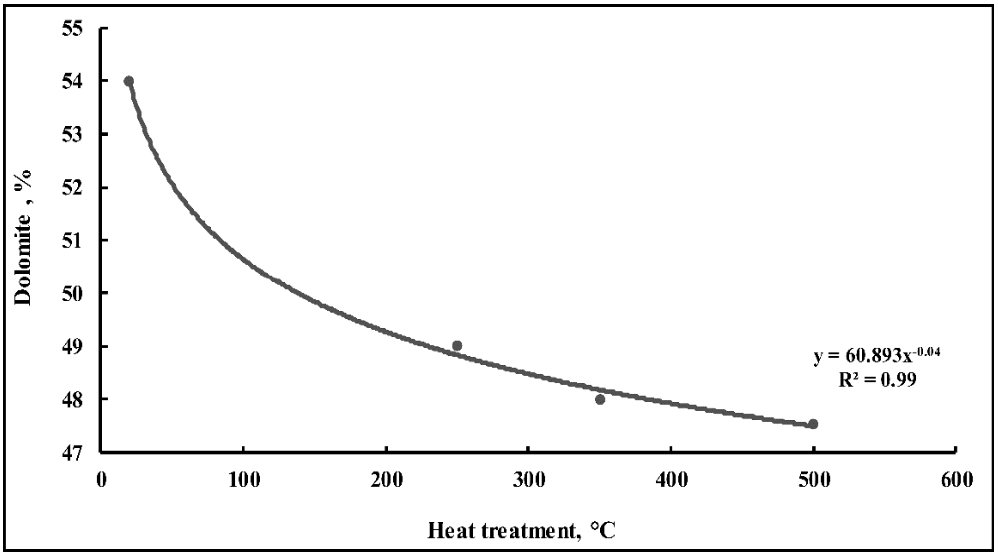


Figure 9.15: Dolomite behavior through heat treatment.

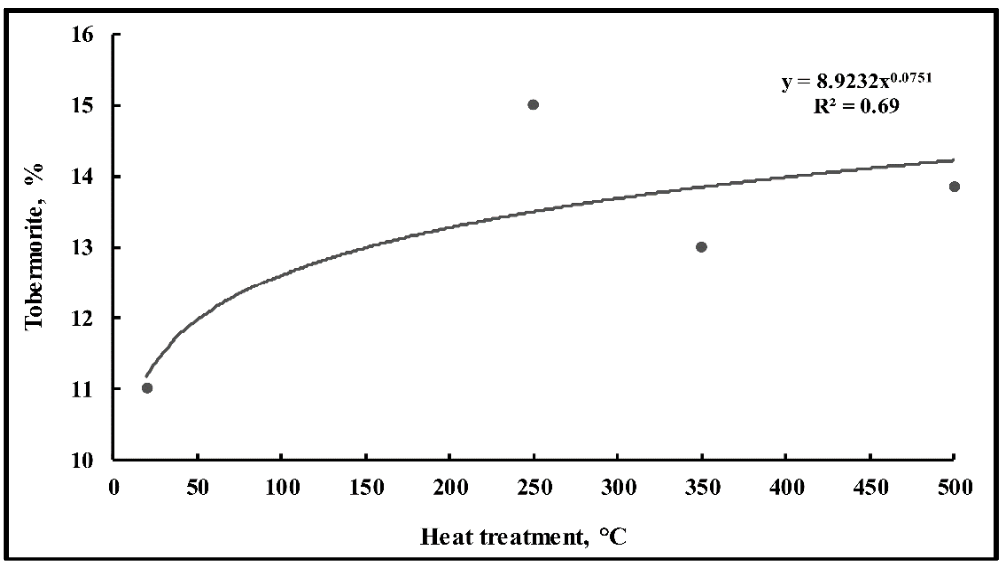


Figure 9.16: Tobermorite behavior through heat treatment.

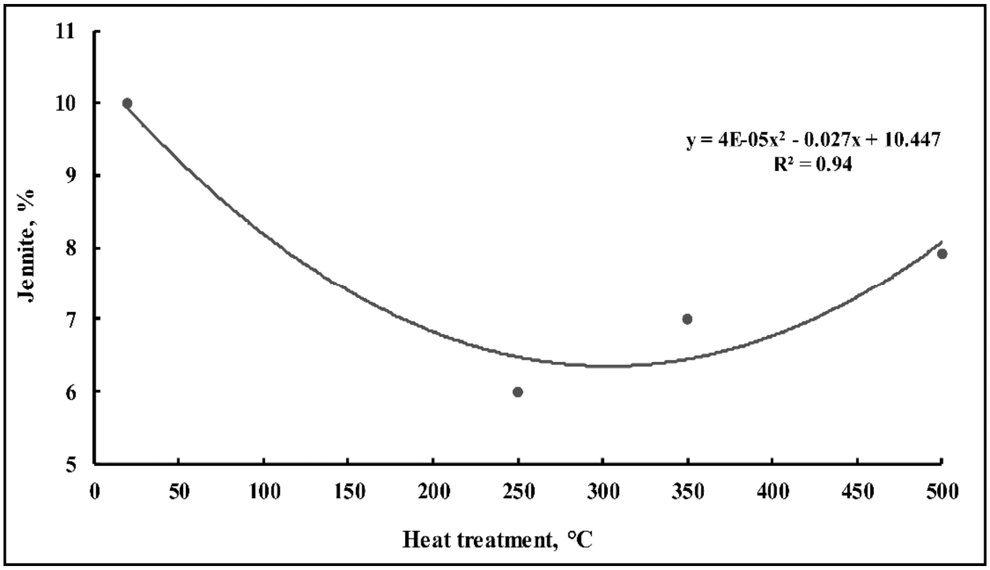


Figure 9.17: Jennite behavior through heat treatment.

9.3.3 Behavior of CSH Compounds through Acid Treatment

The findings of XRD analysis indicated the following observations:

- Though HCl has strong ability to attack materials, there is a slight dissociation of dolomite to CSH compounds.
- It is noticeable that a significant reduction to the percentage of jennite CSH type, indicating a similar behavior with heat treatment between 20 °C-250 °C. This large decrease could possibly refer to the sensitivity of jennite structure to the acidic environment compared to tobermorite. This appears to be reasonable due to the significant percentage of tobermorite that was obtained within the same acidic environment.
- The analysis of XRD of the ITZ region with acetic acid treatment showed that there is a considerable conversion of both tobermorite and jennite CSH types compared with the heat treatment and acidic treatment with the strong acid, HCl.

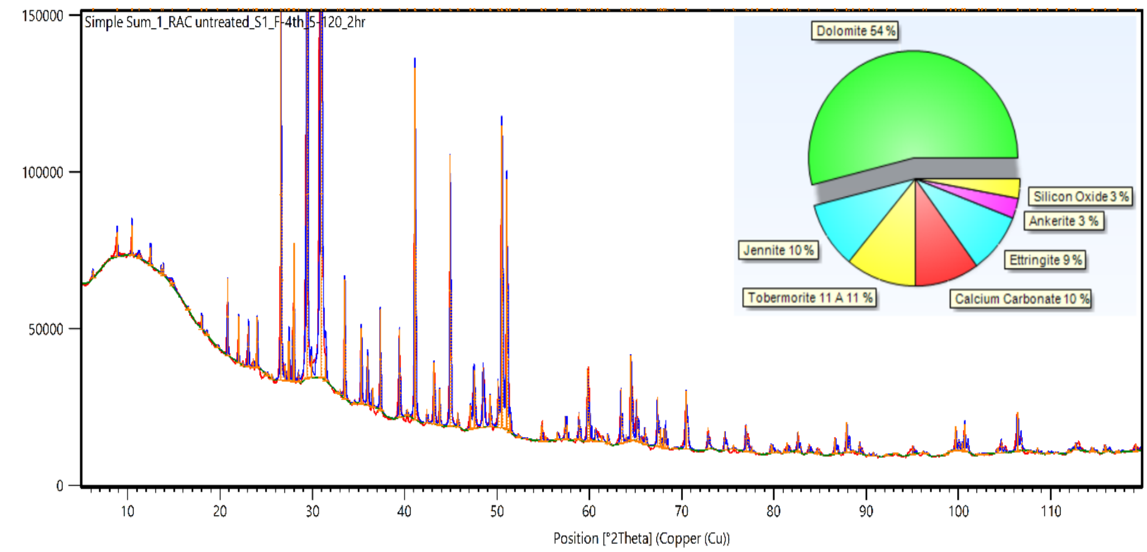


Figure 9.18: XRD analysis of untreated CRCA#2.

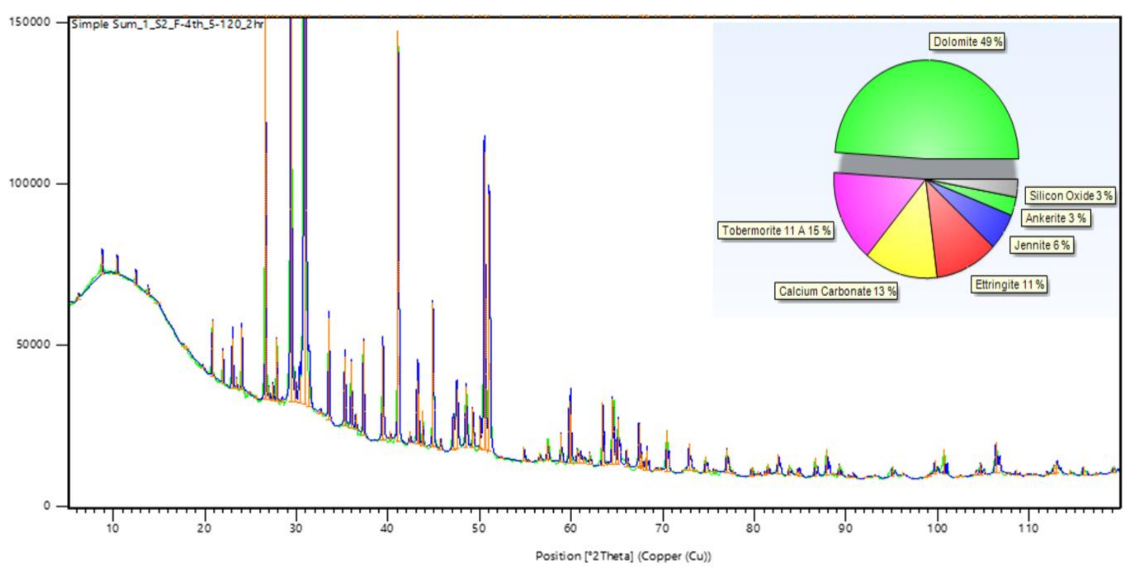


Figure 9.19: XRD analysis of CRCA#2 at 250 °C.

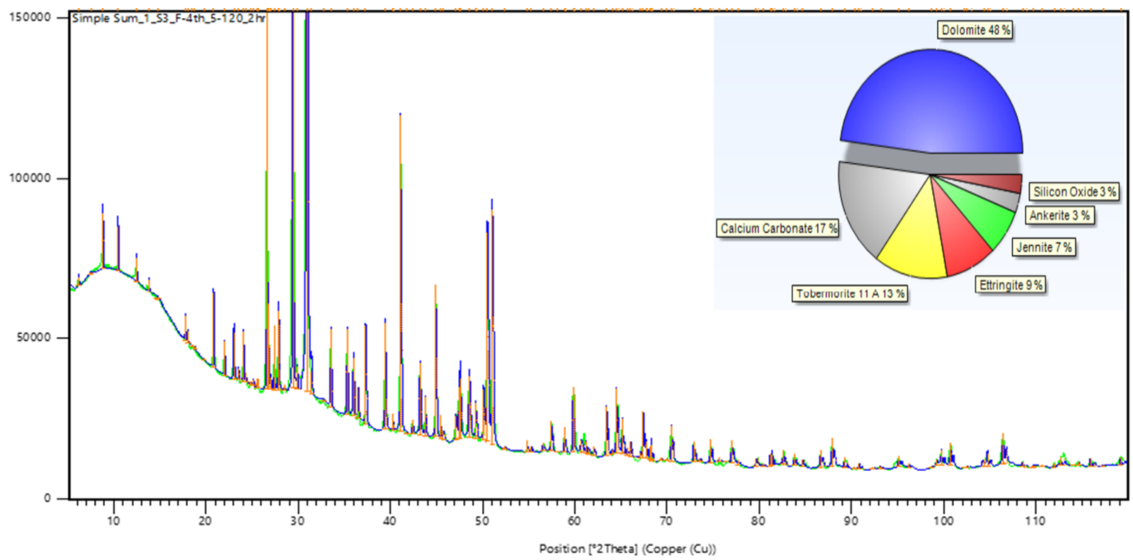


Figure 9.20: XRD analysis of CRCA#2 at 350 °C.

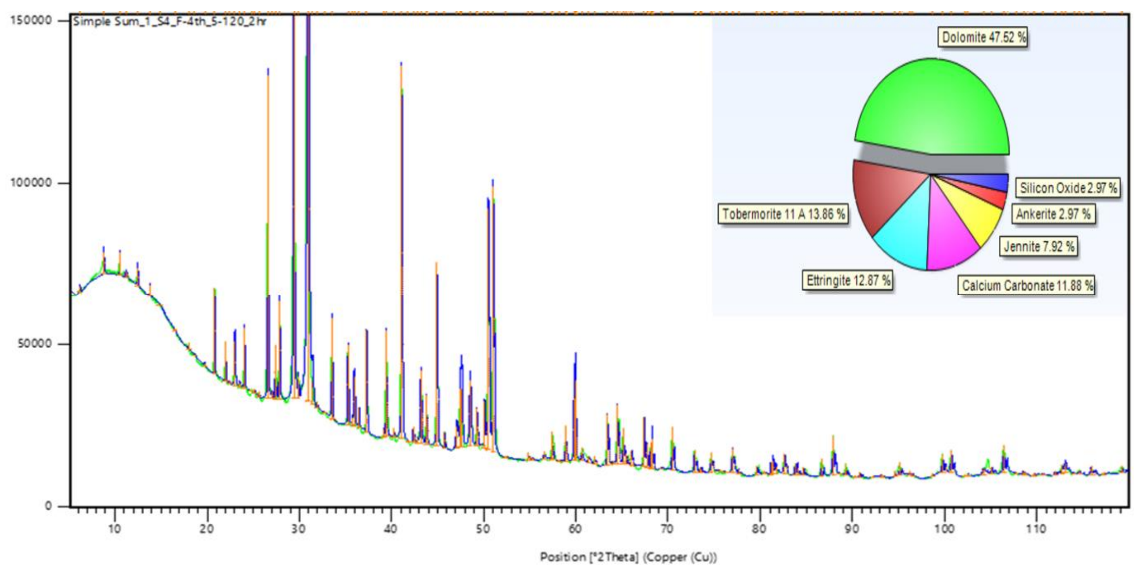


Figure 9.21: XRD analysis of CRCA#2 at 500 °C.

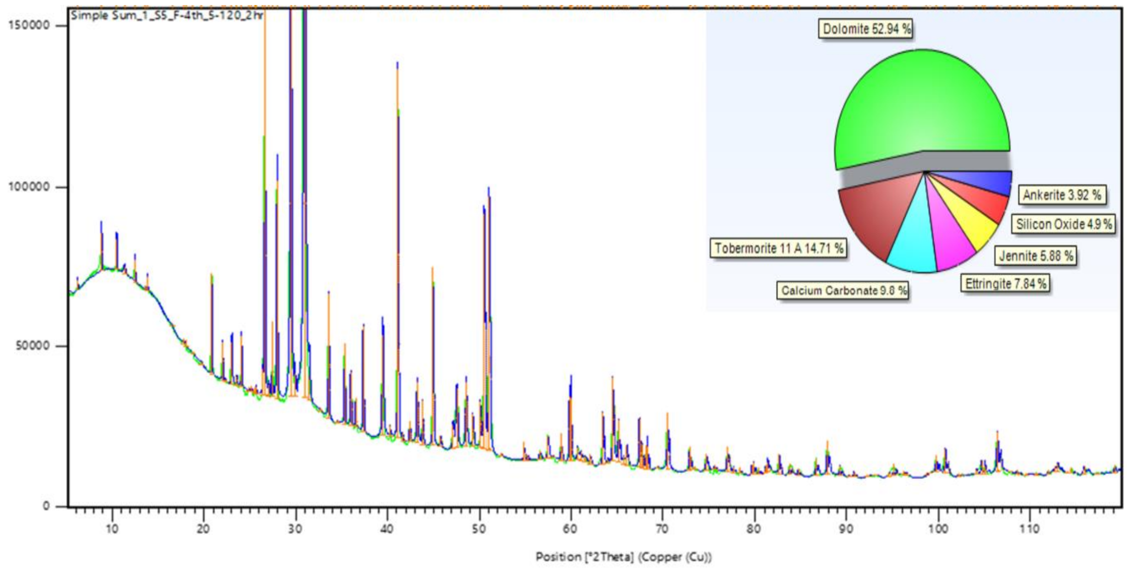


Figure 9.22: XRD analysis of CRCA#2 with HCl acid.

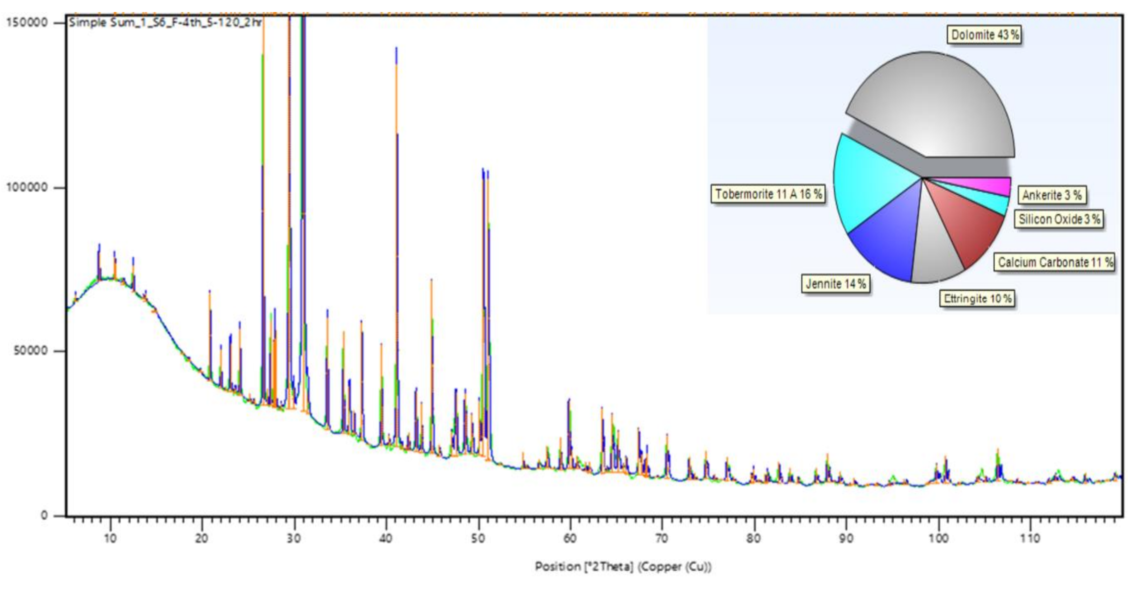


Figure 9.23: XRD analysis of CRCA#2 with C_2H_4O acid.

9.4 Selection Criteria of Best Treatment Methods

After applying different treatment methods, it can be stated that the application of heat treatment and both acid treatment methods are highly successful in improving the microstructure of the ITZ region. However, the use of heat treatment at high temperatures (500 °C) has a negative impact on ITZ microstructure due to the presence of microcracks on the aggregate surface perpendicular to the ITZ region. Additionally, the utilization of acidic treatments demonstrated that a significant difference is observed between HCl and acetic acid for enhancing the microstructure of the ITZ region. However, the use of acetic acid is safe and preferable due to the high corrosive impacts of HCl acid on some aggregate surfaces. De Juan & Gutiérrez (2009) stated that HCl treatment should not be applied with RCA types that originally consisted of limestone aggregates because of negative acidic attacks to the surface of this aggregate type.

Based on this, the use of heat treatment at 300 °C and acetic acid treatment are chosen to be further used with a short mechanical treatment to achieve an application of combination technique of different treatments.

9.5 Summary of This Chapter

This chapter examined the impact of different treatment methods on ITZ improvement in terms of CSH compounds. Depending on the obtained findings, the main points of this chapter are summarized as follows:

- The application of heat treatment method is highly effective for improving the ITZ region. It is observed that heat treatment at high temperature (500 °C) has no impact on the ITZ region. However, it is found that cracks form in the mortar of CRCA at high temperature (500 °C), indicating a negative impact on mortar properties. Therefore, it is highly recommended to use this treatment method at temperatures between 300 °C and 350 °C.
- The use of acid treatment is highly successful in enhancing the ITZ region. However, treatment method using weak acid seems to be more successful and effective than strong acid due to a considerable variance in the obtained results for both types of acid treatment.

- The application of acetic acid treatment leads to a considerable reduction in the Ca/Si ratio for the ITZ region, resulting in considerable improvement in the ITZ region.
- An increase for both C-S-H compounds is registered for different treatment types. However, a significant increase is observed for acetic treatment compared to other treatment approaches.
- Acetic treatment type exhibits the best performance for increasing tobermorite and jennite compared to other treatment types. However, there was a significant difference for both acid treatments in terms of jennite, indicating a specific sensitivity to HCl.

CHAPTER 10

SELECTION OF THE BEST MIX DESIGN FOR THE CONTROL MIX BASED ON SUPERPAVE MIX DESIGN SPECIFICATIONS

In this chapter, part of the outcomes has been presented at the Canadian Society for Civil Engineering (CSCE) Conference (Al-Bayati and Tighe, 2018).

10.1 Introduction

Generally, aggregates in asphalt mixtures are classified into two main groups; namely, coarse and fine aggregates. While aggregates that are larger than 4.75 mm are categorized as coarse, aggregates that are smaller than 4.75 mm typically are categorized as fine. The existence of both aggregate types in asphalt mixtures seems to be mainly responsible for providing a skeleton to resist the repeated traffic load applications and contributing to the viscous-elastic properties of the mixture (Read & Whiteoak, 2003; Zulkati, et al., 2011). With respect to aggregate size, filler refers to aggregate particles that are finer than 75 μm in size or can pass through the No. 200 sieve (0.075 mm) (Huang et al., 2007; Zulkati, et al., 2011).

It is generally agreed that a portion of aggregate that is suspended and freely discrete from aggregate particles in an asphalt binder can be known as a mineral filler (Anderson & Bahia, 1997; Remisova, 2015). Based on this, it is reasonably postulated that mineral filler cannot be considered as aggregate or as a single component in a mixture; therefore, it is equitably counted as an integral component of mastic which is generally described as an actual binder for a mixture (Anderson & Bahia, 1997; Remisova, 2015). Additionally, due to its very small size, a filler is viewed as a fine material that has an ability to modify and enhance the properties of the asphalt-concrete mixture; and therefore, the filler appears to be a modifier and is not considered as a part of aggregate gradation (Zulkati, et al., 2011).

The role of the filler in the asphalt mixture can be described by various mechanisms. The first important role is that filler can provide more additional points of contact between the larger aggregate particles; therefore, it can be regarded as a continuation of the fraction of asphalt aggregate mixture. The stability of the mixture is increased through increasing the viscosity of the asphalt binder and altering its characteristics is another significant role for the presence of filler in the asphalt mixture (Dos Santos et al., 2013). Possible interaction with asphalt could be the most important function that filler particles play in the asphalt mixture. Due to its high fineness, asphalt-filler mastic is formed. In certain mastic characteristics, interactions between filler and asphalt could possibly occur that may influence the mixture's performance. However, due to its large surface area, absorption of some asphalt amounts on the filler surface is quite possible, resulting in a different performance behaviour of the asphalt mixture (Taylor, 2007; Lesueur, 2009).

10.2 Literature Review

Due to the diverse influence of filler addition on asphalt mixtures, numerous studies have investigated various aspects related to this influence and these aspects can be fundamentally classified into two main categories. The first category mainly includes the influence of filler addition on the asphalt mixture's performance. It was found that the addition of higher filler concentrations leads to strong mixtures. This was mainly attributed to better asphalt cohesivity and good stability that was obtained from a good packing distribution of the filler (Zulkati, et al., 2011). The addition of lime as a filler can improve the resistance of hot mix asphalt mixtures to moisture damage, reduce oxidative aging, improve the mechanical properties and resistance to fatigue and rutting, and enhance the asphalt-aggregate bond (Epps & Little, 2001; Dos Santos et al., 2013; Sutradhar et al., 2015). Fillers can also increase the resilient modulus of an asphalt mixture (Tayebali et al., 1998). It was observed that the addition of fillers leads to improvement in the temperature susceptibility and durability of the asphalt binder and asphalt-concrete mixture (Bahia et al., 1999; Lesueur & Little 1999; Gorkem & Sengoz, 2009; Wu et al., 2011; Muniandy et al., 2013). It has been previously proven that mineral filler can be responsible for improving mechanical, rheological, and thermal behaviour of asphalt mixtures. Workability can be also enhanced by the utilization of mineral filler as a filling material that occupies the spaces between different aggregate sizes (Dos Santos et al., 2013). Moreover, mineral filler leads to improving stiffness at the upper range temperatures of asphalt mixtures and reducing stiffness at lower temperatures (Anderson & Bahia, 1997; Remisova, 2015). The second category is extensively focused on the influence of filler on the asphalt binder or mastic properties. It has been previously concluded that the presence of filler is highly related to a reduced optimum asphalt content (Brown et al., 1989; Kandhal et al., 1998; Tayebali et al., 1998; Muniandy et al., 2013). Mineral filler in hot mix asphalt plays a significant role in stiffening and toughening an asphalt binder. It seems to be responsible for improving adhesion of bitumen to aggregate (Sutradhar et al., 2015). In the perspective of volumetric properties, (Dos Santos et al., 2013) explored the influence of filler type and content on HMA volumetric parameters. The findings of the research revealed that VMA and VFA decrease as the filler content increases. It was concluded that lower values of VMA and VFA generally refer to the existence of thin asphalt film. It was also found that aggregate type influenced the volumetric properties.

While comprehensively scanning the literature related to the filler addition into the asphalt mixtures, it should be noted that investigation of its impact on the volumetric properties of the asphalt mixtures is rarely found in the relevant literature. As many investigations were primarily limited in assessing the performance of asphalt mixtures that included mineral filler proportions, only one characteristic; namely, optimum asphalt content that can be counted as a volumetric property was evaluated (Muniandy et al., 2013; Patil et al., 2016). Additionally, as a part of the Marshall mix design, the relationship between asphalt binder content and some volumetric properties such as VMA and VFA were examined (Rahman et al., 2012; Kar et al., 2014; Sutradhar et al., 2015; Priyanka et al., 2015; Patil et al., 2016). To the best of the authors' knowledge, none of the literature studies mentioned above have ever explored the effect of filler on the volumetric properties according to the Superpave mix design. Therefore, this research is a comprehensive study that mainly aims to examine the influence of filler with various proportions on various volumetric properties based on the Superpave mix design.

10.3 Mix Design Blend with Different Filler Proportions

As mentioned earlier, Superpave mix design was performed according to AASHTO R 30-2 (2006). For filler addition, three proportions (2%, 2.5%, and 3%) were used to determine the mix blend. The mixture that included various proportions of filler is given in Table 10-1.

Table 10-1: Mix Design Blend with Different Filler Proportions

Filler content, %	Aggregate type, %			
	CA[a] #1, HL8 stone	CA#2, ¼ chip	FA[b] #1, Manufactured sand	FA#2, Blend sand
2.0	40	12	36	10
2.5	40	12	35.5	10
3.0	40	12	35.0	10

Note: CA[a] = Coarse aggregate; FA[b] = Fine aggregate

10.4 Volumetric Properties of the Mixture with Filler Addition

The laboratory data on the volumetric characteristics of HMA mixtures that included various proportions are tabulated in Table 10-2. More details on the results of the volumetric properties are discussed in the following subsections.

Table 10-2: Volumetric Characteristics of Mixtures with Various Filler Percentages

Property	Dust plant, %			Acceptable Limitations of MTO Specifications
	2.0	2.5	3.0	
OAC (%)	4.9	4.83	**4.54**	-
VMA (%)	14.65	14.5	13.4	13 min.
VFA (%)	72.69	72.50	70.10	65-75
Dp	**0.43**	0.6	0.8	0.6-1.2
Gmm $N_{initial}$ (%)	88.56	88.60	88.30	≤ 89
Gmm N_{des} (%)	96.0	96.0	96.0	96.0
Gmm N_{max} (%)	97.3	97.10	97.19	≤ 98.0
G_{mb}	2.398	2.40	2.425	-
G_{mm}	2.498	2.50	2.526	-

10.4.1 Optimum Asphalt Content (OAC)

The OAC in HMA mixtures with various filler proportions is graphically analyzed in Figure 10.1. A comparable performance that can be represented as a polynomial equation for the filler is registered. It is observed that the optimum asphalt binder content decreases when the filler percentage is increased. This behaviour can be mainly attributed to the fact that an increase in the filler amounts can lead to filling the voids that generally exist between aggregate particles, resulting in a reduction of the voids in the mineral aggregate. Thus, the available space for asphalt binder is decreased (Mehari, 2007). Huang et al. (2007) stated that the required asphalt binder content decreases to form the same quantity of mastic for lubricating the aggregate when filler content is increased. Depending on the workability of the asphalt mixtures, a higher filler content lowers the required asphalt binder due to the compaction of the mixtures on the needed air voids. It is noteworthy that a significant decrease in the optimum asphalt binder content is observed when filler content is increased from 2.5% to 3%.

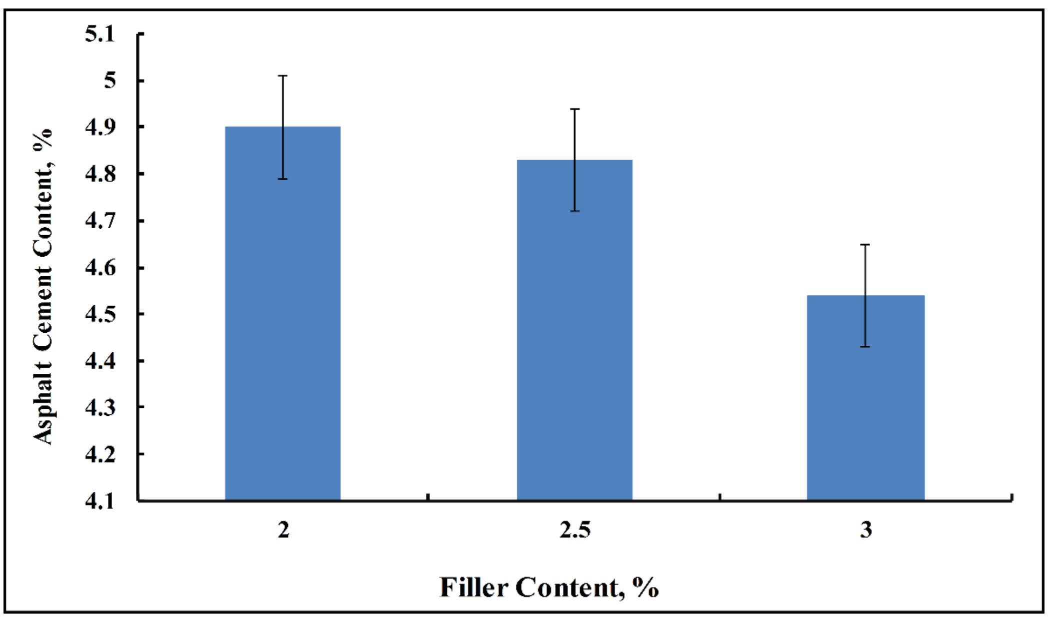


Figure 10.1: Optimum asphalt cement content for mixtures with various filler proportions.

10.4.2 Voids in Mineral Aggregates (VMA)

Figure 10.2 illustrates the effect of filler with different percentages on VMA of HMA mix design. It was demonstrated that an increase in filler content can lead to a decrease in VMA of the HMA mixture. The lowered VMA value could possibly indicate the existence of a thin asphalt film around the aggregate particles. It has been previously found that the utilization of high amounts of filler produces a thin asphalt film which could be more likely to be a detrimental factor with regards to mixture durability (Dos Santos et al., 2013). However, compared to the required percentage of the minimum VMA to MTO specification that is typically accounted as 13 for this category of the HMA mix design, the obtained outcomes were higher than the required percentage, resulting in a highly successful filler addition.

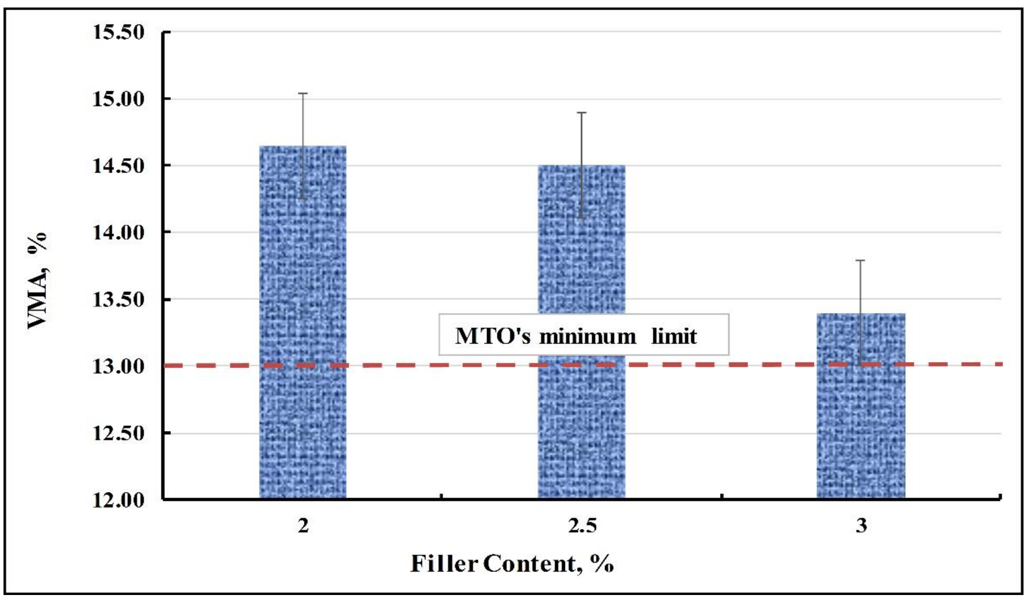


Figure 10.2: Voids in mineral aggregates (VMA) for mixtures with various filler proportions.

10.4.3 Voids Filled with Asphalt (VFA)

The influence of filler with various proportions on VFA for HMA is presented in Figure 10.3. The findings showed that the VFA value proportionally decreases depending on an increase in the filler content. As explained in VMA property, the existence of a thin film appears to be the main reason behind the reduction in the VFA values. The comparison of the obtained VFA values and the required values for the MTO specification that range between 65% and 75% indicates the research findings were higher than the lower limit percentage, resulting in there is no impact for the percentage of filler addition on this volumetric property.

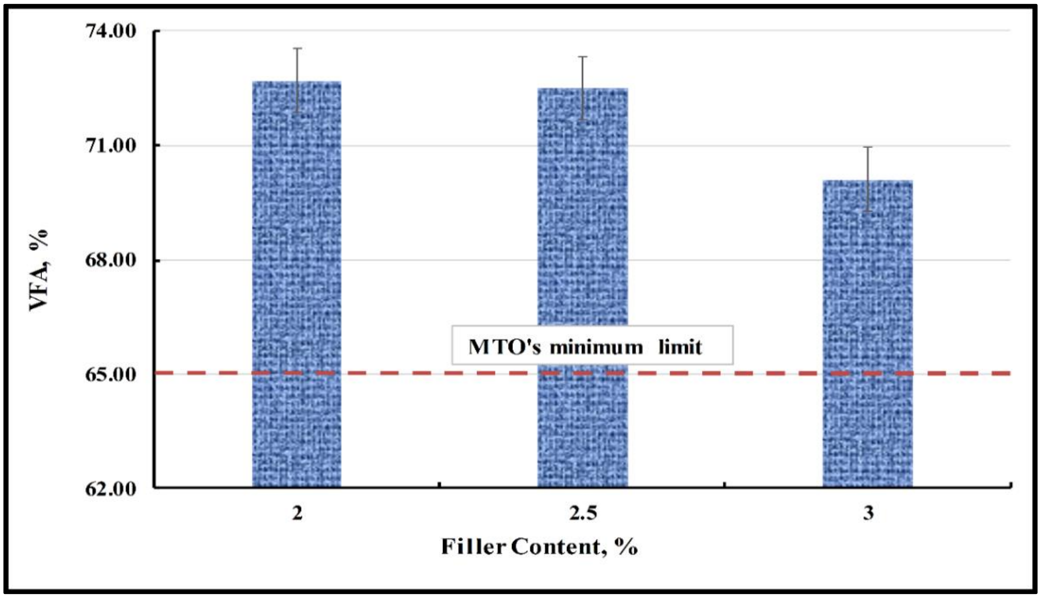


Figure 10.3: Voids filled with asphalt (VFA) for mixtures with various filler proportions.

10.4.4 Dust to Binder Ratio (Dp)

Figure 10.4 demonstrates the Dp ratio (also known as the dust proportion) that represents another mixture design criterion. Dp can be defined as the ratio of aggregates expressed as a percent by weight that can pass through the 0.075 mm sieve (#200) to the effective asphalt content or optimum asphalt binder accounted as a percentage by weight. The findings of the investigation indicated that the Dp ratio seems to be directly proportional to the filler content. The Dp proportion increases when the filler content is increased; therefore, it can be concluded that the Dp proportion behaves inversely compared to other volumetric properties of the mixtures. The outcomes revealed that the Dp values are 0.43 and 0.6 for mixtures with filler content of 2.0% and 2.5%, whereas the experimental value of Dp with filler content of 2.5% was 0.6, whereas the obtained value of Dp for the mixture with filler content of 3% was 0.8. The MTO specification requires an acceptable range for Dp between 0.6 and 1.2; thus, it can be concluded that the obtained value of Dp for the mix design with a filler content of 2% is lower than the minimum required value, resulting in an unacceptable mix design. In contrast, the experimental values of Dp for mix design with a filler content of 2.5% and 3% were within the acceptable range of MTO specifications. It has been previously reported that low Dp values generally indicate unstable mixtures, whereas high Dp values could possibly indicate a lack of sufficient durability (FHWA).

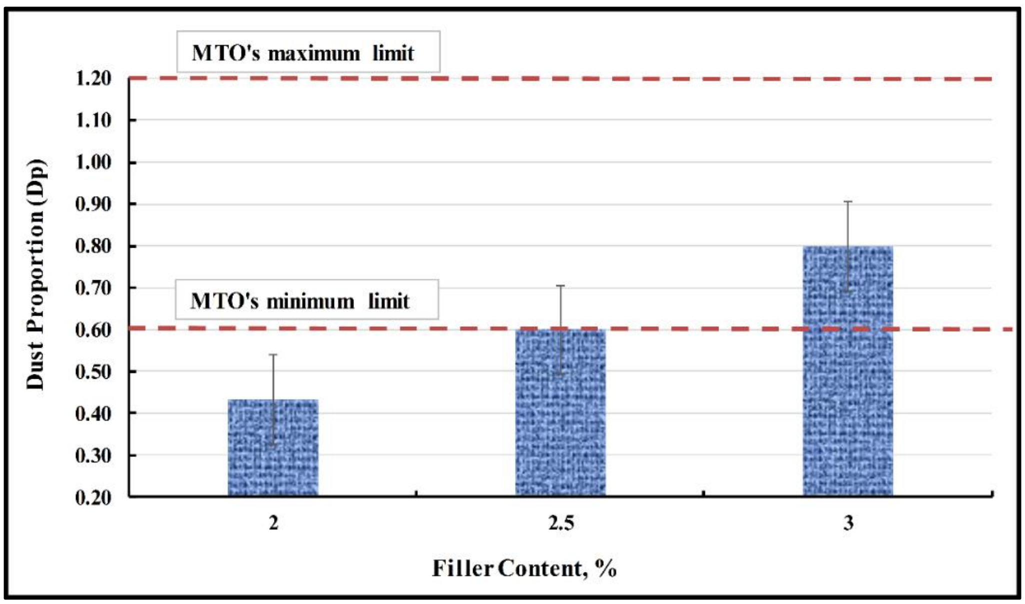


Figure 10.4: Dust proportion (Dp) for mixtures with various filler proportions.

10.4.5 Maximum Theoretical Specific Gravity (G_{mm}) & Bulk Specific Gravity (G_{mb})

It is generally known that G_{mm} simply refers to the ratio of the mass of the asphalt and aggregate mixture to the volume that does not include the air voids, whereas G_{mb} generally indicates the ratio of the mass of the asphalt and aggregate mixture to the volume that includes the air voids. The behaviour of the properties G_{mm} and G_{mb} for HMA using different filler proportions is displayed in Figure 10.5. It is observed that when the filler content is increased, there was an increase in the G_{mm} and G_{mb} values. However, the behaviour of the above-mentioned properties was different. While the behaviour of G_{mm} can be described as a linear equation, an exponential equation reflects the behaviour of G_{mb}.

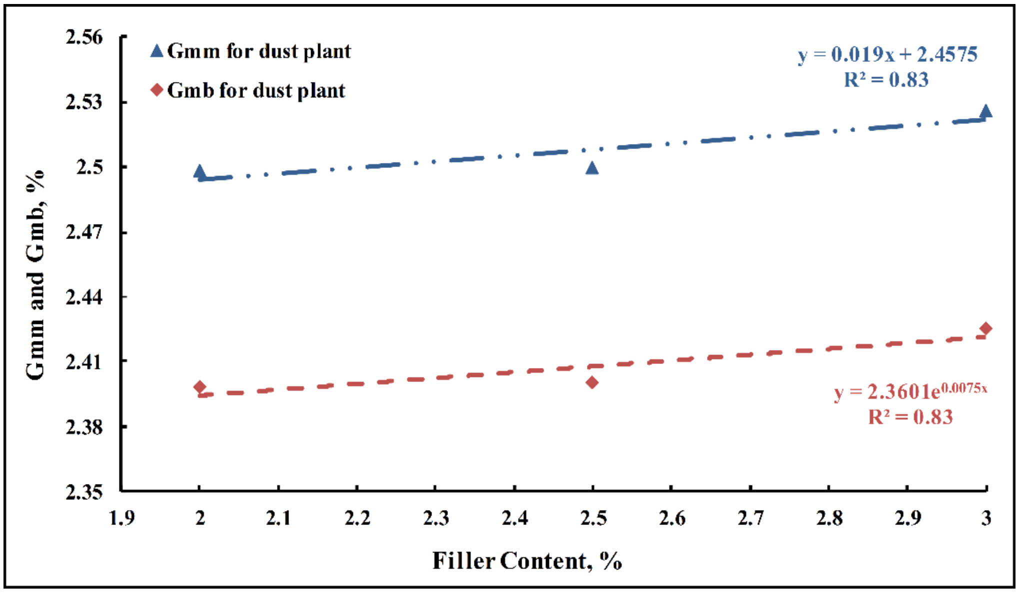


Figure 10.5: G_{mm} and G_{mb} of mix at various filler proportions.

10.5 Evaluation of Mixture Design with Filler Addition

An additional important characteristic of mixture volumetric requirements is the mixture density during compaction at N_{ini} and N_{max}. The detailed features of this required property that was obtained for mixtures with different filler percentages are tabulated in Table 10-3. The previous laboratory results of the addition of filler with various proportions and the obtained data in Table 10-3 emphasized that the addition of 2.5% filler is highly successful that it achieves all MTO requirements for volumetric properties of HMA. It is concluded that the addition of 2.0% filler is unsuccessful because a Dp ratio lower than the MTO specification was obtained. Additionally, the addition of filler with 3% is also unsuccessful. Mixture with the mentioned filler percentage had a lower value of OAC, meaning that the HMA mixture is dry and the asphalt binder is not sufficient to completely coat the aggregate particles. Therefore, the mechanical properties of asphalt mixtures are evaluated with a filler percentage of 2.5% for filler type, namely, DPt.

Table 10-3: Results of the Property of Mixture Density during Compaction Volumetric

Volumetric design	**Dust plant, %**		
	2.0	**2.5**	**3.0**
G_{mm} $N_{initial}$ (%)	88.56	88.60	88.30
G_{mm} N_{des}. (%)	96.00	96.00	96.00
G_{mm} N_{max} (%)	97.3	97.1	97.2

10.6 Summary of This Chapter

This chapter focused on the evaluation of the influence of mineral filler on the volumetric properties of HMA. Depending on the obtained results, the main points of this chapter can be summarized as follows:

The obtained results indicated that the properties of OAC, VMA, and VFA decrease as the filler content is increased. Compared to other volumetric properties, Dp ratio, G_{mm}, and G_{mb} behaved inversely in which the values of these properties increase when the filler content is increased. The addition of filler (2.5%) is very successful due to satisfying all MTO requirements for volumetric properties of HMA mixtures. Based on the specifications, the addition of 2.0% filler seems to be unsuccessful due to obtaining a Dp ratio lower than the MTO requirements. Mix design with 3.0% filler is also unsuccessful because of the lower value of OAC. This means that the mix is dry and there is insufficient asphalt binder to coat the aggregate particles.

CHAPTER 11

INVESTIGATING THE INFLUENCE OF RECYCLED CONCRETE AGGREGATE TREATED WITH DIFFERENT METHODS ON VOLUMETRIC PROPERTIES OF HOT MIX ASPHALT

In this chapter, the obtained results of CRCA#1 have been published in the Resources, Conservation & Recycling Journal (Al-Bayati et al., 2018). The findings of CRCA#2 have been submitted to Journal of Materials in Civil Engineering.

11.1 Introduction

It is generally accepted that asphalt concrete (AC) is a heterogeneous material that is fundamentally composed of various substituents: asphalt cement, natural or artificial aggregate, mineral filler, additives, and air voids. Among various constituents, aggregate makes up the largest portion of pavement mixture and therefore, it has an important role and considerable impact on the engineering properties of the asphalt mix (Afaf, 2014). The design of asphalt mixtures can be described as a complicated process that requires very accurate proportions of aggregate and asphalt binder in order to achieve specific requirements of volumetric and mechanical properties. (Anderson & Bahia, 1997). Therefore, the main objective of this research in this chapter was to investigate the influence of CRCA with different types and various proportions on the volumetric properties of HMA.

11.2 Gradation of Mix Design with CRCA

As mentioned earlier, Superpave mix design was performed according to AASHTO R 30-2 (2006). For CRCA addition, four proportions (0%, 15%, 30%, and 60%) were used to determine the mix blend. To meet the targeted mix design values of Miller group and MTO specifications that are related to the volumetric requirements as previously shown in Table 2, the gradation of the mix was changed for each CRCA percentage. The gradation of virgin aggregate and various percentages of CRCA, targeted mix design of Miller group, and MTO specifications are numerically tabulated in Table 11-1, whereas the particle size gradations with different CRCA proportions is graphically plotted in Figure 11.1.

Table 11-1: Gradations with Various CRCA Proportions, Targeted Mix Design, and MTO Specifications.

Sieve Size, mm	Passing (%) for Different CRCA Percentages						The Target of Mix Design	MTO Limitation
	0.0% CRCA	15% CRCA#1	30% CRCA#1	60% CRCA#1	30% CRCA#2	60% CRCA#2		
25	100	100	100.0	100.0	100	100.00	100	100
19	95.2	95.2	95.3	95.2	96.6	97.32	96.8	100 - 90
16	89.0	88.7	88.5	87.4	86.6	82.92	90.6	90 - 23
12.5	81.8	81.1	80.5	78.2	73.9	64.06	83	
9.5	73.2	72.3	71.8	69.0	67.8	59.12	73.3	
6.7	63.3	63.0	63.1	61.0	61.5	55.12	63.3	
4.75	57.1	56.7	55.9	53.8	56.0	51.69	55.9	
2.36	42.8	42.8	41.3	41.2	41.8	40.96	43.5	49 - 23
1.18	30.7	30.7	30.5	30.5	31.2	30.53	32.5	
0.6	22.9	23.0	23.6	23.6	24.3	23.59	25.1	
0.3	10.2	10.3	10.3	10.3	10.3	10.30	11.8	
0.15	5.4	5.5	5.6	5.5	5.5	5.54	5.5	
0.075	2.1	2.2	2.2	2.1	2.1	2.13	3.8	8 - 2

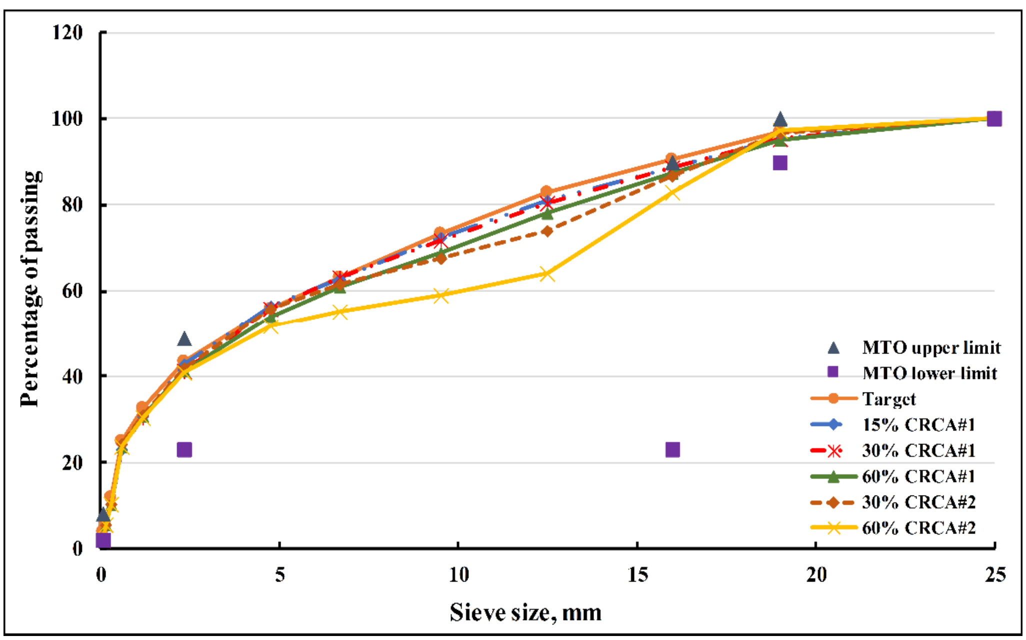


Figure 11.1: Particle size gradations with different percentages of CRCA.

11.3 Mix Design Blend with CRCA Addition

To achieve successful HMA mixtures that include different proportions of both untreated CRCA and CRCA treated with various treatment approaches, the application of the mix design blend appears to be the principle step responsible for achieving the targeted goals. Due to utilizing a protocol with a lengthy process, Table 11-2 and 11-3 represent the final mix design blend, which includes different proportions of untreated and treated CRCA in HMA mixtures for CRCA#1 and CRCA#2, respectively. Mix blend mixtures consist of two different types of coarse and fine natural aggregate, namely, CA#1, CA#2, FA#1 and FA#2, and two types of CRCA and one type of filler, namely, dust plant. To prepare a mix blend design, different proportions of the above-mentioned materials are mixed according to the targeted mix design provided by the Miller Group and MTO specifications as shown earlier in Table 11-1 and Figure 11-1. To assess a prepared mix design blend, volumetric properties are evaluated through the preparation of a HMA mixture for each mix design blend. To meet all the volumetric property requirements of MTO specifications, many trial blends were attempted. However, it is important to mention that the obtained findings of trial blends were fundamentally based on the results of volumetric properties of these trials and are discussed in the next section. For both 0% and 15% proportions of the CRCA#1, and 30% and 60% proportions of the CRCA#2 addition, one trial was needed in order to satisfy MTO requirements. To meet the MTO specifications, two trials were performed for successful CRCA#1 addition with both percentages of: 30% and 60%. Because treatment methods specifically affect the physical characteristics of CRCA; e.g. water absorption, specific gravity, the use of the successful mix blend that includes 30% untreated CRCA and satisfies MTO specifications for utilizing the mix blend that contained treated CRCA with the same percentage seems to be quite reasonable. Therefore, the mix blend that included 30% treated CRCA#1 & CRCA#2 with both heat treatment and soaking in weak acid solution, followed by a short mechanical treatment was similar to the satisfactory mix blend that involved 30% untreated CRCA.

Table 11-2: Mix Design Blend with CRCA#1 Addition

	Control Mix Blend 1	15% untreated CRCA Blend 1	30% untreated CRCA Blend 1	30% untreated CRCA Blend 2	30% treated CRCA heat & Sh.M.T Blend 1	30% treated CRCA soaking & Sh.M.T Blend 1	60% untreated CRCA Blend 1	60% untreated CRCA Blend
CA#1, HL8 Stone	40	32.5	24.5	24.5	24.5	24.5	9.4	10.4
CA#2, ¼ chip	12	11.5	14	14	14	14	11	11
FA#1, Manufactured Sand	35.5	34.9	32.4	30.4	30.4	30.4	34.4	31.5
FA#2, Blend Sand	10	10.5	10.0	12.0	12	12	10.1	12
CRCA	0	8.0	16.0	16.0	16.0	16.0	32.0	32.0
Dust plant	2.5	2.6	3.1	3.1	3.1	3.1	3.1	3.1

Table 11-3: Mix Design Blend with CRCA#2 Addition

	Control Mix Blend 1	30% untreated CRCA Blend 1	30% treated CRCA heat & Sh.M.T Blend 1	30% treated CRCA soaking & Sh.M.T Blend 1	60% untreated CRCA Blend 1
CA#1, HL8 Stone	40	24.5	24.5	24.5	14.9
CA#2, ¼ chip	12	13.5	13.5	13.5	8.0
FA#1, Manufactured Sand	35.5	30.0	30.0	30.0	30.0
FA#2, Blend Sand	10	13.0	13.0	13.0	12.0
CRCA	0	16.0	16.0	16.0	32.0
Dust plant	2.5	3.0	3.0	3.0	3.1

11.4 Volumetric Properties of Mix Design with CRCA Addition

The laboratory data on the volumetric characteristics for HMA mix design with CRCA addition is tabulated in Table 11-4 and 11-5. For the first blend of HMA included CRCA#1 addition with 30% and 60% proportions, the experimental results demonstrated that the percentage of VMA is lower than the minimum required value; namely 13%, for MTO specifications. Those mixtures are weak and unstable, and therefore cannot be applied in the field. To ensure there is no deficit in the asphalt binder of HMA; the mix is durable, meeting VMA criteria is required (Kandhal & Chakraborty, 1996; Hislop, 2000; Bardini et al., 2013). Additionally, it has been previously reported that mixtures designed with soft aggregate type usually have a problem in satisfying VMA characteristic requirements, whereas mixtures

Table 11-4: Mix Design Volumetric Properties for Treated and Untreated CRCA #1 Mixtures

Aggregate Type / HMA Property	0 %	15% UNT	30% UNT		30% TRD H.Sh.M.T.*a	30% TRD S.Sh.M.T.*b	60%		Acceptable Limitations of MTO Specifications
	Blend 1	Blend 1	Blend 1	Blend 2	Blend 1	Blend 1	Blend 1	Blend 2	
O.A.C AC (%)	4.83	4.9	4.97	5.31	5.21	4.9	5.54	5.71	-
VMA (%)	14.5	13.6	**12.87**	13.66	13.88	13.84	**12.73**	16.18	13 min.
VFA (%)	72.5	70.8	68.7	70.7	70.9	71.1	68.8	74.8	65-75
Vv (%)	4.0	3.99	4.02	4.0	4.01	4.0	4.0	4.04	4.0
Dp	0.6	0.63	0.81	0.74	0.73	0.73	0.81	0.6	0.6-1.2
G_{mm} $N_{initial}$ (%)	88.6	88.9	-	88.38	88.36	88.35	-	88.5	≤ 89
G_{mm} N_{des} (%)	96	96	-	96.0	96.0	96.0	-	96.0	96.0
G_{mm} N_{max} (%)	97.1	97.4	-	97.1	97.15	97.15	-	97.02	≤ 98.0
G_{mb}	2.4	2.395	2.385	2.373	2.393	2.375	2.344	2.351	-
G_{mm}	2.5	2.494	2.485	2.472	2.493	2.474	2.441	2.450	-

H.Sh.M.T*a = Heat and short mechanical treatment., S.Sh.M.T*b = Soaking and short mechanical treatment.
TRD = Treated, UNT = Untreated

Table 11-5: Mix Design Volumetric Properties for Treated and Untreated CRCA #2 Mixtures

Aggregate Type / HMA Property	0 %	30% UNT	30% TRD H.Sh.M.T.*a	30% TRD S.Sh.M.T.*b	60%	Acceptable Limitations of MTO Specifications
	Blend 1	Blend 1	Blend 1	Blend 1	Blend 1	
O.A.C AC (%)	4.83	5.12	5.03	4.87	5.2	-
VMA (%)	14.5	14.0	14.0	14.52	13.27	13 min.
VFA (%)	72.5	71.4	71.3	72.3	70.03	65-75
Vv (%)	4.0	4.0	4.0	4.0	4.0	4.0
Dp	0.6	0.7	0.7	0.7	0.8	0.6-1.2
G_{mm} $N_{initial}$ (%)	88.6	88.6	87.5	88.6	88.8	≤ 89
G_{mm} N_{des} (%)	96.0	96.0	96.0	96.0	96.0	96.0
G_{mm} N_{max} (%)	97.1	97.1	96.0	97.1	97.2	≤ 98.0
G_{mb}	2.4	2.384	2.392	2.384	2.367	-
G_{mm}	2.5	2.483	2.492	2.484	2.465	-

H.Sh.M.T*a = Heat and short mechanical treatment., S.Sh.M.T*b = Soaking and short mechanical treatment.
TRD = Treated, UNT = Untreated.

designed with a blend of hard and soft aggregate types could possibly have difficulty meeting VMA criteria (Guide, 2001). Therefore, the findings of the prepared mixtures that included soft and hard aggregate, namely CRCA and NA for those trials that revealed a difficulty satisfying the VMA minimum requirements appear to be logically consistent with this possibility. Hence, further trials were needed for meeting VMA MTO specifications. It is important to mention that a detailed explanation for all the results of volumetric properties is provided in the following sections.

11.4.1 The Effect of CRCA on Optimum Asphalt Binder Content

To examine the influence of untreated CRCA on the OAC property, the obtained results are presented in Figure 11.2. It is demonstrated that OAC is strongly correlated with the percentage of untreated CRCA due to obtaining an optimum regression. A polynomial equation obviously reflects the behaviour of OAC when untreated CRCA proportions are increased. Generally, it is observed that the NA replacement by untreated CRCA leads to an increase in the OAC for the mixtures. In terms of OAC, both mixtures that included untreated CRCA#1 and CRCA#2 exhibited the same trends and behaviour. As the proportion of untreated CRCA increases, the OAC of the mixture is increased. This is mainly attributed to the high absorption property of CRCA. This finding is confirmed by Beal and You’s research (Mills-Beale and You, 2010) that found the optimum asphalt content increased linearly with increasing CRCA addition. In terms of studying the effect of CRCA types on the OAC, the outcomes revealed that the mixtures that included untreated CRCA#1 have a higher OAC percentage than the mixtures that included untreated CRCA#2 for the same untreated CRCA proportion. These results are in total agreement with the physical and mechanical properties that showed that CRCA#1 has a higher water absorption than CRCA#2 due to the existence of a higher percentage of adhered mortar attached to its surface.

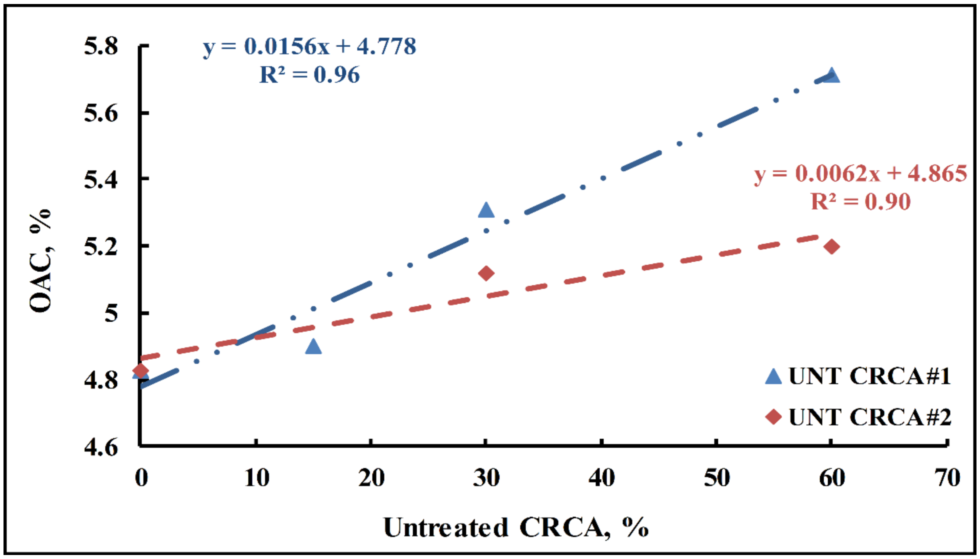


Figure 11.2: Behaviour of optimum asphalt content for mixtures including different types and proportions of untreated CRCA.

In order to obtain a better understanding, the effects of different treatment methods on the OAC of HMA mixtures are illustrated in Figure 11.3. Compared to the mixture that included 30% untreated CRCA, the outcomes revealed that there is an important reduction in the OAC for mixtures that included 30% treated CRCA with various types of combination techniques. This behaviour is registered for both CRCA types. However, a considerable difference between different combination approaches was observed. It is interesting to note that the OAC decreased from 5.31% to 5.21% and 5.12% to 5.03% for the mixtures that included treated CRCA#1 & CRCA#2 respectively due to the combination of heat treatment at 300°C and short mechanical treatment. Hence, a slight reduction in this property was registered with a reduction value of 1.88% and 1.76% for the mixtures that included treated CRCA#1 & CRCA#2, respectively. Surprisingly, the combination of pre-soaking with weak acid and short mechanical treatment led to a considerable decrease of OAC that ranged from 5.31% to 4.9% and 5.12 to 4.87 for the mixtures that included treated CRCA#1 and CRCA#2, respectively. Due to the application of this technique, a reduction of approximately 8% and 5% for mixtures that included treated CRCA#1 and CRCA#2, respectively was observed. Based on this, this type of combination appears to be the most efficient compared to other approaches. Additionally, CRCA#1 seems to have a higher rank than CRCA#2 for utilization in the HMA mixtures though it has a higher percentage of attached adhered mortar.

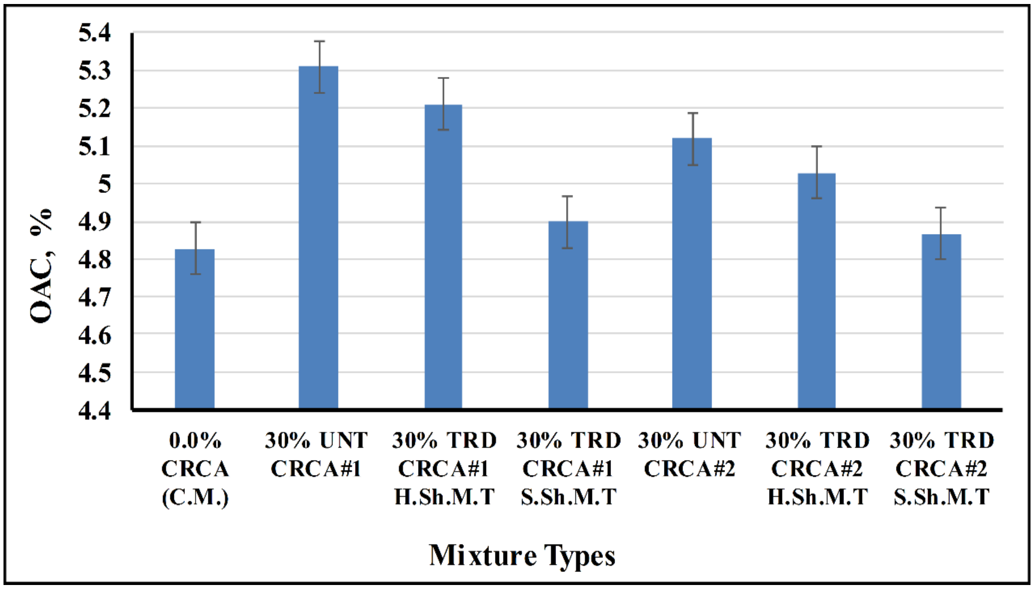


Figure 11.3: Behaviour of optimum asphalt content for mixtures including different types and proportions of treated and untreated CRCA.

11.4.2 Behaviour of Optimum Asphalt Content for Mixtures Included CRCA

Experimental results of OAC are also further analyzed by comparing them with the relevant RCA literature as shown in Figure 11.4 As can be seen, a second order equation with a high regression completely reflects the relationship behaviour between OAC of a mixture and water absorption of the added RCA. Though the RCA literature discusses a wide range of water absorption, the largest percentage of the relevant studies has a mixture OAC ranging between approximately 3% and 7%. However, the OAC for the mixtures that included 30% untreated CRCA#1 and CRCA#2 is categorized within the average range of the RCA literature. As mentioned earlier in the section about treated CRCA, a considerable improvement in water absorption was obtained, indicating high success for various treatment methods. While a significant reduction was recorded for heat treatment at 300 °C followed by short mechanical treatment, the combination of weak acid and the same mechanical treatment method effectively improved water absorption of CRCA. It is obvious that the best improvement for water absorption was registered for the combination of heat treatment at 300 °C and short mechanical method for CRCA#1, whereas the combination of soaking treatment with $C_2H_4O_2$ and short mechanical method showed the best improvement for water absorption for CRCA#2. In contrast, optimum performance for enhancing the OAC of mixtures that included 30% treated CRCA is accounted for by the integration of soaking in weak acid and the same mechanical treatment for mixtures that included both CRCA#1 and CRCA#2. Hence, results of water absorption and OAC appear to be inconsistent. This contradiction could possibly be due to various factors including rheological properties of asphalt binder, aggregate and RCA type, and others.

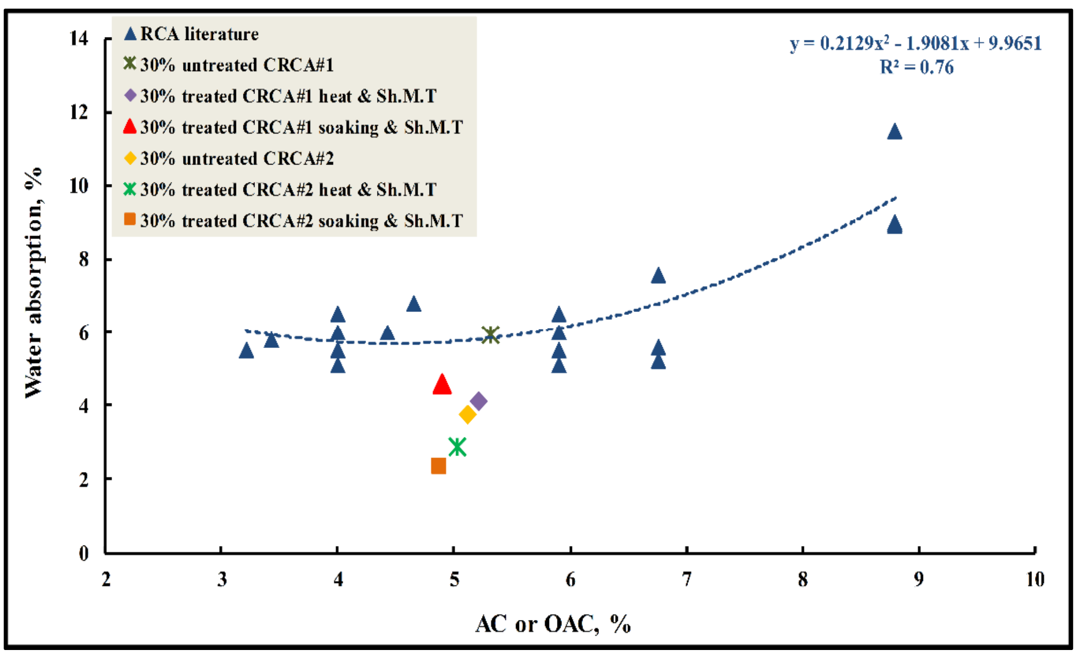


Figure 11.4: Obtained results in terms of water absorption and AC & OAC as compared with some available RCA literature.

11.4.3 The Effect of CRCA on VMA Property

The behaviour of the VMA property for the mix samples that included different untreated CRCA types with various proportions is graphically presented in Figure 11.5. It is observed that the VMA of the mixture including 0% untreated CRCA (control mix) is 14.5% higher than the required MTO specifications, 13, registering a successful control mix for this property. For untreated CRCA addition, the outcomes revealed that the behaviour of VMA was inconsistent based on the CRCA type. With untreated CRCA#1 addition, the percentage of VMA gradually decreased to reach 13.6% for the mixture composed of 15% untreated CRCA. This behaviour is mainly attributed to an increase in the asphalt binder content, which increased from 4.83% to 4.9%, due to the addition of CRCA. This is owing to the fact that the asphalt binder fills in the particle voids and reduces their volume. This leads to an increase in the bulk density of the mixture and results in a reduction of the VMA percentage. With respect to the CRCA addition, it causes absorption of some of the asphalt in the mixture due to the porosity of the CRCA surface, resulting in a reduction in the effective asphalt content, and therefore, the VMA is reduced (Mills-Beale and You, 2010; Bhusal et al., 2011). A significant difference in the percentage of flat and elongated forms between untreated CRCA#1 and NA; namely 2.87 and 0.95 respectively, could possibly play an important role in explaining this behaviour. It was previously stated that through the Superpave compaction process, where the particles are kneaded into a more stable condition, both flat and elongated particles exhibit a horizontal configuration. This behaviour leads to a reduction in the VMA of the mixture (Guide, 2001).

It is interesting to note that the VMA increased to only 13.66% from 13.6% when the untreated CRCA#1 addition reached 30%, indicating little impact of untreated CRCA at lower proportions (up to 30%) on the VMA property. However, the VMA percentage obviously appears to be more than the required value, 13, of the MTO standards. It was further noted that VMA in the mix, composed of 60% untreated CRCA, is higher than the control mix that is made up of the NA (0% untreated CRCA). While the VMA value is 14.5% for the control mix (0% untreated CRCA), the VMA percentage is drastically increased to 16.18% when the untreated CRCA proportion in the mixture reached 60%. This results in a considerable positive impact for the high percentages of untreated CRCA addition on this property. The behaviour of VMA at higher percentages of untreated CRCA addition could be clarified by the following explanation. As the proportion of untreated CRCA that is usually more porous than NA is quite high, it can be considered that there is a high percentage of voids in the mixture. The high proportion of voids leads to a lowering in the bulk density of the mixture, and therefore, VMA, which is inversely related to bulk density, is increased with the increase in CRCA addition. This outcome is confirmed by a previous study (Rafi et al., 2011). Another approach that could confirm this behaviour is the use of weak aggregate that can be easily disintegrated because the compaction during the mix design process results in an increasingly fine aggregate. This increase possibly makes the asphalt binder content higher than usual (Bhusal et al., 2011; Afaf, 2014). Experimental findings strongly support this through an important increase in the OAC property from 5.31% to 5.71% when untreated CRCA proportion reached 60%. Due to obtaining a very significant regression, it is important to mention that the VMA values and different proportions of untreated CRCA are completely related. A polynomial equation evidently describes the behaviour of the relationship between the two above-mentioned variables.

In terms of CRCA#2 addition, the percentage of VMA gradually decreases when CRCA percentage is increased to reach 13.27% for the mixture that included 60% untreated CRCA. The reason behind this trend could be the same reason as stated previously.

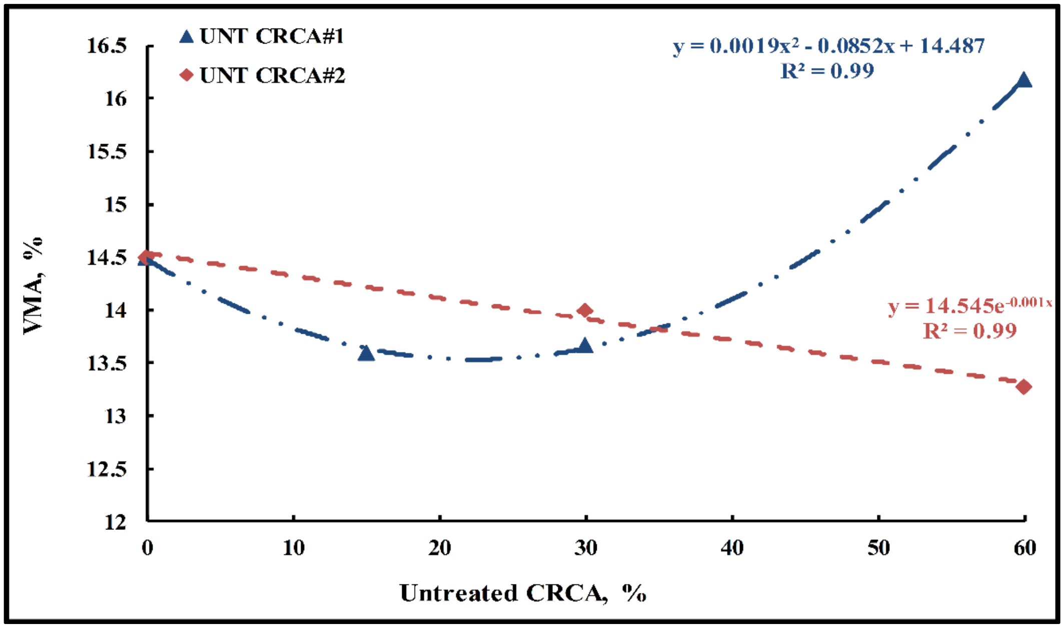


Figure 11.5: Behaviour of VMA for mixtures including different types and proportions of untreated CRCA.

To obtain a better understanding, the obtained outcomes are further evaluated by comparison with previous investigations. Figure 11.6 demonstrates the correlation between two volumetric properties, namely, VMA and OAC when compared to some available studies in the RCA literature. In general, it is revealed that NA has a high percentage of VMA compared to RCA. However, a few exceptions for both NA and RCA exist in the relevant literature. It is also noted that a small improvement in the VMA value is registered for mixtures that included 30% treated CRCA#1 with various treatment approaches compared to the mixture with 30% untreated CRCA#1. Nevertheless, no significant difference between the impact of different treatment methods on this property is observed. Though a considerable improvement in CRCA characteristics is registered, the VMA values for the treated CRCA with different combination approaches are less than the control mix value. However, one exception is observed for the mixtures that included 30% treated CRCA#2 with soaking treatment followed by the short mechanical treatment. These mixtures registered a VMA value equal to the control mix value. More importantly, the VMA values of the mixtures that included various treated CRCA are higher than the required limits of the MTO standards. It is noteworthy that the values of VMA for mixtures that included different CRCA types with various proportions of untreated CRCA and the OAC property are strongly correlated due to obtaining a considerable regression. A polynomial equation obviously reflects the behaviour of the relation between the above-mentioned volumetric properties for CRCA#1, whereas an exponential equation describes the behaviour of the same properties for CRCA#2.

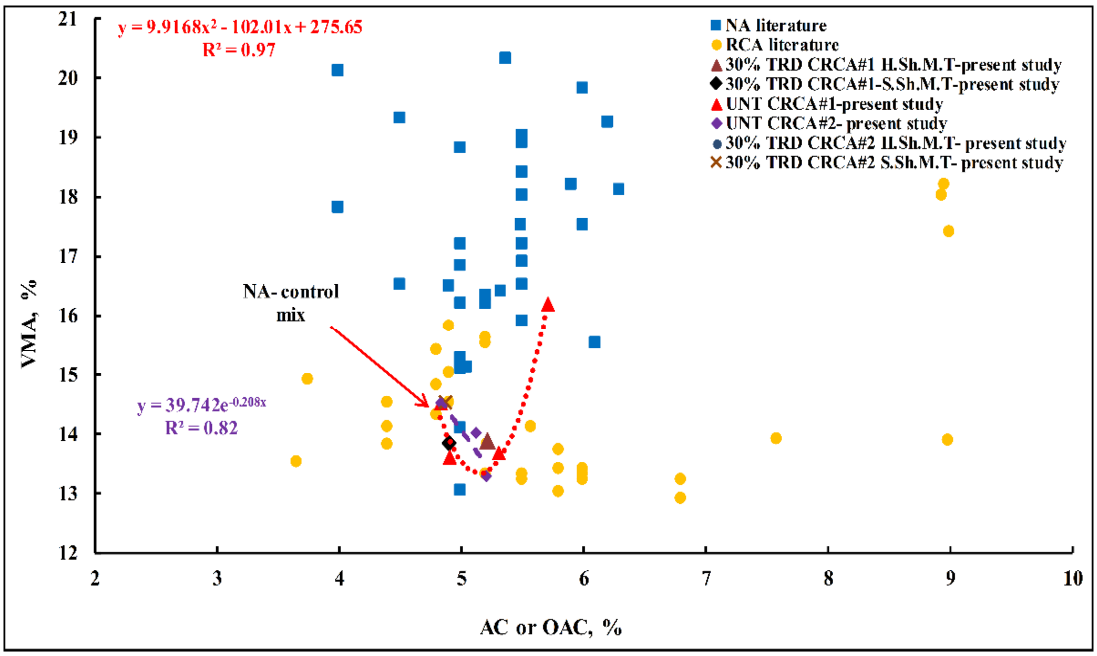


Figure 11.6: Obtained results in terms of VMA and AC or OAC as compared with some available RCA literature.

11.4.4 The Effect of CRCA on VFA Property

Figure 11.7 demonstrates the percentage of VFA for the mix samples including different untreated CRCA types with various proportions. VFA is known as the ratio of the volume of effective binder to the VMA; it is synonymous with the asphalt-void ratio (Superpave Fundmentals). The significance of VFA property is that it represents a measure of relative durability and there is a strong relationship between this property and density (Mehari, 2007). When the value of VFA is quite low, the amount of asphalt required to provide durability and density under the influence of traffic and bleed is not enough. Therefore, the VFA represents a very important design criterion. Compared to the behaviour of the VMA property, a comparable behaviour is observed for the VFA characteristic. Similar performance was previously found by Mills-Beale and You (Mills-Beale and You, 2010).

The obtained results revealed that the VFA of the mixture including 0% untreated CRCA (control mix) is 72.5% which is located within the acceptable range of MTO standards, referring to a successful control mix for this volumetric property. With untreated CRCA addition, the outcomes revealed that the behaviour of VFA was inconsistent, depending on the CRCA type.

The percentage of VFA gradually decreases to reach 70.8% for the mixture that included 15% untreated CRCA#1. Then, the VFA value remained approximately stable, indicating there was no influence when untreated CRCA#1 increased to 30%. As the behaviour of VFA is directly related with the VMA property, comparable behaviour for these properties is usually obtained. This consequence is widely acceptable in the relevant literature. While the behaviour of VMA is fully elucidated in the previous section, there is no need to repeat the same clarification. Compared to the untreated CRCA addition of 0%, there is an important increase in the VFA property for the mixture which included 60% untreated CRCA#1. It is interesting to note that the VFA percentage is increased to reach 74.8%; that approximately represents the top limit of acceptable range of this property within MTO specifications. This indicates two factors: a significant positive impact of high proportions of untreated CRCA addition on this property is found; the maximum allowable proportion of untreated CRCA in the mixture appears to be approximately 60%. Due to obtaining an optimum regression value, it is noteworthy that the VFA values and different proportions of untreated CRCA#1 are strongly related. A polynomial equation perfectly describes the behaviour of the relationship between the two above-mentioned.

In terms of untreated CRCA#2 addition, the percentage of VFA gradually decreased when CRCA#2 percentage was increased to reach 70.0% for the mixture that included 60%. This behaviour contrasts with the VFA value of the mixtures that include 60% untreated CRCA#1. As mentioned previously, as the behaviour of VFA is directly related with the VMA property, a comparable behaviour for these properties was usually obtained. An exponential equation completely describes the behaviour of the relationship between VFA and different proportions of untreated CRCA#2, which clearly indicates a strong relationship.

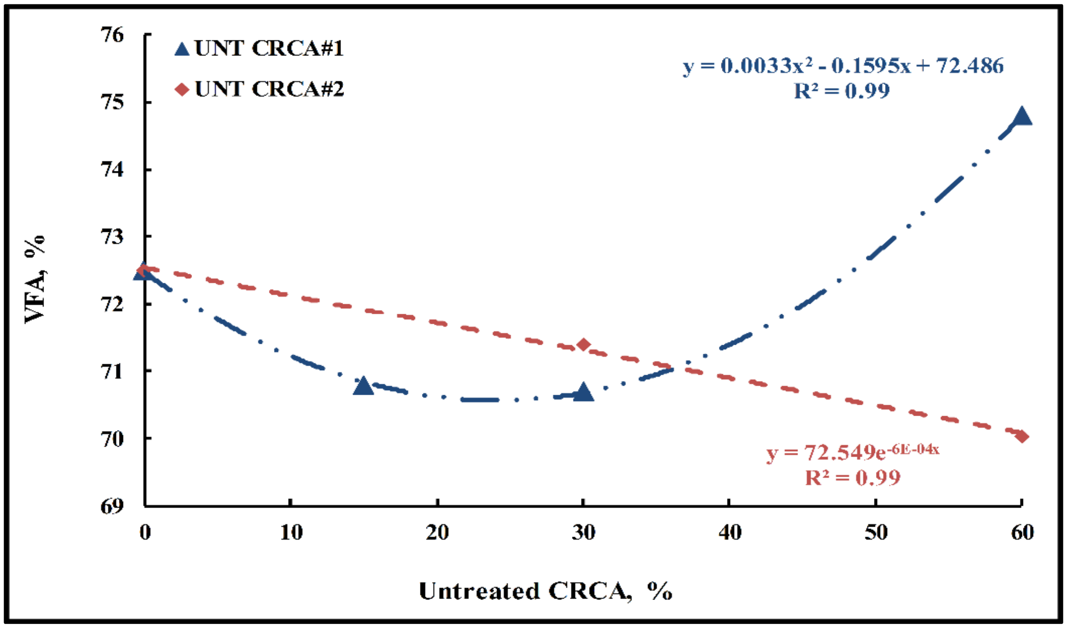


Figure 11.7: Behaviour of VMA for mixtures including different types and proportions of untreated CRCA.

To obtain further clarification, experimental results are assessed through comparison with previous studies. Compared to some available investigations of RCA literature, Figure 11.8 interprets the relation between two volumetric properties, namely, VFA and OAC. It is demonstrated that both of NA and RCA have different VFA values. However, NA seems to have a wider extent, ranging between approximately 60%-97%, as compared to the RCA domain that ranged between 65%-75%. For both CRCA types, it is noteworthy that very little improvement, essentially negligible, in the VFA values is recorded for mixtures that included 30% treated CRCA with different treatment approaches compared to the mixture with 30%

untreated CRCA. Though a considerable improvement in CRCA characteristics is obtained, the VFA values for the CRCA treated with different combinations of approaches are approximately close to the control mix value. This indicates that there is no significant influence of various treatment approaches on this volumetric property. More importantly, the VFA values of the mixtures including treated CRCA are within the acceptable range of MTO specifications. Like VMA behaviour, the values of VFA through adding different proportions of untreated CRCA and OAC property are highly related due to obtaining a significant regression. A polynomial equation evidently describes the relation between the above-mentioned volumetric properties for CRCA#1, whereas a liner equation completely reflects the relation between the same volumetric characteristics for CRCA#2.

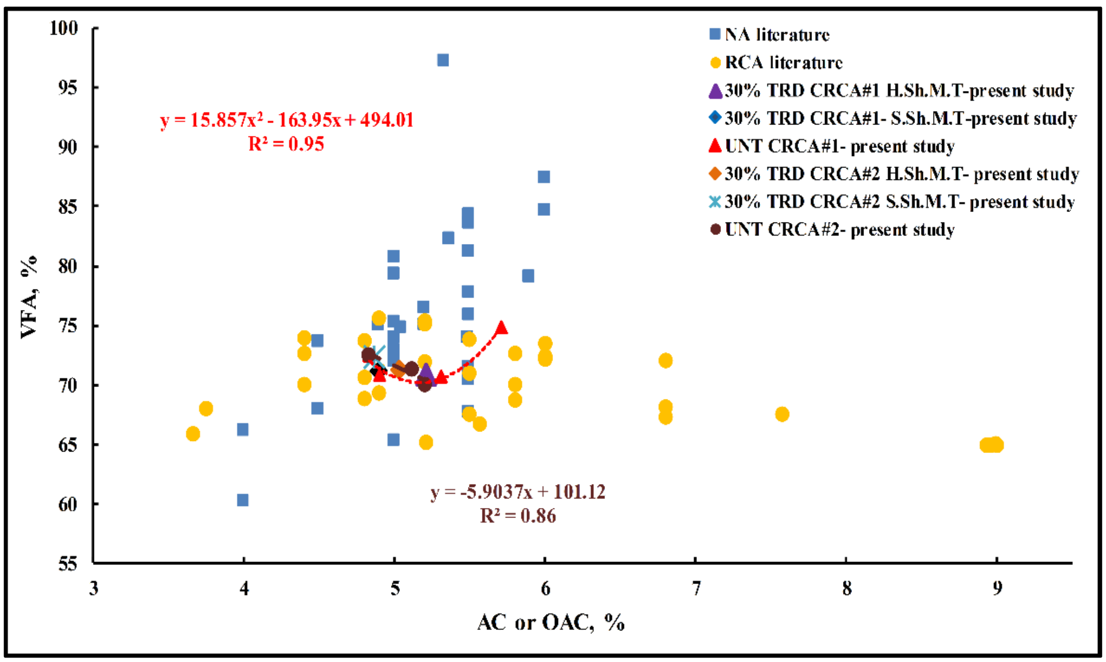


Figure 11.8: Obtained results in terms of VFA and AC or OAC as compared with some available RCA literature.

11.4.5 Maximum Theoretical Specific Gravity (G_{mm}) & Bulk Specific Gravity (G_{mb})

It is generally known that G_{mm} simply refers to the ratio of the mass of the asphalt and aggregate mixture to the volume that does not include the air voids, whereas G_{mb} generally indicates the ratio of the mass of the asphalt and aggregate mixture to the volume that includes the air voids. Figure 11.9 illustrates the behaviour of properties G_{mb} and G_{mm} in the mixtures that included different untreated CRCA types with various proportions. It is noteworthy that the mixtures that included both CRCA types have the same trend and behaviour in terms of G_{mb} and G_{mm}. As the proportion of untreated CRCA addition increases, both G_{mb} and G_{mm} of the mixes are decreased. Comparable behaviour was obtained by a previous investigation (Bhusal et al., 2011). It is important to mention that there are no specific limitations for these properties within MTO standards. Due to obtaining an optimum regression, it is concluded that there is a strong correlation between the values of both G_{mb} and G_{mm} and the proportions of untreated CRCA. For both CRCA types, Exponential equations completely interpret the behaviour of the relationship between the above-mentioned characteristics. Additionally, it is observed from the Figure 11-9 that the G_{mm} and G_{mb} of the mixtures that included CRCA#2 have a higher value than the mixtures that included CRCA#1 for the same proportion. This could be attributed to the lower amount of adhered mortar attached to the CRCA#2 surface, which leads to a higher density.

Compared to the mixture with 30% untreated CRCA, it is also observed that an insignificant increase in both of G_{mb} and G_{mm} properties is obtained for mixtures that included 30% treated CRCA#1 and CRCA#2 with various treatment approaches. This behaviour is recorded for both CRCA types. Due to the influence of the combination of heat and short mechanical treatment, the values of G_{mb} and G_{mm} increased to 2.39 and 2.49 from 2.37 and 2.47, respectively for mixtures that included CRCA#1 and from 2.38 and 2.48 increased to 2.39 and 2.49, respectively for mixtures that included CRCA#2. This indicates a small impact of this treatment approach on the above-mentioned characteristics, whereas the integration between soaking in weak acid and the same mechanical treatment has a very small influence for both CRCA types, essentially negligible, on these volumetric properties as shown in Tables 11-4 and 11-5.

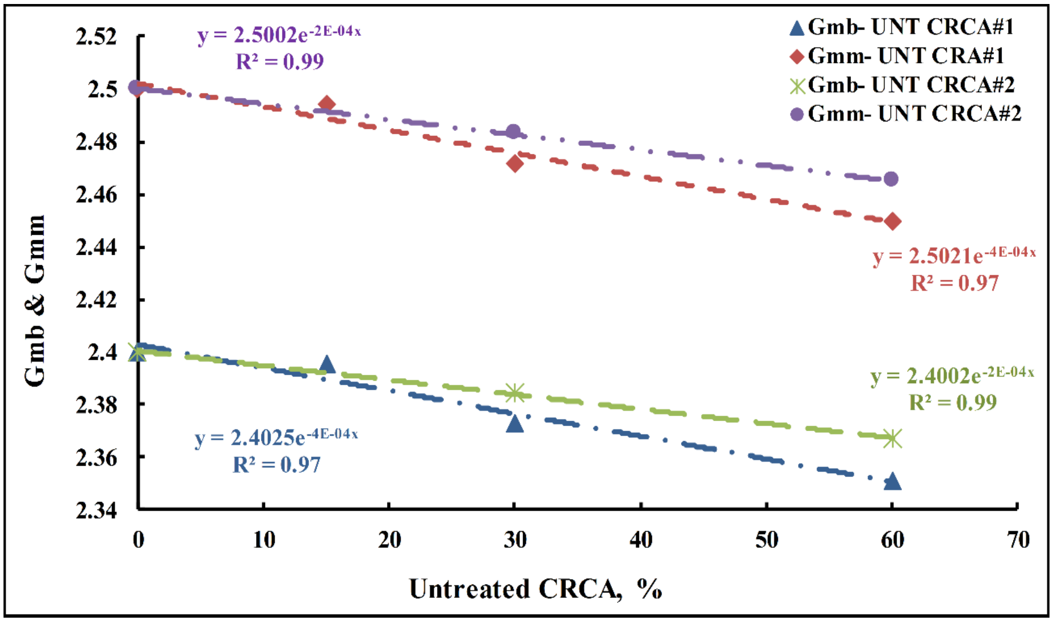


Figure 11.9: Behaviour of G_{mm} and G_{mb} for mixtures including different types and percentages of untreated CRCA.

11.4.6 Dust to Binder Ratio (Dp)

Dp ratio (also known as the dust proportion) that represents another mixture design criterion. Dp can be defined as the ratio of aggregates expressed as a percent by weight that can pass through the 0.075 mm sieve (#200) to the effective asphalt content or optimum asphalt binder accounted as a percentage by weight. Laboratory findings demonstrated that the Dp property of the mixture including 0% untreated CRCA (control mix) is 0.6 which represents the lower limit of the acceptable range of MTO standards. This indicates that a successful control mix for this volumetric property is obtained. As other volumetric properties, the behaviour of this volumetric property is different based on the CRCA type. With untreated CRCA#1 addition, the Dp ratio gradually increases to reach 0.63 and 0.74 for the mixtures including 15% and 30% untreated CRCA. This increase results in a small influence of untreated CRCA#1 addition at lower proportions on this characteristic. These results could be explained by an increase in CRCA percentages, leading to an increase in the absorbed asphalt binder (Pba), resulting in decreased the effective asphalt binder (pbe), thus the Dp ratio increased. However, the values of the Dp ratio are located within the acceptable limits that ranging between 0.6-1.2. It is interesting to note that the Dp value for the mixture including 60% untreated CRCA#1 is comparable to the control mix, indicating an important decrease for this volumetric property. Based on this, a negative impact for the higher percentages of untreated CRCA#1 addition on the Dp ratio is found This behaviour could be confirmed by the use of weak aggregate that can be easily disintegrated because the compaction during the mix design process results in an increasingly fine aggregate. This increase possibly makes asphalt binder content higher than usual (Bhusal et al., 2011; Afaf, 2014). Experimental findings strongly support this through an important increase in the OAC property from 5.31% to 5.71% when untreated CRCA proportion reached 60%.

Thus, the effective asphalt content (Pbe) increases, which results in a reduction of the Dp ratio. This result completely agrees with the VMA results. Due to obtaining a high regression value, the results indicated that the Dp values and different proportions of untreated CRCA#1 are highly related. A polynomial equation completely reflects the conduct of the relation between the two above-mentioned variables. Meanwhile, with untreated CRCA#2 addition, the ratio of Dp gradually increased with increasing CRCA#2 percentage to reach 0.8 for the mixture that included 60%. This behaviour contrasts with the Dp ratio of the mixtures that include 60% untreated CRCA#1. This could be further confirmed as mentioned earlier; by increasing RCA proportions, the Pbe is decreased, resulting in an increase in the Dp ratio. An exponential equation completely describes the behaviour of the relationship between Dp and different proportions of untreated CRCA#2 which clearly indicates a strong relationship.

It is noteworthy that the Dp values for the mixtures that included 30 % untreated and treated CRCA with different combination approaches approximately similar values for both CRCA types at the same proportion. This indicates that there is no influence of various treatment approaches on this volumetric property. However, it is important to mention that the Dp values of the mixtures including different treated CRCA are within the acceptable range of MTO standards.

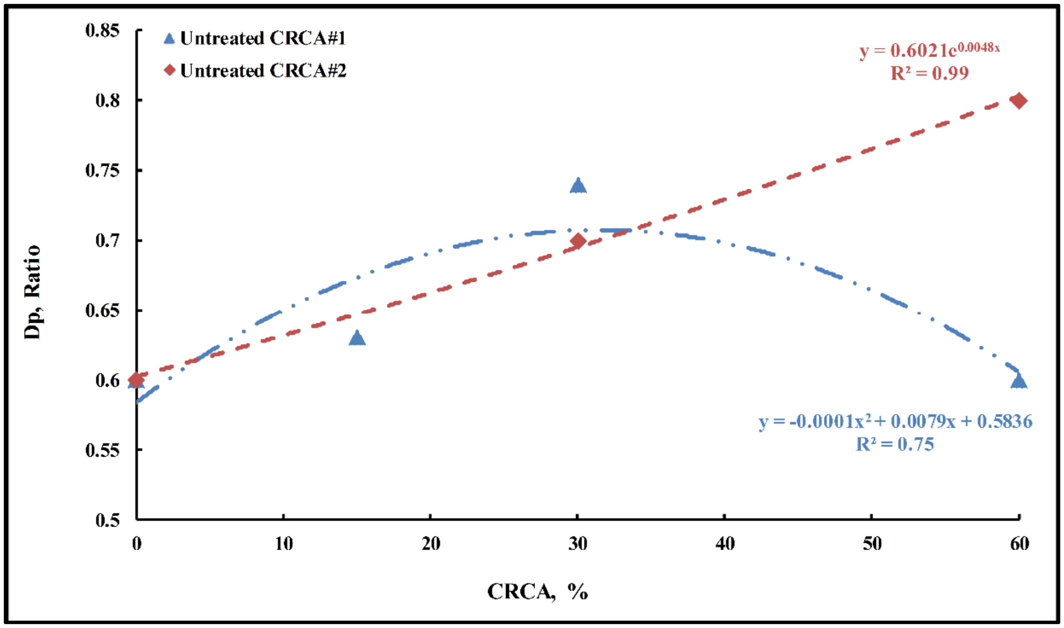


Figure 11.10: Behaviour of Dp ratio for mixtures including different types and percentages of untreated CRCA.

11.4.7 Percentage of Theoretical Maximum Specific Gravity

Further important properties of volumetric requirements are G_{mm} $N_{initial}$ (%), G_{mm} N_{des}. (%), and G_{mm} N_{max} (%). For lower proportions of untreated CRCA, the obtained findings indicated that the values of these properties are close to the required MTO standards, namely, ≤ 89, 96, and ≤ 98. This conduct was recorded for both CRCA types. Though the proportion of untreated CRCA reached 60%, the values of the volumetric properties mentioned above remain approximately constant, resulting in no influence of higher proportions of untreated CRCA on these properties. For all CRCA types, it is interesting to note that the values of above-mentioned properties for the mixtures that included 30% treated CRCA with different combination approaches remain approximately constant and close to the control mix. This indicates that there is no influence of various treatment approaches on these volumetric properties. However, it is important to mention that the values of the mixtures that included different treated CRCA are within the acceptable limits of MTO specifications. The obtained results are presented in Table 11-4 and Table 11-5.

11.5 Evaluation of Mixture Design with CRCA Addition

The previous laboratory findings emphasized that the addition of different CRCA types with various proportions is considerably successful for both untreated and treated CRCA due to successfully achieving all MTO requirements for volumetric properties of HMA. However, treated CRCA with different treatment methods seems to be more successful than untreated CRCA application. The promising obtained results release the restrictions of RCA applications and give a strong indication of the possibility of using RCA in HMA.

11.6 Summary of This Chapter

This chapter is conducted to evaluate the influence of CRCA on the volumetric properties of HMA. Based on the outcomes, the chapter findings are summarized as follows:

- For lower proportions of CRCA addition; namely, 0% and 15%, one trial was needed to achieve MTO requirements, whereas two trials were required for the higher proportions of CRCA#1 addition (30% and 60%).
- The mixed blend included 30% treated CRCA with both heat treatment and soaking in weak acid solution, then followed by short mechanical treatment was similar to the satisfied mix blend that included 30% untreated CRCA.
- The NA replacement by CRCA leads to increasing the OAC of mixtures. However, the percentage of increased OAC is highly related to the RCA type.
- Compared to the mixture that included untreated CRCA, the findings demonstrated that there is an important reduction in the OAC of mixtures that included treated CRCA with various types of combination techniques. This behavior is registered for both CRCA types. However, the type of the combination approach has a considerable impact on the percentage of the reduction.
- Regarding the VMA property, the outcomes revealed that the behavior of VMA through the untreated CRCA addition was inconsistent depending on the CRCA type.
- Compared to the mixture that included 30% untreated CRCA, small improvements in VMA and VFA properties were observed for mixtures that included 30% treated CRCA with different treatment techniques.

- The mixtures that included both CRCA types have exhibited the same trend and behavior in terms of G_{mb} and G_{mm}. As the proportion of untreated CRCA addition increases, both G_{mb} and G_{mm} of the mixes are decreased.
- It is observed that insignificant increases in both G_{mb} and G_{mm} properties are obtained for mixtures that included treated CRCA with various treatment methods compared to the mixture that included untreated CRCA.
- In terms of Dp ratio, the laboratory results revealed that the behavior of Dp is inconsistent depending on the type of CRCA through the untreated CRCA addition. Additionally, there is no influence of various treatment approaches on this volumetric property.
- The findings indicated that the CRCA addition with different proportions is very successful for both untreated and treated CRCA due to achieving all Ministry of Transportation Ontario (MTO) requirements for volumetric properties of HMA. However, CRCA treated with various treatment methods appears to be more successful than untreated CRCA application.

CHAPTER 12
INVESTIGATION OF THE EFFECT OF RECYCLED CONCRETE AGGREGATE ON RUTTING AND STIFFNESS CHARACTERISTICS OF HMA

In this chapter, part of the results of CRCA#1 have been presented at the Transportation Association of Canada (TAC) Conference (Al-Bayati and Tighe, 2018) while the other part of CRCA#1 result has been presented at the Canadian Technical Asphalt Association (CTAA) Conference (Al-Bayati and Tighe, 2018). The obtained findings of CRCA#1 and CRCA#2 have been presented at the Transportation Research Board (TRB) conference (Al-Bayati and Tighe, 2019). These outcomes were then published in the Journal of Materials in Civil Engineering (Al-Bayati and Tighe, 2019).

12.1 Introduction

One of the critical issues concerning HMA pavement performance is the manifestation of rutting from repeated traffic loads (Golalipour et al., 2012; Moghaddam et al., 2014). Rutting is the accumulation of permanent deformations resulting from the passing of heavy vehicles, which is observed as longitudinal depressions along the road surface (Gul, 2008).

It is known that pavement rutting represents one of the serious types of asphalt road distress (Gul, 2008; Walubita et al., 2012; Zhang et al., 2015; Oufa & Abdolsamedb, 2016) that can influence the safety of the road and quality of ride, especially when its depth reaches critical values (Walubita et al., 2012; Zhang et al., 2015; Oufa & Abdolsamedb, 2016). The presence of rutting on flexible pavement layers has always been a problem adversely affecting the performance of pavements. Further, the decreased thickness in the rutted portions may accelerate fatigue cracking (Oufa & Abdolsamedb, 2016). Permanent deformation could possibly exist in the HMA layers or underlying asphalt layers (Walubita et al., 2012; Zhang et al., 2015; Oufa & Abdolsamedb, 2016). Three main reasons can lead to the existence of rutting in the asphalt pavements, including i) permanent deformation in the subgrade layer, ii) permanent deformation is accumulated in the HMA layer(s), iii) and surface wearing due to studded tires. However, permanent deformation could occur under the influence of all the above-mentioned causes (Gul, 2008; Subrahmanyam et al., 2016).

Figure 12.1: Rutting distress in HMA pavement (Pavement Interactive, 2008).

Permanent deformation in asphalt pavement basically depends on three main group of factors. The first group of factors is related to the characteristics of the asphalt mix such as aggregate characteristics, gradation, asphalt binder stiffness, design methodology, asphalt binder type, and the degree of asphalt mix compaction. The second main group of factors is not associated with the HMA mix properties and includes the pavement temperature, axle loading, lateral wander of traffic, tire type, tire pressure, axle configuration, vehicle type, vehicle speed/stop, etc. The other important group of factors is related to the properties of the road substructure such as the thickness of layers, materials quality of the base and subbase layers, and the bearing capacity of the subgrade (Gul, 2008; Golalipour, et al., 2012; Ngxongo & Allopi, 2017). Of all the above-mentioned factors, the characteristics of the aggregates has perhaps the greatest effect on the occurrence of rutting. This fact was confirmed by many researchers (Gul, 2008; Golalipour, et al., 2012). The major aggregate-related mechanisms that are behind permanent deformation in asphalt pavement include: i) the reduction of friction between aggregates coated with asphalt binder, ii) loss of interconnection between aggregates particles, resulting in pushing the aggregates away from each other and increasing air voids in asphalt mixtures, and iii) loss of adhesion between aggregate and asphalt binder in asphalt mixture (Huang et al., 2009; Ngxongo & Allopi, 2017).

12.2 Previous Related Studies

Many researchers have investigated the effect of using RCA in various proportions ranging between 25% to 100% on the permanent deformation and the stiffness of HMA mixtures. The outcome of these studies revealed that an increase in the RCA proportion leads to an increase in the resistance to permanent deformation of the asphalt mixtures, leading to greater enhancement of the rutting resistance. In contrast, Beale and You (2010) found that an increase in RCA percentage results in an increase in the permanent deformation rate. Additionally, the obtained indicated that the dynamic stiffness of the mixtures is increased with decreasing ratios of RCA and test temperature influenced the resilient modulus more than the effect of RCA percentages. Pérez et al. (2009) evaluated the resistance of asphalt mixtures that included RCA with NA aggregate with respect to fatigue cracking and dynamic stiffness. The findings of the study revealed that the mixture that included RCA had a higher dynamic modulus than mixtures without RCA even if a large amount of bitumen is used. Wong et al. (2007) reported that there is no considerable effect of a filler obtained from RCA on the stiffness and permanent deformation of asphalt mixtures. Gul & Guler (2014) studied the effect of various proportions of RCA (0%, 25%, 50%, and 75%) as a fine and coarse aggregate on the rutting susceptibility of asphalt mixtures. Rutting susceptibility of the asphalt mixtures that included RCA was investigated under repeated creep tests. The obtained results showed that the mixtures that included a fine-graded RCA have a better resistance to permanent deformation than the mixtures that included a coarse-graded form, regardless of the RCA percentage and method of evaluation used. In terms of RCA content, the outcomes of their study demonstrated that an increase in the RCA percentage enhances the permanent deformation resistance of the mixtures that included coarse RCA, whereas the mixtures that included fine RCA exhibited the opposite behaviour. The application of coarse RCA leads to enhanced resistance of permanent deformation of asphalt mixtures even with the use of higher RCA proportions (80% or 100%) (Zhu et al., 2012; Wu et al., 2013). On the other hand, Arabani et al. (2013) found that the control mixture (0% RCA) is more stable than the mixtures that included coarse RCA. Additionally, Perez et al. (2012) obtained a similar conclusion for the mixtures that included coarse RCA with a proportion of up to 40%. It can be stated that most of the previous research has focused on the effect of untreated RCA on the permanent deformation of HMA mixtures. None of the above-mentioned investigations considered the effect of treated RCA on the permanent deformation resistance of asphalt mixes.

12.3 Evaluation of Permanent Deformation

The obtained results in the wheel tracking test represent the relationship between the accumulative asphalt mixture deformation in terms of rutting depth and the number of cycles for different cases as revealed in Figures 12.2 to 12.5. As generally expected, the permanent deformation of asphalt mixtures increases with increasing number of cycles (Pasandín & Pérez, 2013). For all cases, it is important to mention that the worst permanent deformation is observed for the control mixture (0% CRCA) among various rutting values. This indicates that the adhesion between CRCA and asphalt binder is higher than the adhesion between the same asphalt binder and NA. This type of behaviour could be explained by noting that CRCA has a rough surface with many crushed faces. Such surface features lead to increase in the contact area between asphalt binder and CRCA and generate more abrasion force, providing a significant interconnecting force to resist the impact of wheel load on the asphalt mixture (Lee et al., 2012).

12.3.1 Effect of Untreated CRCA on the Permanent Deformation

Figure 12.2 demonstrates the influence of untreated CRCA proportion on permanent deformation. Among different proportions, the better resistance to permanent deformation was achieved by the mixtures that included 30% untreated CRCA#1, indicating an important enhancement in the rutting resistance. The results also showed a slight difference in the resistance to permanent deformation of the asphalt mixtures when the proportion of CRCA was increased from 15% to 60%. This results in little impact of the CRCA proportion on the permanent deformation of the asphalt mixture. However, there are two possible reasons behind this. It is generally known that as asphalt content of a mixture increases the CRCA percentage is increased. Firstly, a high asphalt content can provide a higher plastic flow susceptibility. Due to high asphalt content, the high plastic susceptibility can lead to losing the internal friction among aggregate particles. Hence, the wheel loads are carried and resisted by asphalt content only instead of the structure aggregate particles, resulting in an increase in the permanent deformation of the asphalt mixture (Shen & Du, 2004). Secondly, a high proportion of CRCA in the mixture (60% untreated CRCA#1), which leads to a high adhered mortar loss under the impact of compaction of wheel loads, resulting in a poor adhesion between the CRCA particles and asphalt binder. However, due to a significant improvement in the permanent deformation resistance, the use of untreated CRCA in various percentages results in its successful utilization in HMA mixtures compared to the mixtures that included NA. These results were confirmed by previous investigations (Paranavithana & Mohajerani, 2006; Lee et al., 2012; Gul & Guler, 2014).

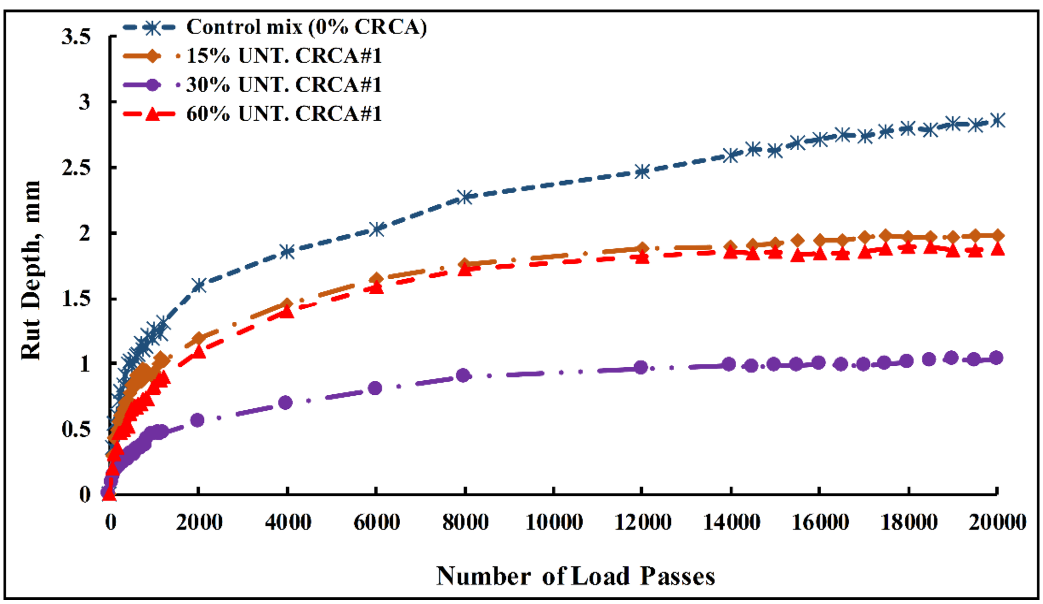


Figure 12.2: Influence of untreated CRCA proportion on the permanent deformation of asphalt mixtures.

Figure 12.3 shows the effect of CRCA types with various proportions on the permanent deformation. For the mixtures that included 30% untreated CRCA, the outcomes showed that the mixtures that included CRCA#1 exhibit a better resistance to permanent deformation than the mixtures that included CRCA#2. This could be because CRCA#1 has a rougher surface with many crushed faces as compared to untreated CRCA#2 due to the more attached adhered mortar. These results confirm the findings of the adhered mortar percentage as previously shown in Table 1. In contrast, the mixtures that included untreated CRCA#1 up to 60% registered a lower resistance to permanent deformation than the mixtures that included the same proportion of untreated CRCA#2. As mentioned earlier, the reason behind this behaviour could be explained by the existence of the high proportion of CRCA in the mixture (60% untreated CRCA#1), which leads to a high adhered mortar loss under the impact of compaction of wheel loads, resulting in a poor adhesion between the CRCA particles and asphalt binder. Additionally, the results also show that a slight difference in the resistance to permanent deformation is registered when the proportion of CRCA#2 increases from 30% to 60% in the asphalt mixtures. For CRCA#2 type, these findings indicate little impact of the CRCA proportion on the permanent deformation of the asphalt mixture. The reason behind this could be attributed to the low adhered mortar content for this type of CRCA; subsequently, these results confirm the findings of the adhered mortar percentage as previously shown in Table 4-1, it could be due to the two possible reasons mentioned previously. Nevertheless, these rutting values were still lower than the control mix value.

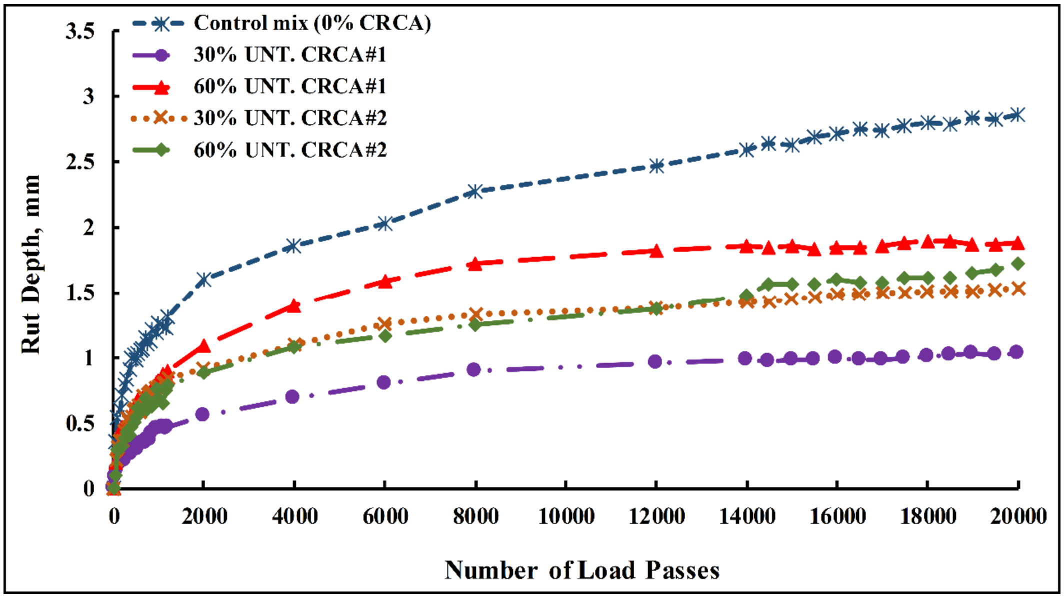


Figure 12.3: Influence of CRCA on the permanent deformation of asphalt mixtures.

12.3.2 Effect of Treated CRCA on the Permanent Deformation

To evaluate the influence of the combination of different treatment approaches on permanent deformation, the average rutting depth of the mixtures that included untreated and treated CRCA for both CRCA types are presented in Figures 12.4 and 12.5. For the influence of the integration of heat treatment and short mechanical treatment, the obtained results showed that the combination of these treatments leads to a reasonable increase in resistance to the permanent deformation for the mixtures that included 30% CRCA#2 compared to the mixtures that included the same proportion of untreated CRCA#2. This indicates that the mentioned combination approach is successful for enhancing the resistance to permanent deformation. However, this behaviour was opposite to the conduct of the mixtures that included CRCA#1. The mixtures that included 30% treated CRCA#1 had much higher permanent deformation than the mixtures that included 30% untreated CRCA#1 as shown in Figure 12.4. This could be explained by the existence of a high proportion of adhered mortar attached to the CRCA#1 surface, which is more brittle under the impact of the combination of different treatments and the effect of the compaction of wheel loads, resulting in a poor adhesion between the CRCA particles and asphalt binder. Hence, it can be concluded that the type of RCA has a considerable effect on enhancing the resistance of the mixture to permanent deformation under the impact of this treatment approach.

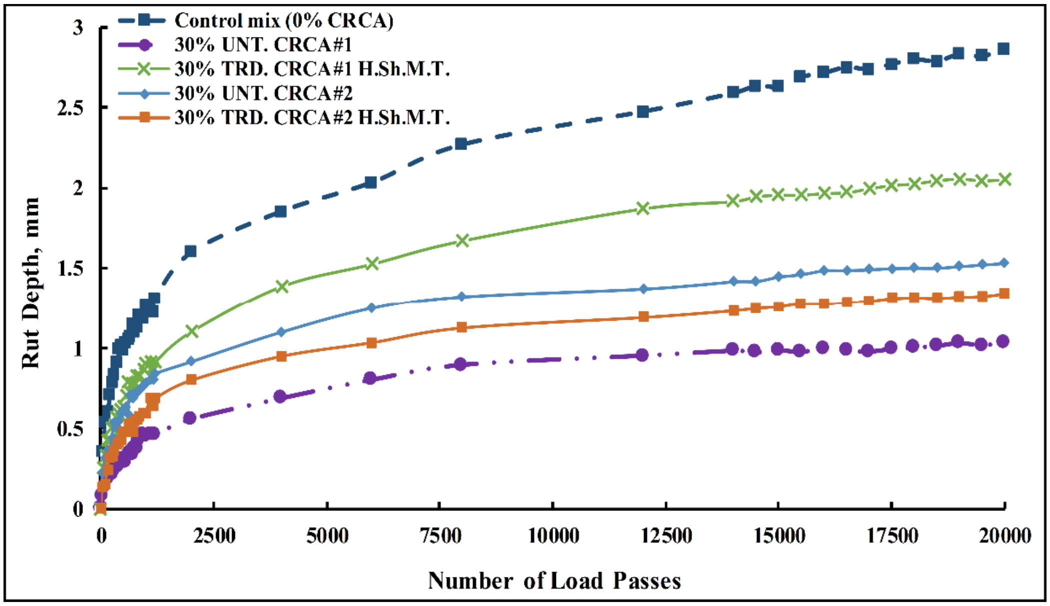


Figure 12.4: Influence of treated CRCA with heat & short mechanical treatment on the permanent deformation of asphalt mixtures.

For the combination of pre-soaking method and a short mechanical treatment, the obtained findings revealed that the mixtures that included 30% treated CRCA#1 or CRCA#2 had a lower resistance to the permanent deformation compared to the mixtures that included the same type and proportion of untreated CRCA as shown in Figure 12.5. Hence, this combination technique seems to be a less successful compared to the previous combination approach. However, the rutting values of the mixtures that included treated CRCA with different treatment approaches for both CRCA types are still lower than the permanent deformation of the control mix. It seems that these treatment techniques lead to reduced stiffness of asphalt mixtures at high temperature. Additionally, this gives an indication that various treatment methods led to an important reduction in the HMA mixture stiffness, which is a desirable property in cold regions. Furthermore, the findings refer to a successful utilization of the combination technique of different treatment methods due to significant improvement in the permanent deformation resistance. Finally, this gives a good indication to the possibility of using CRCA in HMA applications especially in the hot weather and using the treatment methods for RCA applications in cold regions.

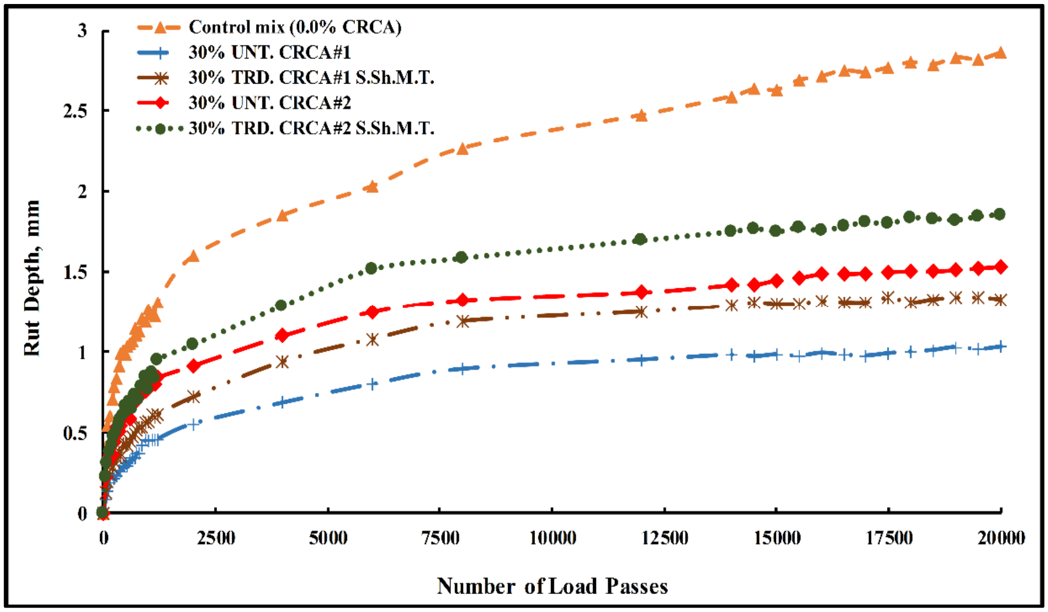


Figure 12.5: Influence of treated CRCA with soaking & short mechanical treatment on the permanent deformation of asphalt mixtures.

12.4 Evaluation of Shear Flow of HMA Mixtures

12.4.1 Influence of Untreated CRCA on Shear Flow

To compare various levels of rutting depth of mixtures that included two different types of untreated CRCA with different proportions, the obtained results are presented in Figure 12.6. The outcomes revealed that regardless of CRCA type and proportion, the rutting resistance is increased for the mixtures that included untreated CRCA compared to the control mixture (0% CRCA). Again, this is because the adhesion between CRCA and asphalt binder is higher than the adhesion between NA and asphalt binder as mentioned previously. A similar trend is registered for different rutting measurement methods: HWRT, total rutting depth (manually), and shear upheave. The findings also pointed out that the mixtures that included 30%

untreated CRCA for both CRCA types have more resistance to rutting than the mixtures that included 15% and 60% untreated CRCA in terms of the total rut depth, HWRT rut depth. In terms of shear upheave height, the mixture that included 30% untreated CRCA#2 demonstrated greater resistance to rutting.

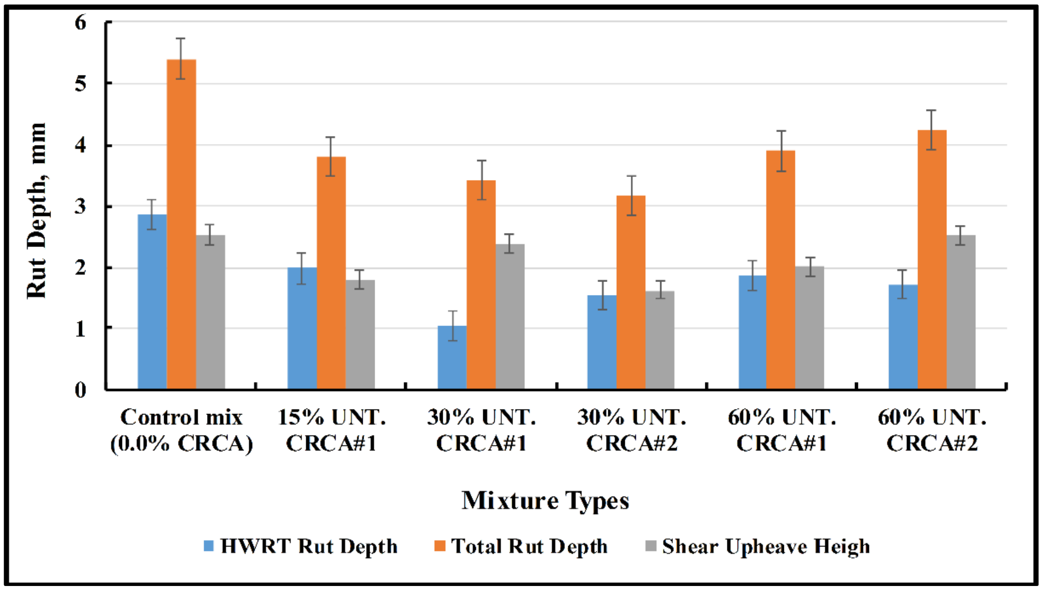


Figure 12.6: Influence of untreated CRCA types with different proportions on the shear flow of asphalt mixtures.

12.4.2 Influence of Treated CRCA on Shear Flow

To evaluate the effect of the combination of different treatment techniques on the permanent deformation of mixtures, Figure 12.7 shows the experimental results of rutting depth measured by various methods. The findings showed that the mixture that included 30% treated CRCA#2 with heat and a short mechanical treatment had more resistance to rutting than the other mixtures in terms of total rut depth. In terms of upheave rut depth, a reduction in the permanent deformation was observed for the mixture that included 30% treated CRCA#2 with the combination of weak acid treatment and a short mechanical treatment compared to other mixtures. However, there was a slight variation in the impact of treatment approaches on the rutting values depending on the type of CRCA. Generally, this behaviour indicates a successful utilization of the combination technique of different treatment methods for improving the permanent deformation resistance of asphalt mixtures. More importantly, this conduct refers to a high reliability of the use of CRCA in the HMA applications.

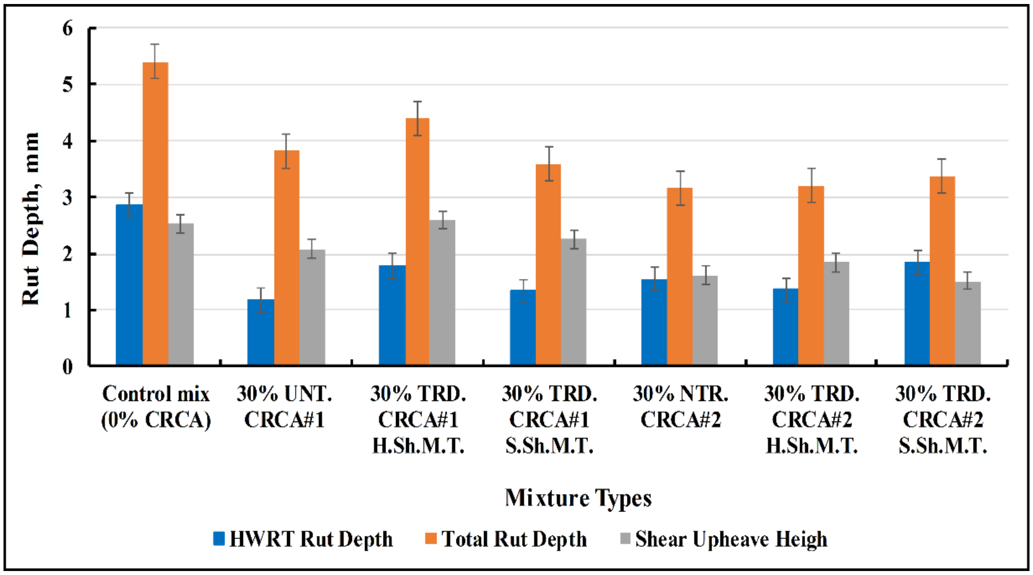


Figure 12.7: Influence of treated CRCA with different treatment methods on the shear flow of asphalt mixtures.

12.5 Effect of CRCA on the Stiffness Modulus of Mixtures

The temperature and loading rate represent the primary factors related to the stress-strain behaviour of HMA mixture. The HMA mixtures response to various temperatures and loading rates was measured by utilizing the Dynamic Modulus test. By creating a master curve, the change in asphalt binder and mixture behaviour over time can be observed. The Master curve was built up by using the principle of the time-temperature superposition. Figures 12.8 and 12.9 demonstrate the outcomes of the dynamic modulus test which is presented as a complex modulus value |E*| versus the reduced frequency. Also, these Figures show the master curves that were constructed of HMA mixtures at a reference temperature of 21 °C that included both untreated CRCA with various proportions and types and treated CRCA with different treatment methods. It can be observed that the master curves seem to be parallel to each other and the mixtures become stiffer with the addition of CRCA. Generally, the trend of the master curves was similar for all HMA Mixtures though the mentioned mixtures included different CRCA types with various proportions in the mixtures were different. The dynamic modulus trend for various mixtures demonstrated that there is a reduction in the stiffness of HMA mixtures when the temperature is increased from -10 °C to 54 °C. When the load frequency increases from 0.1 Hz to 25 Hz, the stiffness of mixtures is increased. The average stiffness modulus of all mixtures that included CRCA was higher than of the control mixture at elevated and moderate temperatures and low-frequency loading. In contrast, there was a lower stiffness modulus at a lower temperature and a high load frequency. It is important to mention that it is difficult to discover the behaviour of various mixtures at some points at specific temperatures and frequencies. Further figures have drawn to demonstrate the complex modulus (E*) for each mixture at different temperatures and frequencies.

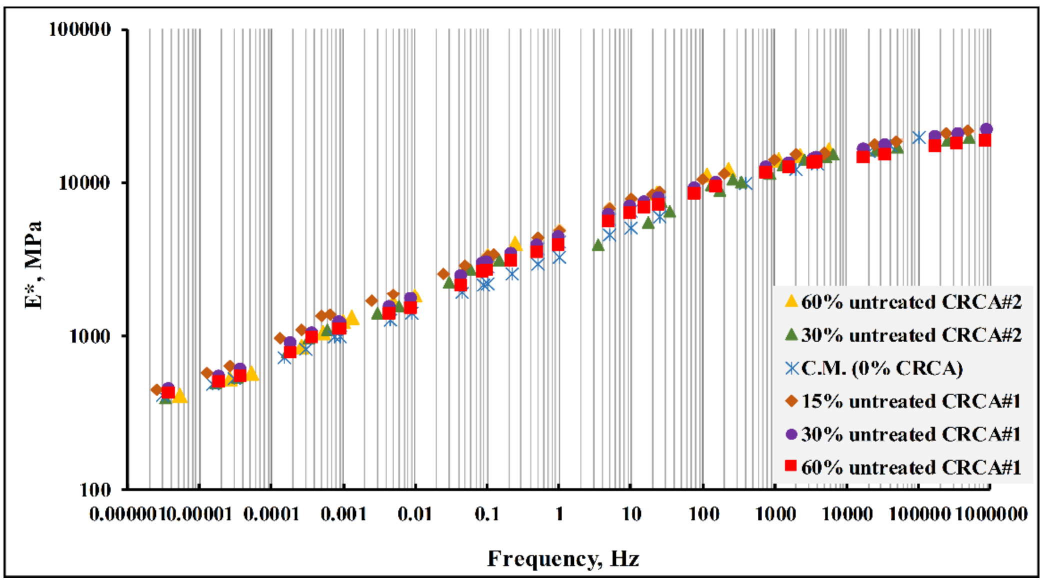


Figure 12.8: Complex modulus for asphalt mixtures including different untreated CRCA types with various proportions.

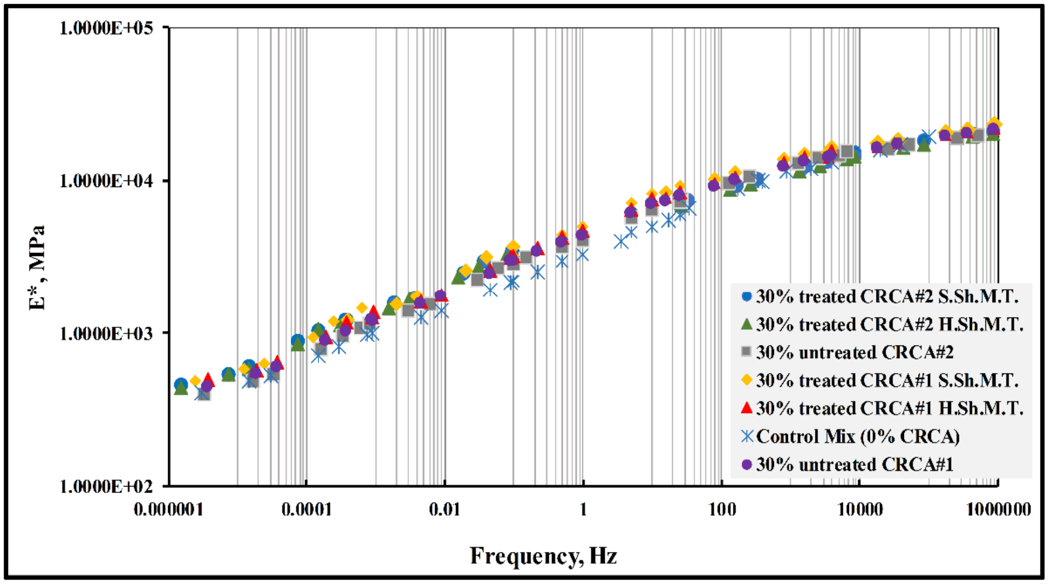


Figure 12.9: Complex modulus for asphalt mixtures including treated CRCA with different treatment approaches, various CRCA types, and different proportions.

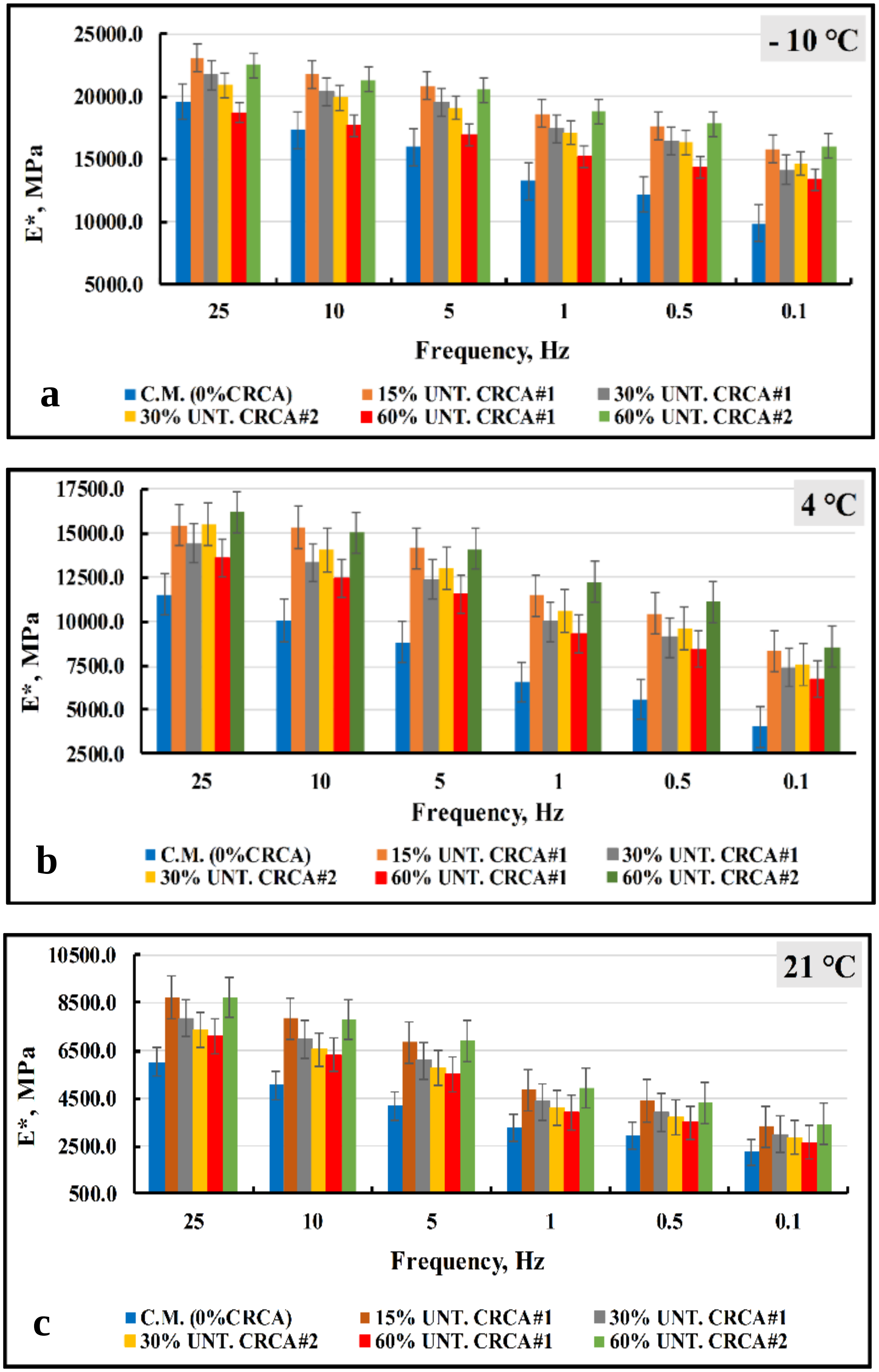
12.5.1 Effect of Untreated CRCA on the Stiffness Modulus of Mixtures

The outcomes demonstrated that the mixtures that included both treated and untreated CRCA for different CRCA types have a stiffness modulus higher than the control mix at various temperatures and frequencies. These findings confirm the HWRT results that are previously shown in Figures 12.2 and 12.3.

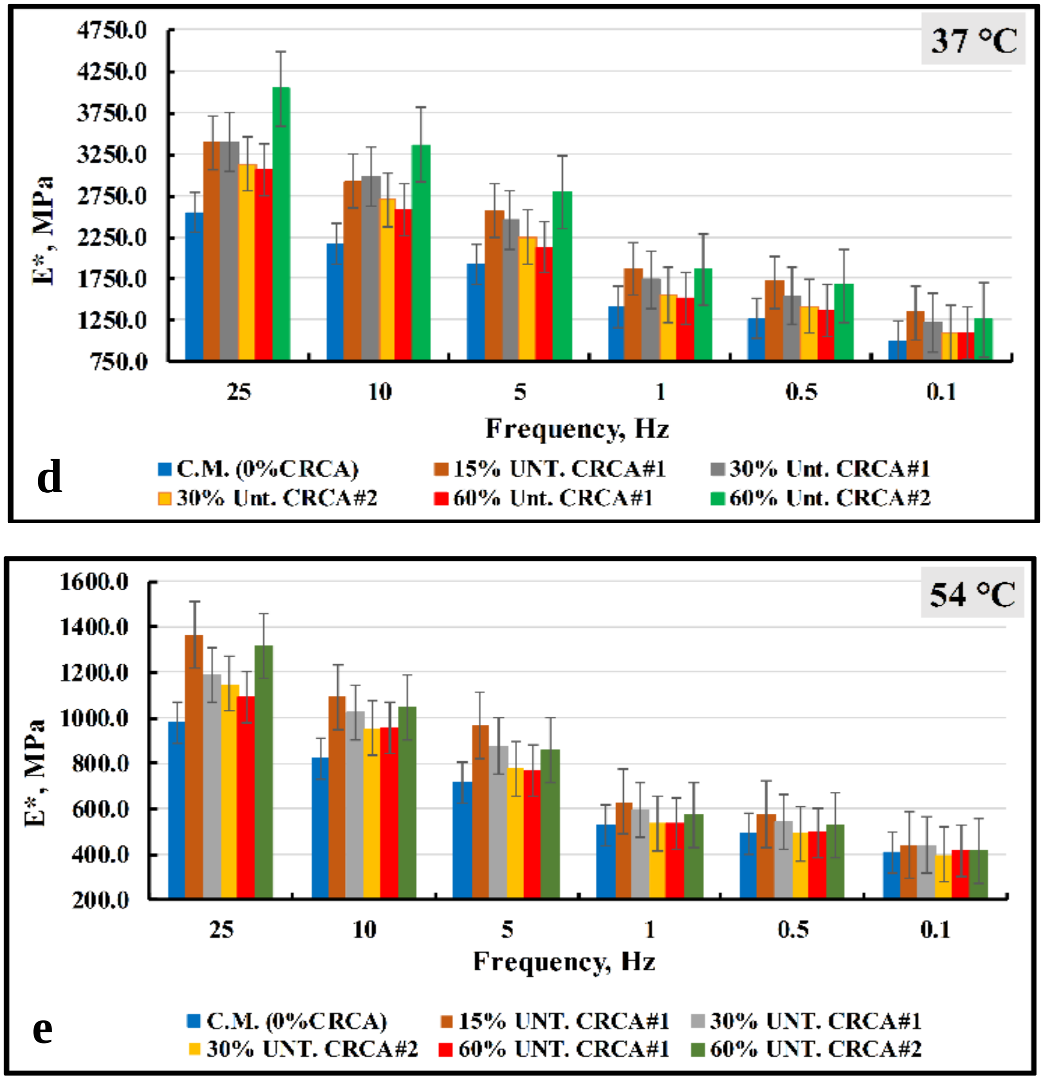
At low temperature (-10 °C), the findings revealed that there is a variation in the stiffness modulus of mixtures that included different CRCA percentages as shown in Figure 12.10. It is noteworthy that the mixture included 60% CRCA#1 has a lower stiffness than the control mix at high and moderate frequencies. This means that there is an increase in the cracking resistance of the mixture, and this will help to minimize fatigue and low-temperature cracking. However, the mixtures that included CRCA#1 up to 30% or CRCA#2 up to 60% have a higher stiffness than the control mix and this would reduce the mixtures resistance to cracking at low temperature. The main reason behind these variations is the RCA inhomogeneity and its inferior physical and mechanical properties compared with NA aggregate. More specifically, this is due to a higher porosity and a large surface area for RCA in comparison with NA. The presence of attached cement mortar leads to create various bitumen film thickness on the aggregate particles, resulting in changes in the stiffness modulus of the mixtures (Radevic´ et al., 2017). At moderate (4 °C) and elevated temperatures (higher than or equal to 21 °C), the obtained findings also showed that the utilization of CRCA with a proportion up to 60% for both CRCA types would increase the stiffness of the mixture compared with the control mixture. This behaviour will be beneficial for the high-temperature performance, which is represented by a reduction of rutting potential. These findings confirm the HWRT results that are previously shown in Figures 12.2 and 12.3.

Figure 12.10 (e) at (54 °C) generally demonstrates the results of the dynamic modulus test of HMA mixes at this temperature (54 °C), which is very close to the HWRT test temperature for all the frequencies used in the test. It is noted that the stiffness measurements for the control mixes for all the frequencies were lower than the stiffness of the mixes that included untreated CRCA, which means more rutting susceptibility. These results are completely in line with the results of the rutting tests as shown previously in Figures 12.2 and 12.3.

As seen in Figure 12.10, the results demonstrated that the mixtures that included 15% CRCA#1 and 60% CRCA#2 have a higher stiffness value compared to other mixture types. For the mixture that included 15% CRCA#1, the reason could be attributed to a lower percentage of adhered mortar compared to other mixtures. This seems to be quite reasonable, especially for the mixtures that included CRCA#1, because it was seen earlier that CRCA#1 has a higher percentage of adhered mortar than the CRCA#2. For the mixtures that included 60% CRCA#2, this behaviour could be because the adhesion between CRCA and asphalt binder is higher than the adhesion between the same asphalt binder and NA. This type of behaviour could be explained by noting that CRCA has a rough surface with many crushed faces. Such surface features lead to an increase in the contact area between asphalt binder and CRCA, and generates more abrasion force, providing a significant interconnecting force to increase the stiffness of the mixtures.



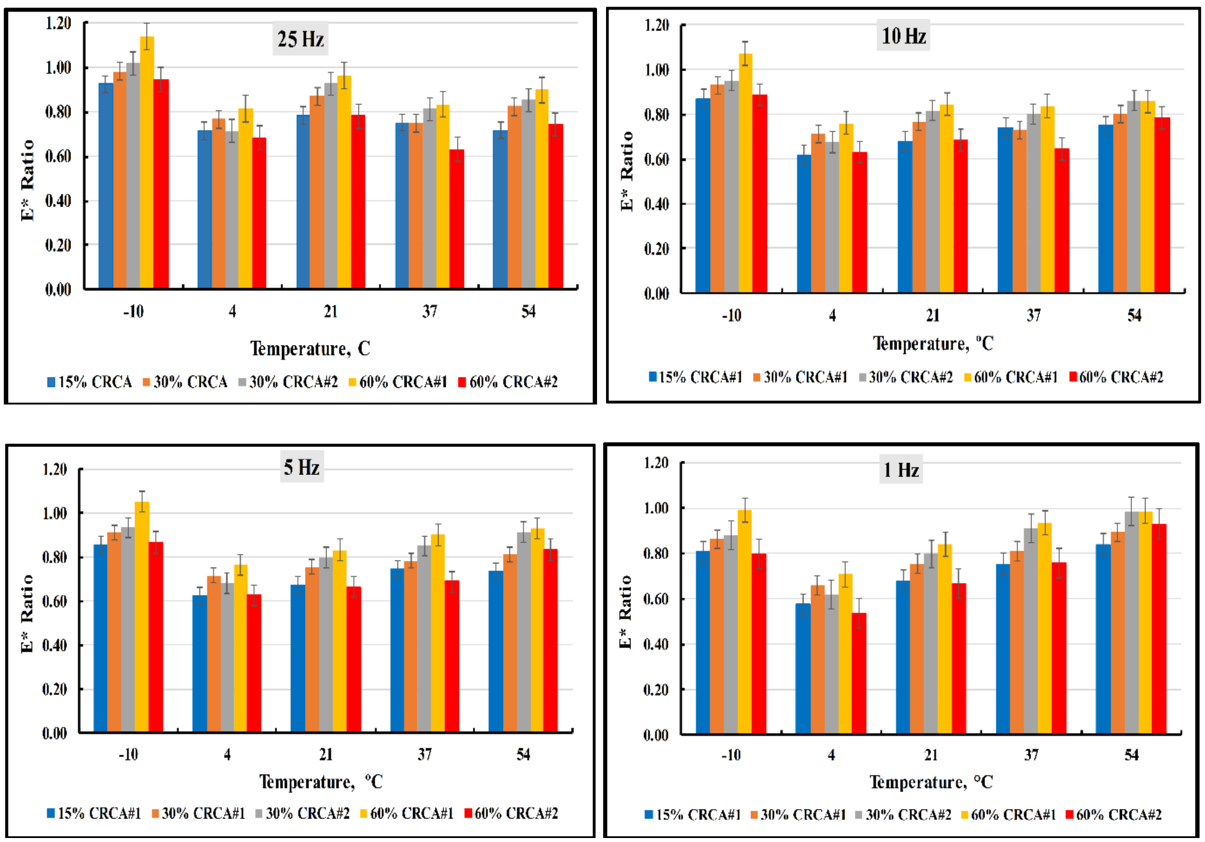
- 10 °C
25000.0
20000.0
15000.0
10000.0
5000.0
E*, MPa
25
10
5
1
0.5
0.1
Frequency, Hz
a
C.M. (0%CRCA)
15% UNT. CRCA#1
30% UNT. CRCA#1
30% UNT. CRCA#2
60% UNT. CRCA#1
60% UNT. CRCA#2
4 °C
17500.0
15000.0
12500.0
10000.0
7500.0
5000.0
2500.0
E*, MPa
25
10
5
1
0.5
0.1
Frequency, Hz
b
C.M. (0%CRCA)
15% UNT. CRCA#1
30% UNT. CRCA#1
30% UNT. CRCA#2
60% UNT. CRCA#1
60% UNT. CRCA#2
21 °C
10500.0
8500.0
6500.0
4500.0
2500.0
500.0
E*, MPa
25
10
5
1
0.5
0.1
Frequency, Hz
c
C.M. (0%CRCA)
15% UNT. CRCA#1
30% UNT. CRCA#1
30% UNT. CRCA#2
60% UNT. CRCA#1
60% UNT. CRCA#2



*UNT. = Untreated; TRD. = Treated; H.Sh.M.T.= Heat & short mechanical treatment; S.Sh.M.T. = Soaking & short mechanical treatment.

Figure 12.10: Dynamic modulus values for mixtures including different CRCA types and various proportions at different temperatures and frequencies.

To obtain a better understanding, the average |E*| ratios between the control mix and the remaining mixtures that included different untreated CRCA types with various percentages at different temperatures and frequencies were measured as shown in Figure 12.11. For all the temperatures and frequencies, the average ratios between the control mix and the mixtures that included different CRCA types and various proportions of untreated CRCA were less than 1.0, indicating that these mixtures have a higher |E*| values than the control mixture. However, it is interesting to note that the mixtures that included 60% CRCA#1 have a different behaviour at low temperature (-10 °C) and moderate and high frequencies, resulting in a higher |E*| ratio. This indicates that the mixtures that included 60% CRCA#1 have a lower modules stiffness than the control mix at low temperature and moderate and high frequencies. As mentioned previously, the mixtures that included 60% CRCA have more resistance to low-temperature cracking.



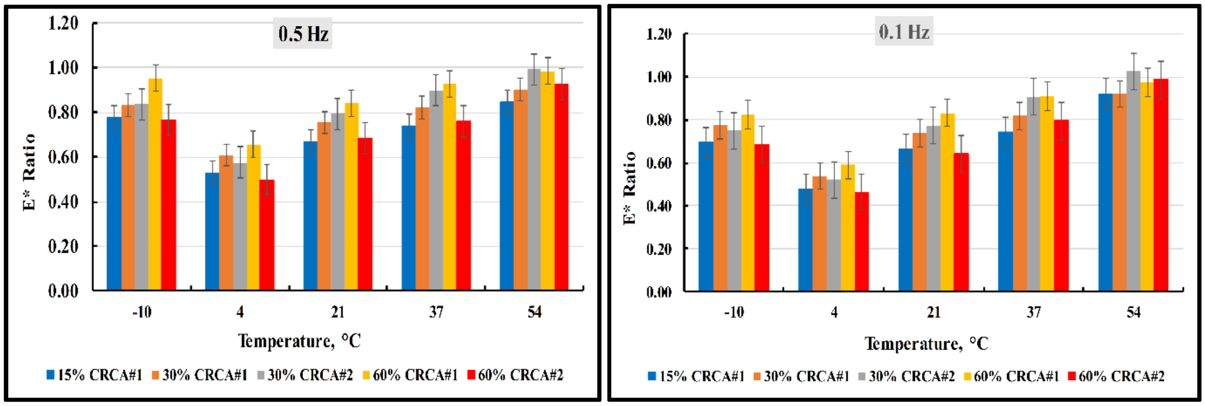


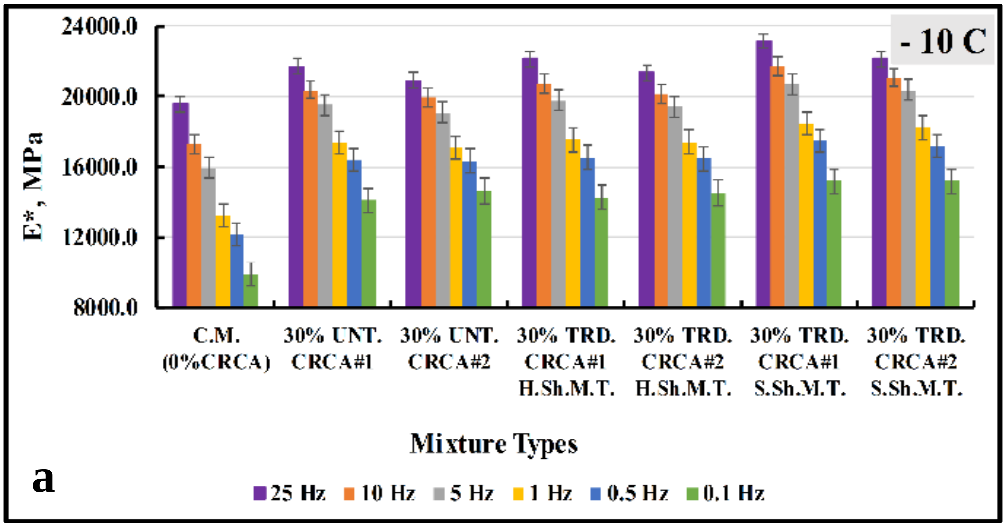
Figure 12.11: Average |E*| ratios between the control mix and the remaining mixtures.

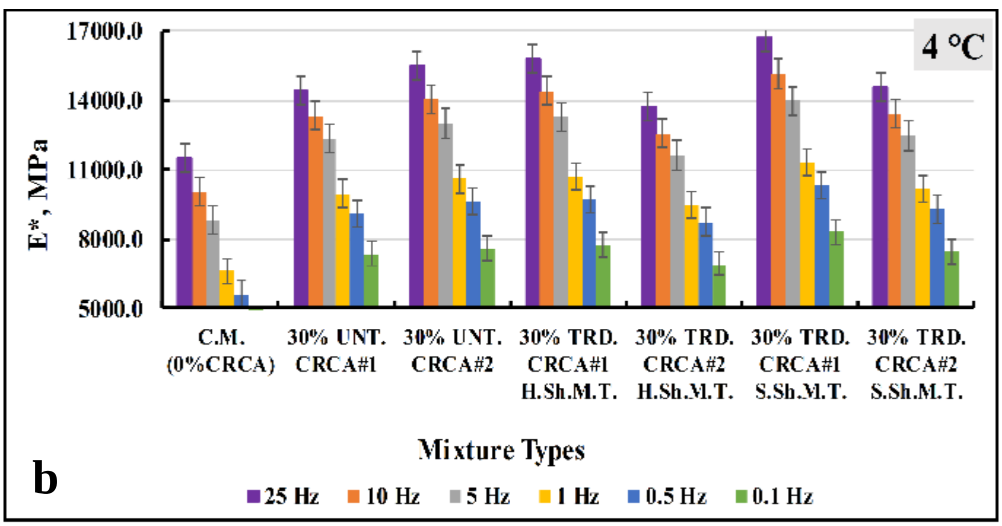
12.5.2 Effect of Treated CRCA on the Stiffness Modulus of Mixtures

Figure 12.12 presents the stiffness modulus of the mixtures that included treated CRCA with different treatment methods. The outcomes demonstrated that the mixtures that included treated CRCA for different CRCA types have a stiffness modulus higher than the control mix at various temperatures and frequencies. These findings confirm the HWRT results that were previously shown in Figures 12.4 and 12.5. In terms of the effect of treatment methods on the stiffness modulus, it is observed that the mixtures that included 30% treated CRCA#1 with pre-soaking and short mechanical treatment had the highest stiffness value among different mixtures at various temperatures and frequencies. This is followed by the mixtures that included 30% treated CRCA#1 with heat treatment and the same mechanical treatment, then the mixtures that included 30% treated CRCA#2 with pre-soaking and the same mechanical treatment. This behaviour indicates a successful utilization of the combination technique of different treatment methods for enhancing the stiffness modulus of asphalt mixtures.

In addition, Figure 12.12 (e) at 54 °C demonstrate the results of the dynamic modulus test of HMA mixes at 54 °C which is very close to the HWRT test temperature for all the frequencies used in the test. It is noted that the stiffness measurements for the control mixes for all the frequencies were lower than the stiffness of the mixes that included treated CRCA, which means more rutting susceptibility. These results are completely in line with the results of the rutting tests. Additionally, the findings revealed that the mixture that included 30%

treated CRCA#1 with the pre-soaking method and short mechanical treatment leads to a noticeable increase in the average stiffness modulus, followed by the mixture that included 30% treated CRCA#2 with the same treatment technique, then the mixtures that included both 30% treated CRCA#1 and CRCA#2 with heat treatment and short mechanical treatment.





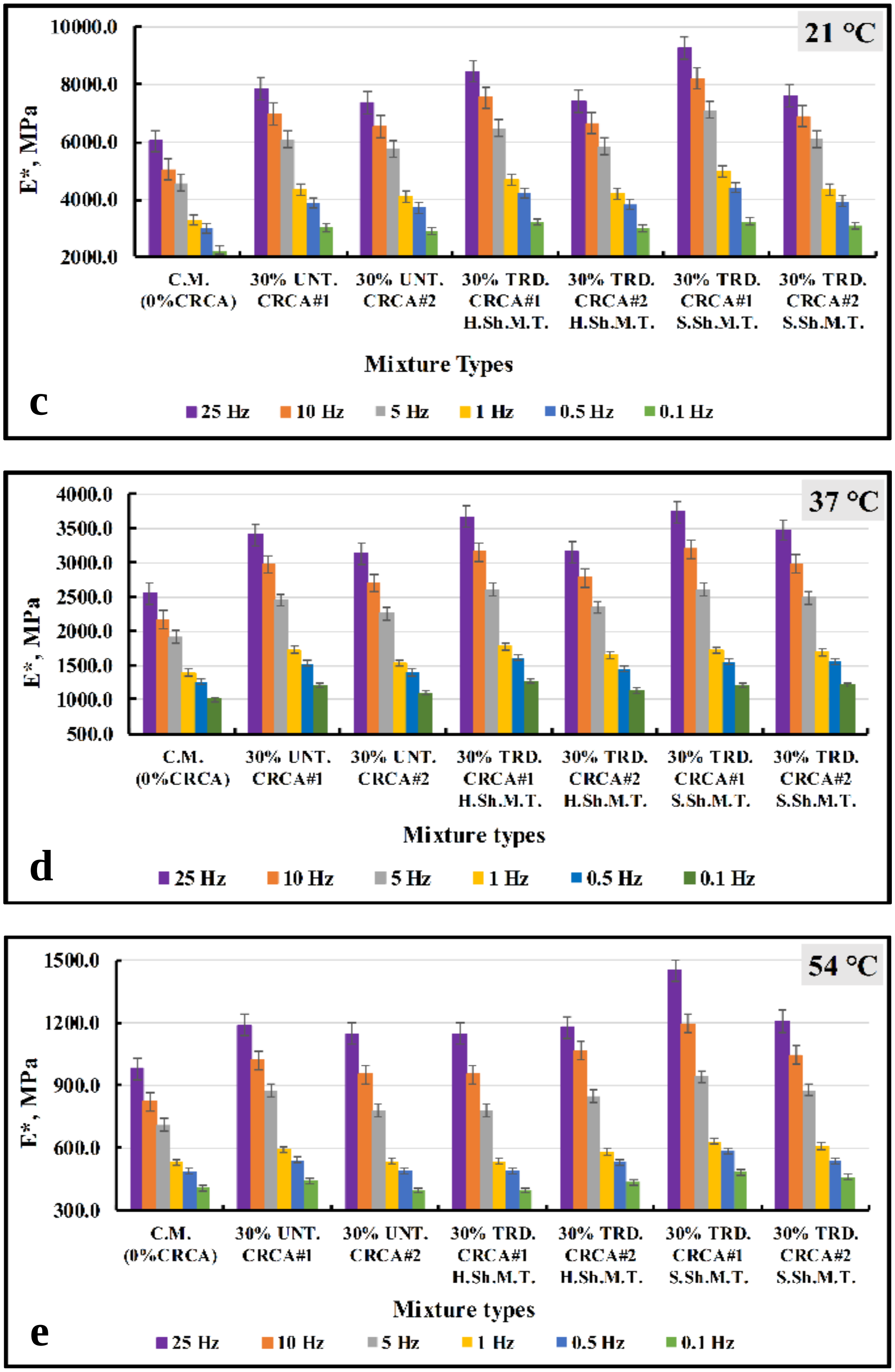


Figure 12.12: Dynamic modulus values for mixtures including different types of treated CRCA with different treatment methods at different temperatures and frequencies.

12.6 Dynamic Modulus Test for Evaluating Permanent Deformation and Fatigue Factors

This study also evaluated the rutting factor (E*/sin δ) and fatigue factor (E*sin δ) depending on the results of the dynamic modulus |E*| of different HMA mixtures at specific temperatures and frequencies.

12.6.1 Rutting Factor

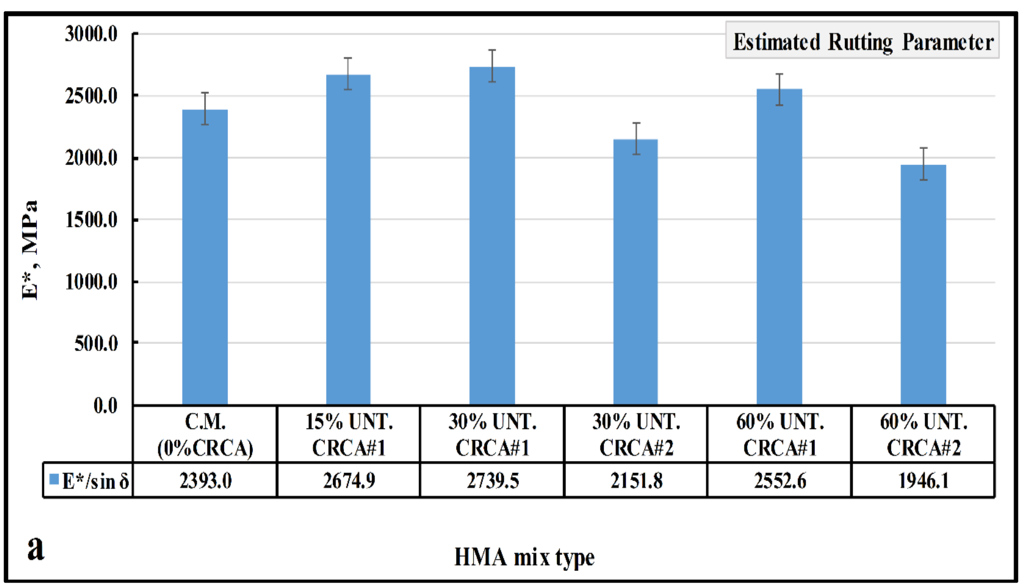
The temperature of 54 ºC and loading frequency 5 Hz were used for measuring the rutting factor (E*/sin δ), whereas the fatigue factor (E*sin δ) was computed at the 21 ºC temperature and loading frequency 5 Hz (E*/sin δ) (Witczak et al., 2002). A previous study used the data obtained at 21 °C and 10 Hz as a reference to study the susceptibility to the fatigue of HMA mixtures. The outcomes refer to mixtures sensitivity to permanent deformation (rutting) and fatigue crack. The highest value of rutting parameter (E*/sin δ) indicates a lower susceptibility of mix to the impact of rutting, whereas a lower value of fatigue factor (E*sin δ) points out to a good resistance to fatigue cracking.

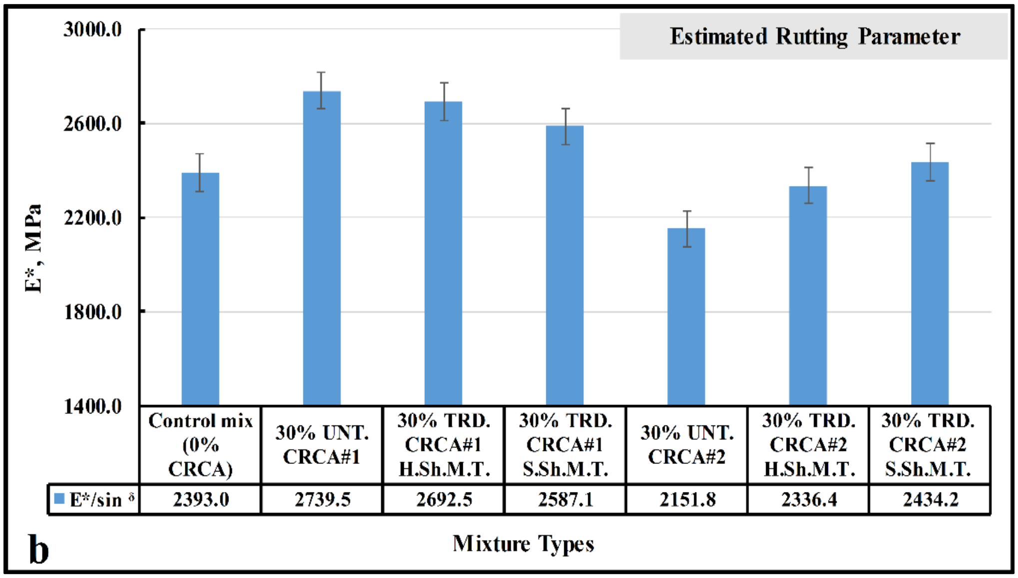
Figure 12.13 (a) demonstrates the rutting factor (E*/sin δ) of HMA mixtures that included different CRCA types and various proportions. The outcomes showed that the mixture that included 30% untreated CRCA#1 has a higher rutting factor values than other mixtures. This outcome confirms the rutting results as previously shown in Figures 12.2 and 12.3. Additionally, the outcomes showed that the mixtures that involved untreated CRCA#1 have a higher rutting factor values than the control mix. These results confirm the previous results of both |E*| and rutting that were shown in the Figures 12.2 and 12.10. This indicates that the mixtures that included untreated CRCA have a good resistance to the impact of permanent deformation under the effect of traffic and moderate temperatures. The reason behind this could be due to the RCA surface properties (i.e., rough texture, shaped particles, and sharp edges) that result in a better interaction and higher surface friction between aggregate particles (Radević et al., 2017).

The results revealed that the mixture that included 30% CRCA#1 has the highest value of rutting parameter. This is followed by the mixtures that included 15% CRCA#1 and 60%

CRCA#1, respectively. For the mixtures that included CRCA#2, the mentioned mixtures exhibit inconsistent behaviour compared to the other test results such as rutting and dynamic modulus test. The outcomes revealed that the mixtures that included CRCA#2 up to 60% have a lower rutting resistance than the control mix, which are opposite to the results of HWRT and dynamic modulus tests.

The effect of treatment methods on the rutting factor (E*/sin δ) of HMA mixtures that included treated CRCA with various treatment methods is presented in Figure 12.13 (b). The findings showed that the mixtures that included treated CRCA#1 with different treatment methods have lower rutting factor values than the mixture that included the same proportion of untreated CRCA#1. These results confirm the previous results of rut testing, which were shown in Figures 12.4 and 12.5. In contrast, there is an opposite behaviour for the mixtures that included CRCA#2. The outcomes demonstrated that the mixtures that included treated CRCA#2 with both types of heat treatment and soaking followed by short mechanical treatment have a higher rutting factor than the mixtures that have the same proportion and type of CRCA. However, the rutting factor (E*/sin δ) of the mixtures that included treated CRCA for both types with various treatment methods is still higher than or very close to the value of the control mix.





*UNT. = Untreated; TRD. = Treated; H.Sh.M.T.= Heat & short mechanical treatment; S.Sh.M.T. = Soaking & short mechanical treatment.

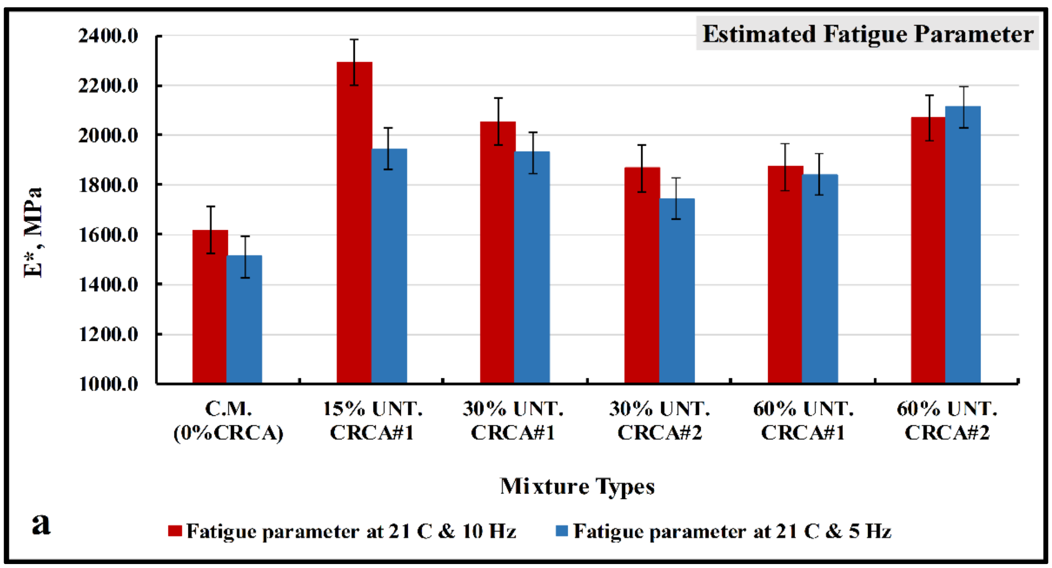
Figure 12.13: Rutting factor at 5 Hz and 54 °C for mixtures including: (a) Different untreated types with various proportions, (b) Different treated CRCA with different treatment methods.

12.6.2 Fatigue Factor

Figure 12.14 reveals the fatigue factor (E*sin δ) of different asphalt mixtures. It is found that the mixtures that included different CRCA types with proportions of CRCA have greater values of fatigue factor than the control mix. This indicates that the mixtures included CRCA have a higher susceptibility to the fatigue cracking than the control mix at the intermediate temperature. Compared to the control mixture, the mixture that included 15% CRCA#1 had the highest value of (E*sin δ) at 10 Hz. This was followed by the mixtures that included 60% CRCA#2 and 30% CRCA#1 at both 5 and 10 Hz, respectively.

For more explanation of the estimated fatigue factor, a higher frequency (10 Hz) at 21 °C was utilized in this study. In Figure 12.14, the findings demonstrated that the fatigue factors (E* Sin) at loading frequency 10 Hz have the same trend for the mixtures that included different CRCA proportions. However, slight differences are registered for the values of fatigue parameters compared to the obtained values at the loading frequency of 5 Hz.

The effect of treatment methods on the fatigue factor (E*sin δ) of HMA mixtures that included treated CRCA with various treatment methods is presented in Figure 12.14 (b). The findings showed that the mixtures that included treated CRCA with different treatment methods had higher fatigue factor values than the mixture that included the same proportion of untreated CRCA. These findings are inconsistent with the results of other tests such as rutting, thermal cracking, and complex modulus. This could possibly be due to the influence of many factors like the conditions of preparation of the compacted sample for each test, the cutting and coring for the samples, heterogeneity of CRCA, etc. Therefore, the application of fatigue test is highly recommended to evaluate the fatigue of HMA mixtures because these results are inconsistent and cannot stand alone to provide the final evaluation for the fatigue of mixtures that included CRCA.



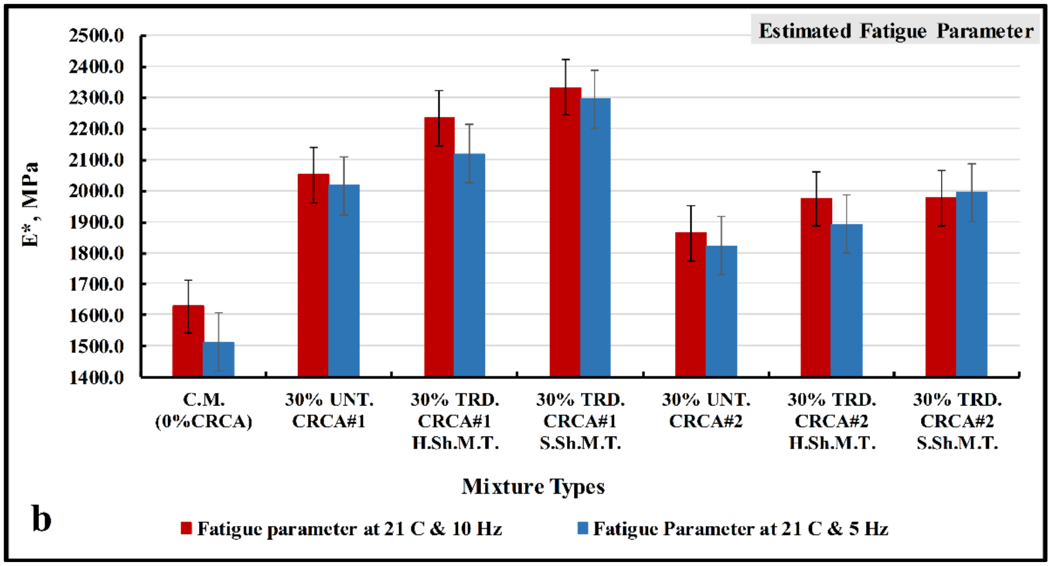


Figure 12.14: Fatigue parameter at 21 °C and different frequencies for mixtures including: (a) different untreated types with various proportions, (b) different treated CRCA with different treatment methods.

12.7 Statistical Analysis

Tables 12-1 and 12-2 summarize statistical aspects for both of rutting and fatigue parameters including standard deviation and coefficient of variation. In terms of rutting parameter, the statistical results generally revealed that the coefficients of variation of the dynamic stiffness |E*| at the temperature of 54 °C have higher values than the coefficients of variation of the phase angle. This indicates that there is a possibility to use phase angle as a parameter to rank the rutting of HMA mixtures. Heterogeneity of CRCA and inferior properties such as the surface texture, porosity, and density could possibly have an effect on the dynamic stiffness value for different HMA mixtures. It is important to mention that the coefficients of variation of fatigue parameter had the same trend though the temperature is different (21 °C).

Table 12-1: Statistical Analysis of the Results of Rutting Parameter

Mixture	Std. dev. for |E*| @ 5 Hz & 54 °C	COV for |E*| @ 5 Hz & 54 °C (%)	Std. dev. for δ @ 5 Hz & 54 °C	COV for δ @ 5 Hz & 54 °C (%)
Control mix (0% CRCA)	121.5	17.0	2.0	12.6
15% untreated CRCA#1	41.9	4.3	0.6	2.9
30% untreated CRCA#1	35.7	4.1	1.7	8.3
60% untreated CRCA#1	632.6	11.5	0.1	0.4
30% untreated CRCA#2	52.3	6.7	1.1	5.0
60% untreated CRCA#2	50.2	5.9	0.03	0.1
30% treated CRCA#1 H.Sh.M.T.	49.4	5.3	1.5	7.2
30% treated CRCA#2 H.Sh.M.T.	47.2	5.6	0.3	1.3
30% treated CRCA#1 S.Sh.M.T.	48.3	5.1	0.9	4.2
30% treated CRCA#1 S.Sh.M.T.	56.4	6.4	0.6	2.7

Table 12-2: Statistical Analysis of the Results of Fatigue Parameter

Mixture	Std. dev. for |E*| @ 5 Hz & 21 °C	COV for |E*| @ 5 Hz & 21 °C (%)	Std. dev. for δ @ 5 Hz & 21 °C	COV for δ @ 5 Hz & 21 °C (%)
Control mix (0% CRCA)	505.8	11.0	0.5	2.7
15% untreated CRCA#1	455.0	6.6	0.5	2.4
30% untreated CRCA#1	267.7	4.4	0.2	1.2
60% untreated CRCA#1	632.6	11.5	0.1	0.4
30% untreated CRCA#2	108.2	1.9	0.8	4.2
60% untreated CRCA#2	0.8	4.2	1.3	7.2
30% treated CRCA#1 H.Sh.M.T.	287.6	4.4	1.1	5.7
30% treated CRCA#2 H.Sh.M.T.	213.0	3.6	0.6	3.1
30% treated CRCA#1 S.Sh.M.T.	766.0	10.8	0.4	2.1
30% treated CRCA#2 S.Sh.M.T.	145.9	2.4	0.2	0.9

δ = Phase angle

The ANOVA single factor analysis carried out of the dynamic stiffness at 5 Hz for temperatures of 21 °C and 54 °C, with a probability of 95%. The results of |E*| represented three replicate specimens of different HMA Mixtures. The statistical analysis revealed that a variance among the data is statistically significant. While a value of F_{actual} (158.5) > $F_{critical}$ (3.11) and a p-value of (1.58 E-10) is obtained for the mixtures at a loading frequency of 5 Hz and a temperature of 54 °C, a value of F_{actual} (115.1) > $F_{critical}$ (3.1) and a p-value of (1.04 E-09) is registered for the mixtures at a loading frequency of 5 Hz and a temperature of 21 °C. From the |E*| results that represent six asphalt mixtures for both CRCA types, it could be concluded that differences among the results are statistically significant, indicating an increase in the CRCA proportion and the CRCA type have a significant effect on the dynamic stiffness, rutting and fatigue of the mixture.

In the analysis of two-way ANOVA, the main impact could be defined from variables as well as their significance. A higher value of the sum of the squares generally refers to which of the variables has the major impact. When there is a significant interaction between two variables, the major impact cannot be determined. The findings showed that both the type of CRCA and its proportion have a significant effect on the stiffness modulus and phase angle. However, there is a significant interaction between these variables. Interestingly, the type of CRCA has the higher effect on the results of phase angle than the CRCA percentage, whereas there is no dominant impact for these variables on the stiffness modulus results. Additionally, CRCA proportion and treatment method have a higher effect than the CRCA type on the rut depth findings. However, a significant interaction is registered between the mentioned variables. It is observed that both the CRCA type and treatment method have a considerable effect on the stiffness modulus results. However, the effects of these variables are acting independently due to an insignificant interaction between the mentioned variables. Interestingly, both the CRCA type and treatment method have an insignificant impact on the phase angle with an insignificant interaction between these variables as shown in Tables 12-3 to 12-5.

Table 12-3: Results of Two-Way ANOVA Analysis for Rutting: P-Value and Sum of Squares

Source of Variation		**Rut Depth**	**Statistically Different**	**Significant at α=0.05**
CRCA type	P-value	0.07885	No	
	SS	0.059		
CRCA%	P-value	<0.00215	Yes	Yes
	SS	0.536		
Interaction	P-value	<0.01064	Yes	Yes
	SS	0.22		
CRCA type	P-value	0.30517	No	
	SS	0.034		
Treatment methods	P-value	<0.02766	Yes	Yes
	SS	0.376		
Interaction	P-value	<0.00275	Yes	Yes
	SS	1.00062		

Table 12-4: Results of Two-Way ANOVA Analysis for Complex Modulus: P-Value and Sum of Squares

Source of Variation		E*, complex Modulus	Statistically Different	Significant at α=0.05
CRCA type	P-value	<1.2085E-06	Yes	Yes
	SS	1.70×107		
CRCA%	P-value	<1.2085E-06	Yes	Yes
	SS	1.67×107		
Interaction	P-value	<1.6652E-06	Yes	Yes
	SS	1.56×107		
CRCA type	P-value	<0.004	Yes	Yes
	SS	3.08×104		
Treatment methods	P-value	<0.035	Yes	Yes
	SS	2.21×104		
Interaction	P-value	0.823	No	
	SS	0.0974×104		

Table 12-5: Results of Two-Way ANOVA Analysis for Phase Angle: P-Value and Sum of Squares

Source of Variation		Phase Angle	Statistically Different	Significant at α=0.05
CRCA type	P-value	<0.00013	Yes	Yes
	SS	46.61		
CRCA%	P-value	<0.01416	Yes	Yes
	SS	9.71		
Interaction	P-value	<0.00066	Yes	Yes
	SS	28.86		
CRCA type	P-value	0.32509	No	
	SS	1.28		
Treatment methods	P-value	0.74154	No	
	SS	0.75		
Interaction	P-value	0.63607	No	
	SS	1.146		

12.8 Summary of This Chapter

This chapter examined the influence of the CRCA addition on the rutting and stiffness modulus of Ontario Superpave mixtures. The main findings of this chapter are summarized as follows:

- The obtained results indicated that the addition of different types of untreated CRCA in various proportions leads to higher rutting resistance, higher stiffness modulus than the control mix. However, the CRCA type has an effect on the obtained rutting characteristics of asphalt mixtures.
- The application of treated CRCA with heat treatment and short mechanical treatment leads to an increase in the rutting resistance, decrease in total rut depth, a slight increase in the stiffness modulus, and an increase in the rutting parameter of asphalt mixtures depending on the type of CRCA.
- The application of treated CRCA with pre-soaking method and short mechanical treatment results in an increase in the stiffness and rutting factor of asphalt mixtures depending on the type of CRCA.
- The results indicate that the application of different CRCA types in various forms: treated and untreated is very successful and can greatly contribute towards more RCA applications in the asphalt pavements.
- The results of ANOVA statistical analysis revealed that an increase in the CRCA proportion, the CRCA type, and the type of treatment method have a high impact on the stiffness and rutting of mixtures.

CHAPTER 13

EFFECT OF COARSE RECYCLED CONCRETE AGGREGATE WITH DIFFERENT TREATMENT METHODS ON THE MOISTUR SUSCEPTIBILITY OF HMA

In this chapter, the obtained findings of CRCA#2 have been submitted to Journal of Materials in Civil Engineering (Al-Bayati and Tighe). Also, the obtained results of CRCA#1 would be presented at the Canadian Society for Civil Engineering (CSCE) Conference (Al-Bayati and Tighe, 2019).

13.1 Introduction

Moisture damage is a phenomenon that relates to the loss of stiffness and strength of an asphalt mixtures because of exposure to moisture under the influence of mechanical loading of traffic, which results in what is known as stripping. Moisture damage that leads to the deterioration in integrity of asphalt pavement plays a key role in the occurrence of other distress types including fatigue cracking, rutting, etc. Therefore, moisture results in an acceleration of the deterioration of asphalt pavement that was initiated by other distresses. In asphalt pavement, the bonding that connects aggregate and asphalt binder affects the response to various distresses, which is strongly influenced by moisture conditions (Moraes et al., 2011). The characteristics of aggregate have a considerable effect on this adhesion, more so than other asphalt binder characteristics *"Size and shape of the aggregate, pore volume and size, surface area, chemical constituents at the surface, acidity and alkalinity, adsorption size surface density, and surface charge or polarity are some of the widely cited aggregate characteristics that can influence moisture damage"* (Moraes et al., 2011).

Numerous studies have been conducted to investigate the use of RCA in HMA mixtures. Zhu et al. (2012) concluded that the addition of CRCA without treatment causes poor moisture resistance and low-temperature flexibility. The addition of treated CRCA, using a pre-coating method with liquid silicone resin, works to improve these properties. The addition of treated CRCA improves strength, absorption, and adhesion with asphalt while it has a negative effect on the permanent deformation at elevated temperatures. However, mixture properties at elevated temperatures are still acceptable.

13.2 Influence of Untreated CRCA on the Tensile Strength

ITS is usually used to measure the tensile strength of asphalt mixtures, which could be further used for evaluating different relevant behaviours such as road surface cracking, permanent deformation, and stripping (Lee et al., 2012).

13.2.1 Influence of CRCA Proportion

Figure 13.1 reveals the behaviour of ITS values of both unconditioned and conditioned HMA samples which were carried out at the optimum asphalt content with various proportions of CRCA#1 (0%,15%, 30%, and 60%). The obtained results demonstrated that ITS values of both sample states are generally higher than the control mix (0% untreated CRCA), resulted in a successful behaviour for various untreated CRCA percentages, even the high proportion of 60%. Due to the crushing process of the old concrete and existence of mortar which is rough surface, the texture of RCA surface consists of shaped particles with sharp edges. This leads to a better interaction and higher friction between the surface particles (better adhesive bond) (Radević et al., 2017). It is interesting to note that the maximum ITS values recorded for the mixtures that included 15% untreated CRCA#1 for unconditioned and conditioned samples are 909.2 kPa and 830.3 kPa with an increase of 79.3% and 81%, respectively. This is followed by the ITS values of the mixtures that included 30% untreated CRCA#1 addition for both unconditioned and conditioned samples with an increase of 68% and 70%, respectively. This was then followed by the mixtures that included 60% untreated CRCA with an increase of 41.4% and 49% for both unconditioned and conditioned samples, respectively. An increase in the CRCA proportion can contribute to reduce the tensile strength of asphalt mixtures due to an increase in the dust proportion that results from the fragmentation of adhered mortar under the effect of compaction. This confirms the fact that the moisture and dust could considerably lead to a significant reduction in the bond strength between the aggregate particles and asphalt binder. Dust coating for an aggregate can work to prevent its surface from complete wetting by the asphalt binder due to an adhesion created between the asphalt binder and dust particles instead of aggregate particles (Moraes et al., 2011). This behaviour is confirmed by previous studies (Ríos et al., 2009; Zhu et al., 2012). In contrast, other investigations have reported that ITS increased as the proportion of RCA increases (Lee et al., 2012). However, due to a significant improvement in the tensile strength, the use of untreated CRCA in various percentages results in its successful utilization in HMA mixtures compared to the mixtures that included NA.

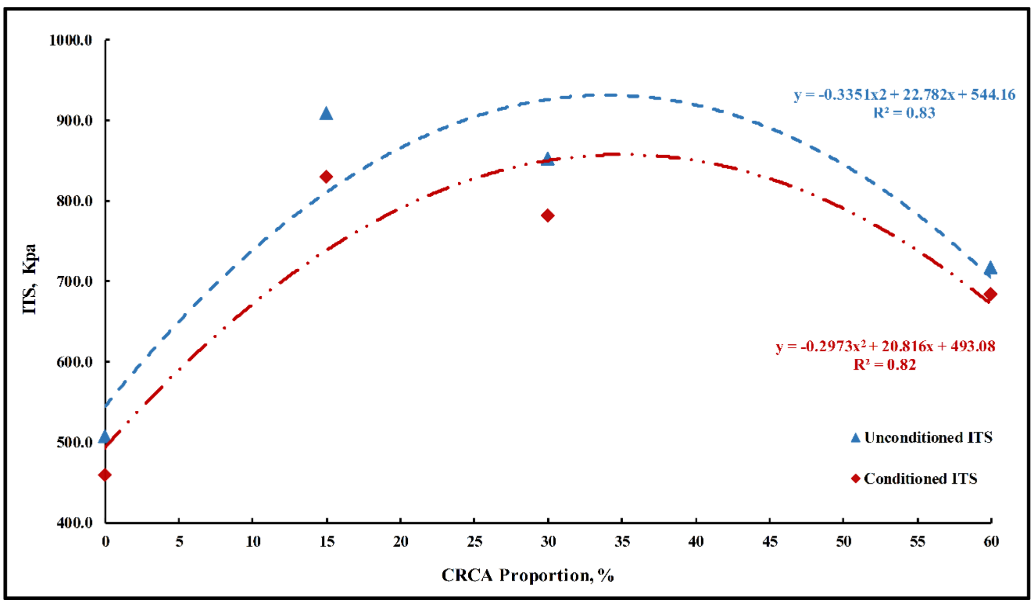


Figure 13.1: ITS for mixtures including untreated CRCA#1 with different proportions.

13.2.2 Influence of the CRCA Types on ITS

To evaluate the effect of CRCA types on tensile strength, Figure 13.2 demonstrates the average of the laboratory outcomes of conditioned and unconditioned ITS samples of the mixtures that included untreated CRCA#1 and CRCA#2 with various proportions. For all cases, it is important to mention that the worst tensile strength is recorded for the control mixture (0% CRCA) among various tensile strength values, indicating a successful behaviour for the addition of various untreated CRCA types with different proportions. It is observed that the mixtures that included untreated CRCA#1 & 2 had the same behavior trend in terms of tensile strength. Generally, an increase in the CRCA percentages leads to a decrease in the ITS values. Additionally, the mixtures that included untreated CRCA#2 up to 60% exhibited better tensile strength in both ITS conditioned and unconditioned state, indicating a higher tensile strength than the mixtures that included the same proportion of untreated CRCA#1. It is interesting to note that the maximum ITS values recorded for 30% untreated CRCA#2 for unconditioned and conditioned samples are 941.5 kPa and 856.5 kPa with an increase of 85.6% and 86.7%, respectively. This is followed by the ITS values of 60% untreated CRCA#2 addition for both unconditioned and conditioned samples with an increase of 71.5% and 56.8%, respectively. This could be explained by the existence of a high proportion of adhered mortar attached to the CRCA#1 surface, which is more brittle under the impact of the compaction of wheel loads, resulting in a poor adhesion between the CRCA particles and asphalt binder. Hence, it can be stated that the type of CRCA has a considerable effect on the tensile strength of the mixture. In conclusion, the HMA mixtures that include CRCA with different types can tolerate higher strains before their failure, which means they are more likely to resist cracking compared to asphalt mixtures that include NA with a low tensile strain at failure.

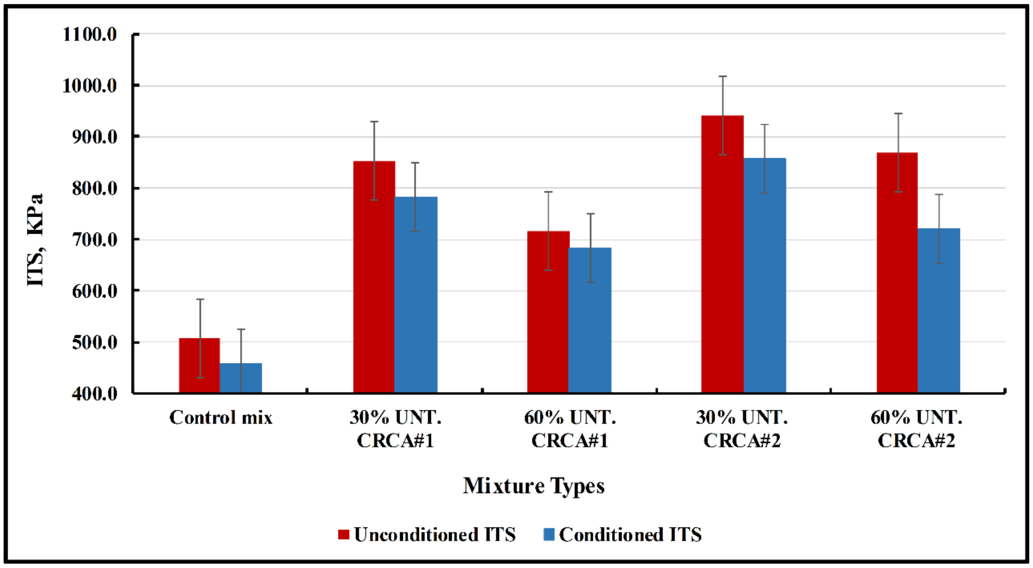


Figure 13.2: ITS for mixtures including different CRCA types with various proportions

13.3 Influence of Treated CRCA on ITS

13.3.1 Effect of Heat and Mechanical Treatment on ITS

To examine the impact of the combination of different treatments on the tensile strength of asphalt mixtures, the average conditioned and unconditioned ITS of the mixtures that included treated and untreated CRCA for both CRCA types are presented in Figures 13.3. For the influence of the integration of heat treatment and short mechanical treatment, the obtained results showed that the mixtures that included 30% treated CRCA#1 or CRCA#2 had a higher tensile strength for both conditioned and unconditioned ITS compared to the mixtures that included the same type and proportion of untreated CRCA. This indicates a successful combination approach for enhancing the tensile strength of HMA mixtures. This behaviour could be attributed to the reduced amount of adhered mortar attached to the CRCA surface under the impact of heat treatment at 300 °C followed by short mechanical treatment. These results confirm the findings of the physical properties of CRCA after the above-mentioned treatments as previously shown in Table 5-4. However, the tensile strength of the mixtures that included treated 30% CRCA#2 was slightly higher than the tensile strength of the mixtures that included the same proportion of treated CRCA#1 for both conditioned and unconditioned ITS. This could be explained by the presence of a low proportion of adhered mortar attached to the CRCA#2 surface. These obtained outcomes also emphasize the findings for the percentage of adhered mortar loss, abrasion loss, and aggregate crushing value as previously shown in Table 4-1. Surprisingly, the mixtures that included 30% treated CRCA#1 registered the highest tensile strength improvement for both conditioned and unconditioned ITS state compared to the mixtures that included 30% untreated CRCA#1 with a percentage value of 12% and 11%, respectively. Meanwhile, the mixtures that included 30% treated CRCA#2 recorded an improvement with a value of 4.0% and 3.5% respectively for both conditioned and unconditioned ITS, which is higher than the mixtures that included 30% untreated CRCA#2. This could be explained by the existence of a high proportion of adhered mortar attached to the surface of CRCA#1, which become more brittle under the influence of the combination of heat and short mechanical treatment. This outcome gives an indication that the integration between heat treatment and short mechanical treatment was a very effective technique to reduce the weak surfaces of attached mortar, that were crushed under the influence of the compaction process. Hence, it can be concluded that the type of RCA has a considerable effect on enhancing the strength of asphalt mixtures under the impact of this treatment approach.

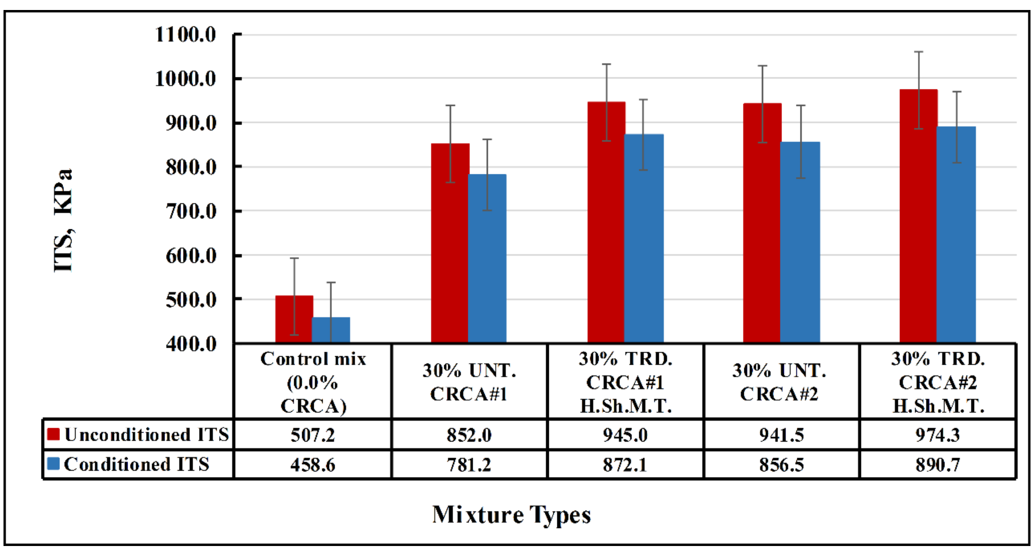


Figure 13.3: ITS for mixtures including different types of treated CRCA with heat and short mechanical treatment.

13.3.2 Effect of Soaking and Mechanical Treatment on ITS

Figure 13.4 demonstrates the effect of the combination of pre-soaking method and short mechanical treatment on the ITS of the HMA mixtures. The obtained results showed that the mixtures that included 30% treated CRCA#2 provided an important enhancement in the tensile strength of mixtures for both conditioned and unconditioned ITS. The mentioned mixtures registered an increase in the ITS with a value of 22% and 9.3% for conditioned and unconditioned samples respectively compared to the mixtures that included the same type and proportion of untreated CRCA. With the use of this treatment approach, it is observed that the mixtures that included 30% treated CRCA#2 have the highest tensile strength for both conditioned and unconditioned ITS compared to both the control mix and the mixtures that included treated CRCA#1 with the same proportion. It is interesting to note that the mixtures that included 30% treated CRCA#1 have a relatively higher conditioned tensile strength than the unconditioned state. This shows that the application of this treatment technique contributes to a reasonable improvement in the resistance of HMA to moisture damage.

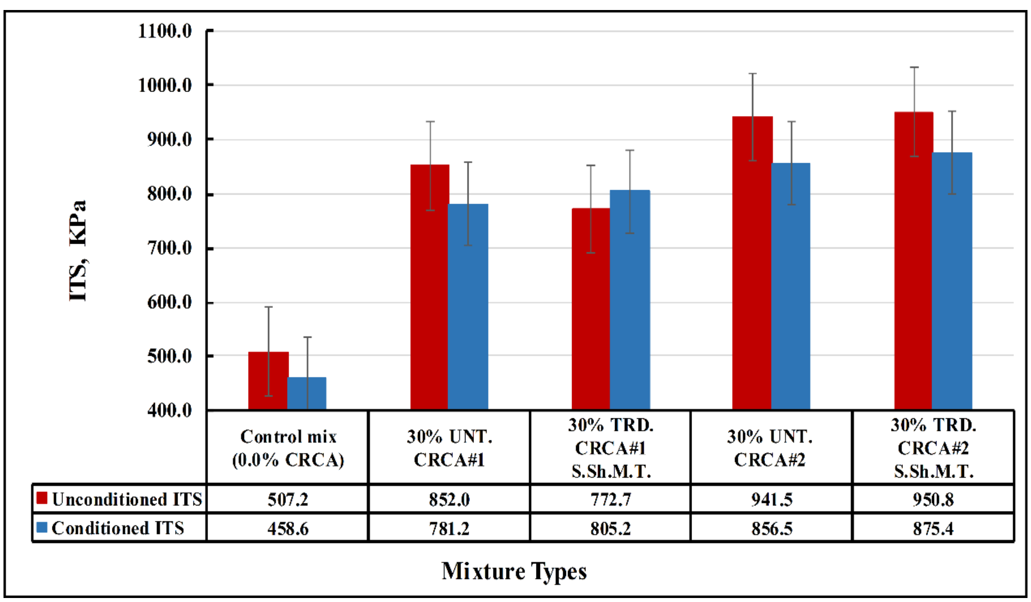


Figure 13.4: ITS for mixtures including different types of treated CRCA with soaking and short mechanical treatment.

13.4 Effect of CRCA Addition on the Moisture Damage

Moisture sensitivity, also known as moisture damage, refers to a type of degradation that mainly influences the mechanical characteristics of an asphalt mixture because of the presence of water (Pasandín & Pérez, 2013). To obtain an asphalt mixture that can successfully resist moisture and water damage, the minimum required TSR value should be 80 % (Liang, 2008; Pérez et al., 2012).

13.4.1 Influence of Untreated CRCA Addition on Moisture Damage

13.4.1.1 Influence of CRCA Proportion

Figure 13.5 shows the behaviour of TSR values of mixtures including different proportions of untreated CRCA#1. The laboratory results demonstrated that all TSR values are higher than 80%, representing the minimum required value of MTO specification for HMA mixtures, resulting in a highly successful behaviour for different untreated CRCA#1 proportion. The values of TSR increases when the CRCA addition is increased even with a high CRCA proportion of 60%. Surprisingly, among various TSR values, the worst TSR value is recorded for the mixture of control mix (0% CRCA). This could be attributed to a good adhesion of CRCA with asphalt binder due to the roughness of adhered mortar surface and the angularity of CRCA particles that can exist as a result of the impact of the crushing process. It is noteworthy that the values of TSR for mixtures that included various proportions of untreated CRCA#1 are strongly correlated due to obtaining a considerable regression. A polynomial equation reflects well the behaviour of the relation between the TSR values and proportions of CRCA#1 addition. Due to the importance of the moisture sensitivity test for cold weather countries, these outcomes are very promising and important for RCA applications.

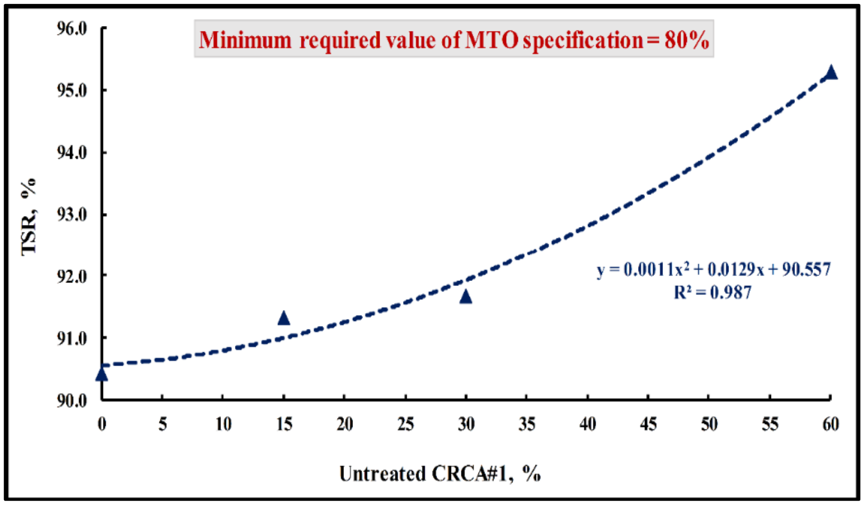


Figure 13.5: TSR values for mixtures including various proportions of untreated CRCA#1.

13.4.1.2 Effect of CRCA Types

Figure 13.6 displays the laboratory outcomes of TSR values of asphalt mixtures that included different untreated CRCA types with various proportions to explore the effect of untreated CRCA type on the moisture sensitivity of mixtures. For both types of untreated CRCA, it is interesting to note that the TSR values are higher than 80% for all proportions. These results strongly indicate a successful utilization of CRCA in asphalt mixtures. Additionally, it is important to note that the mixtures that included untreated CRCA#1 or CRCA#2 have different behaviour trends in terms of TSR. With untreated CRCA#1 addition, the TSR gradually increased to reach a value of 95.3% for the mixture that included 60% untreated CRCA#1, whereas TSR followed an opposite behaviour when untreated CRCA#2 addition reached a similar proportion. Furthermore, the mixtures that included untreated CRCA#1 up to 60% exhibited a better moisture resistance, and registered a higher tensile strength ratio than the mixtures that included the same proportion of untreated CRCA#2. Therefore, it can be stated that the outcomes of moisture sensitivity seem to be completely opposite compared to the ITS test regarding the influence of the type of RCA. In conclusion, the results indicate that the moisture sensitivities of mixtures that included untreated CRCA are highly affected by the type of CRCA.

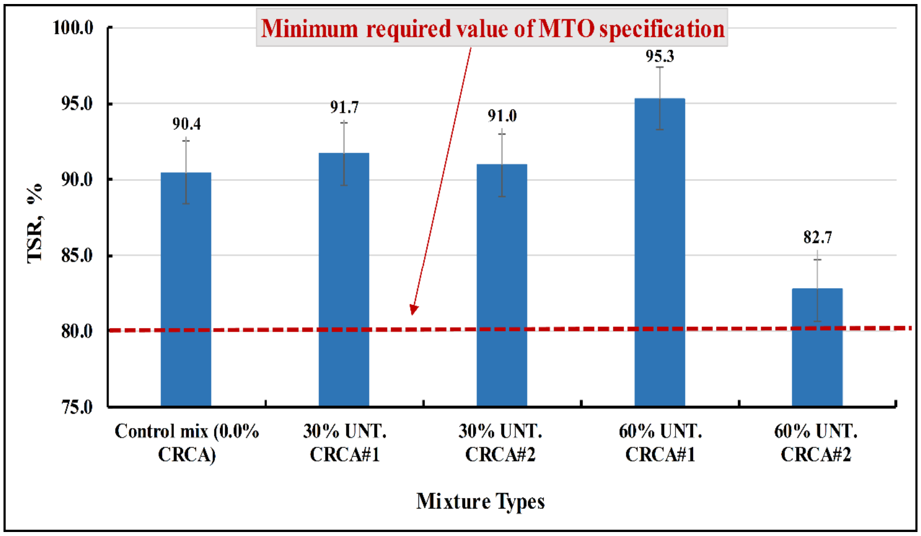


Figure 13.6: TSR values for mixtures including different untreated CRCA types with various proportions.

13.4.2 Influence of Treated CRCA Addition on Moisture Damage

13.4.2.1 Effect of Heat and Mechanical Treatment on TSR

Figure 13.7 explains the influence of heat treatment at 300 °C followed by short mechanical treatment on the TSR values. Compared to the mixture with 30% untreated CRCA, the obtained results showed that little improvement in the TSR values was registered for the mixtures that included 30% treated CRCA with this treatment technique for both CRCA types. The mentioned mixtures have an improvement value of 0.66% and 0.44% in the TSR values for the mixtures that included 30% treated CRCA#1 and CRCA#2, respectively. However, the obtained values are much higher than the minimum required TSR value for MTO specifications. These results suggest that there is a limited impact for this type of treatment on the moisture sensitivity enhancement of the asphalt mixtures.

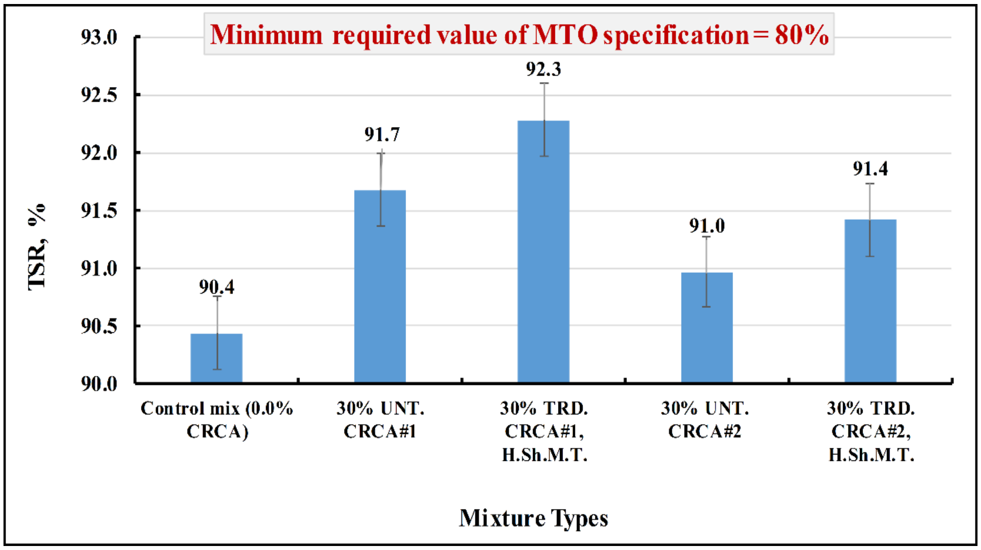


Figure 13.7: TSR values for mixtures included treated CRCA with heat and mechanical treatment.

13.4.2.2 Effect of Soaking and Mechanical Treatment on TSR

To evaluate the influence of the combination of soaking in weak acid solution and short mechanical treatment on the TSR of asphalt mixtures, the average values of TSR are illustrated in Figure 13.8. The obtained results showed that a small improvement in the TSR values is registered for the mixtures that included 30% treated CRCA#2, with an increased percentage of 1.2% compared to the mixture that included 30% untreated CRCA#2. Meanwhile, the mixture that included 30% treated CRCA#1 with the same type of treatment exhibited an important improvement in the TSR values with an increased percentage of 13.4% compared to the mixture with 30% untreated CRCA#1.

These results propose that there is a big effect for this treatment approach on the moisture sensitivity enhancement of HMA mixtures. Hence, this combination type has the best performance in improving TSR value compared to another combination approach. Therefore, it can be stated that the outcomes of moisture sensitivity seem to be completely opposite compared to the ITS test regarding the influence of combination approach type.

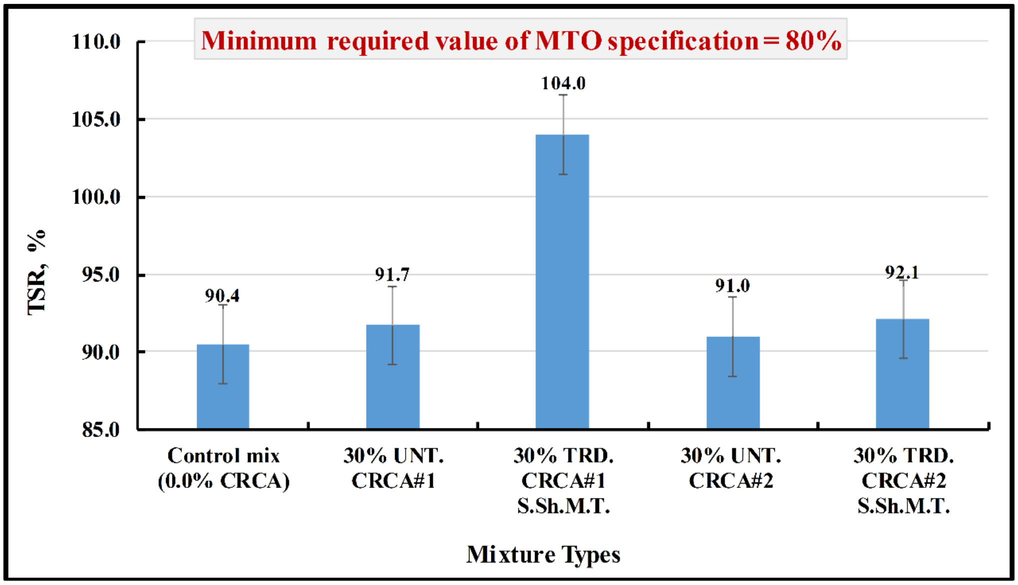


Figure 13.8: TSR for mixtures including different types of treated CRCA with soaking followed by short mechanical treatment.

13.5 Statistical Analysis of the Obtained Results

13.5.1 Statistical Analysis of ITS Results

Table 13-1 summarizes statistical aspects of ITS including standard deviation and coefficient of variation. The statistical results generally revealed that the coefficients of variation of the unconditioned ITS at the temperature of 25 °C are higher values than the coefficients of variation of the conditioned ITS. This indicates there is a possibility to use conditioned ITS as a parameter to rank the tensile strength of HMA mixtures. However, there is some opposite expectation to the behaviour of mixtures that included 60% untreated CRCA#2 and 30% treated CRCA#2 with heat treatment followed by short mechanical treatment. Heterogeneity of CRCA and its inferior properties such as surface texture, porosity, and density could possibly have an effect on the ITS value for different asphalt mixtures.

Table 13-1: Statistical Analysis of the Results of ITS

Mixture	Std. dev. for Unconditioned ITS	COV for Unconditioned ITS (%)	Std. dev. for Conditioned ITS	COV for Conditioned ITS (%)
Control mix (0% CRCA)	58.11	11.46	24.55	5.35
15% untreated CRCA#1	87.09	9.58	31.52	3.80
30% untreated CRCA#1	32.84	3.85	24.30	3.11
60% untreated CRCA#1	69.31	9.67	64.26	9.40
30% untreated CRCA#2	110.12	11.70	63.93	7.46
60% untreated CRCA#2	16.13	1.85	15.66	2.18
30% treated CRCA#1 H.Sh.M.T.	102.32	10.83	55.20	6.33
30% treated CRCA#2 H.Sh.M.T.	35.13	3.61	81.50	9.15
30% treated CRCA#1 S.Sh.M.T.	138.20	17.89	8.10	1.01
30% treated CRCA#1 S.Sh.M.T.	144.52	15.20	4.77	0.54

A two-way ANOVA analysis was carried out on the results of different mixtures which represent three replicate specimens of different HMA mixtures to evaluate the influence of many parameters on the ITS value. The mentioned parameters include various CRCA percentages (0%, 15%, 30%, and 60%); different CRCA types; various treatment types: heat treatment at 300 °C followed by short mechanical treatment and pre-soaking in acetic acid solution followed by short mechanical treatment; and the state of the sample: conditioned or unconditioned sample. The ANOVA analysis was carried out with a probability of 95%. In the analysis of two-way ANOVA, the main impact could be defined from variables as well as their significance. A higher value of the sum of the squares generally refers to which of the variables has the major impact. When there is a significant interaction between two variables, the major impact cannot be determined.

The findings showed that the type of CRCA has a significant effect on the ITS of the unconditioned sample, with Factual (6.41) > Fcritical (5.32) and a p-value of (0.0352). Thus, a variation in the CRCA type will impact the ITS of the unconditioned sample. Additionally, the results demonstrated that there is a statistically insignificant effect of CRCA percentage on the unconditioned ITS, with Factual (4.684) < Fcritical (5.318) and a p-value of (0.0624) for the HMA mixtures in the dry state. However, the effects of CRCA type and proportion act independently due to an insignificant interaction between the mentioned variables, with Factual (0.434) < Fcritical (5.318) and a p-value of (p= 0.53). Interestingly, the type of

CRCA has a higher impact on the results of unconditioned ITS of asphalt mixtures than the CRCA proportion.

In terms of the influence of CRCA type and proportion on the conditioned ITS, the statistical analysis shows that there is a statistically insignificant effect of CRCA type on the conditioned ITS, with Factual (3.923) < Fcritical (5.318) and a p-value of (0.0829) for the HMA mixtures. Meanwhile, the findings idicated that there is a statistically significant effect of CRCA percentage on the conditioned ITS, with a p-value of (0.0031) and F_{actual} (17.468) > $F_{critical}$ (5.318). However, the effects of CRCA type and proportion act independently due to an insignificant interaction between the mentioned variables, with a p-value of (0.497) and F_{actual} (0.506) < $F_{critical}$ (5.318). Surprisingly, the type of CRCA has a greater effect on the results of conditioned ITS of HMA mixtures than the CRCA percentage depending on the sum of the squares (SS) value.

In terms of studying the statistical interaction between CRCA type and treatment methods for both conditioned and unconditioned states, the findings showed that the effects of these variables act independently for both the mentioned states due to an insignificant interaction between the mentioned variables with (p= 0.525 and 0.318) respectively. Interestingly, the CRCA type has a significant impact on both the conditioned and unconditioned ITS with a p-value of (0.0297) and (0.0246) respectively, and a higher value of (SS) than the type of treatment method. This suggests that CRCA type statistically is the main factor impacting the tensile strength of the HMA mixtures for both conditioned and unconditioned states than the type of treatment method. The obtained results of a two-way ANOVA analysis are tabulated in Table 13-2.

Table 13-2: Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of ITS

Source of Variation		Unconditioned ITS	Conditioned ITS
CRCA type	P-value	<0.035168	0.082964
	SS	43907.51	9333.15
	F	6.408942	3.923027
	F- critical	5.317655	5.317655
CRCA%	P-value	0.06238	<0.003082
	SS	32088.33	41558
	F	4.68376	17.46818
	F- critical	5.317655	5.317655
Interaction	P-value	0.528409	0.497284
	SS	2975.178	1202.687
	F	0.434271	0.505528
	F- critical	5.317655	5.317655
CRCA type	P-value	<0.02456	<0.02974
	SS	44064.9	14486.9
	F	6.60331	6.07878
	F- critical	4.74723	4.74723
Treatment methods	P-value	0.15204	0.11597
	SS	29533.1	12354.6
	F	2.21283	2.59203
	F- critical	3.88529	3.88529
Interaction	P-value	0.31751	0.52489
	SS	16873.2	3243.39
	F	1.26426	0.68047
	F- critical	3.88529	3.88529

13.5.2 Statistical Analysis of TSR Results

A one-way ANOVA analysis was performed to examine the influence of CRCA proportion (0%, 15%, 30%, and 60%) on the TSR value of asphalt mixtures. The results indicated that the CRCA percentage has an insignificant impact on TSR with a p-value of (0.971) and Factual (0.076434) < Fcritical (4.066). This indicates that the variation in the CRCA content will not affect the moisture sensitivity of HMA mixtures.

To obtain a better understanding, a two-way ANOVA analysis was carried out for different mixtures to investigate the influence of various parameters on TSR values. The mentioned parameters include: different CRCA proportions (30%, and 60%); various CRCA types; two different treatment approaches: heat treatment at 300 °C followed by short mechanical treatment and pre-soaking in acetic acid method followed by short mechanical treatment. Surprisingly, the findings indicated that the effects of these variables act independently due to an insignificant interaction between the CRCA type and both CRCA's percentage and treatment methods with a p-value of (0.2843) and (0.724), respectively. However, the type of CRCA has a higher effect on the results of TSR than the CRCA percentage in terms of studying the impact of CRCA type and its proportion. Meanwhile, the treatment method is the main factor impacting on the TSR value compared to CRCA type in terms of evaluating the main statistical effect between CRCA type and treatment type. The findings of two-way ANOVA analysis of TSR values are presented in Table 13-3.

Table 13-3: Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of TSR

Source of Variation		**TSR, %**
CRCA type	P-value	0.1282
	SS	169.501
	F	2.8795
	F- critical	5.3177
CRCA%	P-value	0.7300
	SS	7.5208
	F	0.1278
	F- critical	5.3177
Interaction	P-value	0.2843
	SS	77.521
	F	1.3169
	F- critical	5.3177
CRCA type	P-value	0.2900
	SS	121.036
	F	1.225
	F- critical	4.7472
Treatment methods	P-value	0.4653
	SS	161.228
	F	0.8160
	F- critical	3.8853
Interaction	P-value	0.724
	SS	65.528
	F	0.3316
	F- critical	3.8853

13.6 Summary of This Chapter

- It is interesting to note that the maximum ITS values recorded for 30% untreated CRCA#1 and CRCA#2 for both unconditioned and conditioned samples, registered increases of 68%, 70%, 85.6%, and 86.7%, respectively. This is followed by the ITS values of the mixtures that included 60% untreated CRCA1# and CRCA#2 for both unconditioned and conditioned samples with increases of 41.4%, 49.0% 71.5% and 56.8%, respectively.
- A reasonable improvement in the ITS values for both conditioned and unconditioned samples was recorded for the mixtures that included 30% treated CRCA with different treatments compared to the mixtures that included 30% untreated CRCA. However, for CRCA#1, the combination of heat and short mechanical treatment exhibits the best performance for improving ITS values, registering an increase of 12% and 11% for both conditioned and unconditioned samples, respectively.
- For CRCA#2, the combination of pre-soaking and short mechanical treatment has the best performance for improving ITS values for both conditioned and unconditioned samples, registering an increase of 22% and 9.3%, respectively.
- The findings indicated that all TSR values for mixtures that included untreated CRCA with different types and proportions are higher than the minimum required value of MTO specifications. However, it is important to note that the mixtures that included untreated CRCA#1 or CRCA#2 have different behaviour trends in terms of TSR.
- Compared to the mixture that included 30% untreated CRCA, the obtained results showed that little improvement in the TSR values was registered for the mixtures that included 30% treated CRCA with the combination of heat and short mechanical treatment for both CRCA types. The mentioned mixtures have an improvement value of 0.66% and 0.44% in the TSR values for the mixtures that included 30% treated CRCA#1 and CRCA#2, respectively.
- The results of an ANOVA analysis also showed that the CRCA type is the main factor that influences the ITS value of asphalt mixtures for both conditioned and unconditioned samples.

- From the perspective of TSR, the results of the ANOVA analysis revealed that there is no significant effect of CRCA type, proportion, and treatment method on the TSR values. However, the type of CRCA and the treatment methods have a higher effect on the results of TSR compared to the CRCA percentage.
- It is important to mention that the enhancement of the ITZ zone and surface morphology of RCA due to the application of different treatments have an impact on improving the ITS and TSR values of HMA mixtures.

CHAPTER 14
INVESTIGATION OF TREATED CRCA IN HMA MIXTURES THROUGH EVALUATING LOW TEMPERATURE CRACKING

In this chapter, part of the obtained results of CRCA#1 & CRCA#2 have been presented at the Canadian Society for Civil Engineering (CSCE) Conference (Al-Bayati and Tighe, 2018). Part of this chapter related to CRCA#1 & CRCA#2 would be submitted to the Journal of Cold Regions Science and Technology.

14.1 Introduction

One of the most widespread concerns of asphalt pavements in the cold regions of the world is thermal cracks or low temperature cracks (Velasquez et al. 2008, Tan et al. 2012, Akentuna et al. 2016). At low temperature, the upper part of the pavement section is contracted, whereas the granular base holds the pavement's bottom section in place and prevents it from contraction (http://dotapp7.dot.pdf). Then, when the developed stresses exceed the strength of the pavement (Tim 1995, Akentuna et al. 2016, Liu et al. 2017), the low-temperature cracks occur. Low-temperature cracks are the main cause of pavement degradation, increasing pavement roughness and reducing service life in the northern climates (http://dotapp7.dot.pdf).

In cold regions, road pavements can face various types of early performance deterioration due to exposure to low-temperature cracking (Liu et al., 2017). In asphalt pavements, low-temperature cracking, known also thermal cracking, is defined as cracking that is perpendicular to the road pavement centerline (Aschenbrener, 1995). Specifically, this problem happens when the stress buildup due to thermal contraction exceeds the pavement's capability to dissipate the stress (Liu et al., 2017). After the low-temperature crack initiation, water can leak into the generated cracks resulting in a ravelling of pavement joints and loss of base pavement layer support (Aschenbrener, 1995). During the design of asphalt mixtures, a number of factors that have an impact on the performance of the thermal cracking must be considered. *"These include the type of subgrade and pavement thickness. The type of subgrade can have a substantial influence on the severity of thermal cracking. HMA pavements constructed on clay subgrades will have thermal cracks less often than those constructed on granular bases. Increasing the thickness of an HMA layer will result in less thermal cracking than thinner layers. When cracking does occur, it is generally less severe in thicker pavements. The age of the pavement and the traffic have an influence on the thermal cracking performance. Cracking frequency increases with increasing pavement age and with higher traffic."* (Aschenbrener, 1995; Ksaibati & Erickson, 1998). Figure 14.1 presents low-temperature cracks in asphalt mixtures. In this study, experiments were set up to investigate the thermal crack susceptibility of the asphalt mixture samples containing treated and untreated CRCA with different types and proportions using a TSRST test.

Figure 14.1: Thermal cracking in HMA pavement (FHWA, 2011).

14.2 Effect of CRCA Addition on Thermal Cracking

Tables 14-1 and 14-2 present the results of TSRST testing for various asphalt mixtures that include different CRCA types with various proportions of untreated and treated CRCA with different treatment methods. The explanation of the results is provided in detail in the following sections.

Table 14-1: Results of TSRST Test for Different Asphalt Mixtures that Included CRCA#1

Properties/Mixture Types	Control Mix, 0% CRCA	15% UNT. CRCA#1	30% UNT. CRCA#1	30% TRD. CRCA#1, H.Sh.M.T.	30% TRD. CRCA#1, S.Sh.M.T.	60% UNT. CRCA#1
Binder PG	64-28	64-28	64-28	64-28	64-28	64-28
	-31.5	-26.21	-25.76	-28.37	-29.6	-26.0
Fracture Temperature, °C	-31.1	-25.14	-25.70	-27.95	-26.6	-26.5
	-28.1	-24.80	-25.41	-28.27	-27.95	-26.1
Average	**-30.2**	**-25.4**	**-25.6**	**-28.2**	**-28.04**	**-26.2**
	2.94	2.02	2.70	2.36	2.40	2.94
Fracture Stress, MPa	3.10	1.88	3.08	2.79	2.29	2.52
	1.57	1.65	2.76	3.18	2.47	2.69
Average	**2.54**	**1.85**	**2.85**	**2.78**	**2.39**	**2.71**

Table 14-2: Results of TSRST Test for Different Asphalt Mixtures that Included CRCA#2

Properties/Mixture Types	Control Mix, 0% CRCA	30% UNT. CRCA#2	30% TRD. CRCA#2, H.Sh.M.T.	30% TRD. CRCA#2, S.Sh.M.T.	60% UNT. CRCA#2
Binder PG	64-28	64-28	64-28	64-28	64-28
	-31.5	-25.95	-27.37	-26.77	-28.16
Fracture Temperature, °C	-31.1	-24.43	-26.93	-26.19	-24.65
	-28.1	-25.86	-27.19	-26.30	-25.40
Average	**-30.2**	**-25.4**	**-27.16**	**-26.42**	**-26.07**
	2.94	2.52	2.07	2.54	1.93
Fracture Stress, MPa	3.10	2.57	2.47	2.72	2.39
	1.57	2.63	2.56	2.36	2.33
Average	**2.54**	**2.58**	**2.37**	**2.54**	**2.22**

14.3 Influence of CRCA Addition on the Fracture Temperature

14.3.1 Effect of Untreated CRCA on the Fracture Temperature

14.3.1.1 Effect of CRCA proportion on the Fracture Temperature

In Table 14-1, the tabulated outcomes illustrate that the variation in the CRCA proportions has an impact on the fracture thermal stress and the failure temperature. The average values of fracture temperature are plotted in Figure 14.2. Compared to the control mix, 0% CRCA, it is noted that the average fracture temperature is increased due to the CRCA addition. This can be explained by the fact that RCA has more microcracks than NA. Due to the presence of microcracks, the strength of RCA is lower than NA. In addition, the adhered mortar particles could be more brittle under the impact of continuous low temperatures, resulting in cracks appearing easily, subsequently resulting in rapid failures (Wu et al., 2013). The maximum increase of the fracture temperature was up to (2.6 °C) more than the corresponding low-temperature performance grade of the respective asphalt binder used, which was represented by (-28 °C). Meanwhile, it is interesting to note that the increase of CRCA proportion up to 60% led to only a small reduction in the fracture temperatures of HMA mixtures. This type of behaviour could be explained by noting that CRCA has a rough surface with many crushed faces, which increase when the percentage of CRCA addition is increased. Such surface features lead to an increase in the contact area between asphalt binder and CRCA and generate more abrasion force (Lee et al., 2012), providing a significant interconnecting force to resist the impact of low temperature on the asphalt mixture. Based on the obtained results, it can be stated that the asphalt mixtures that include CRCA have a good behaviour related to the resistance of low-temperature cracks, resulting in a successful application in low-temperature regions. However, it is important to mention that the above-mentioned mixtures appear to be unsuitable for regions with severe weather conditions.

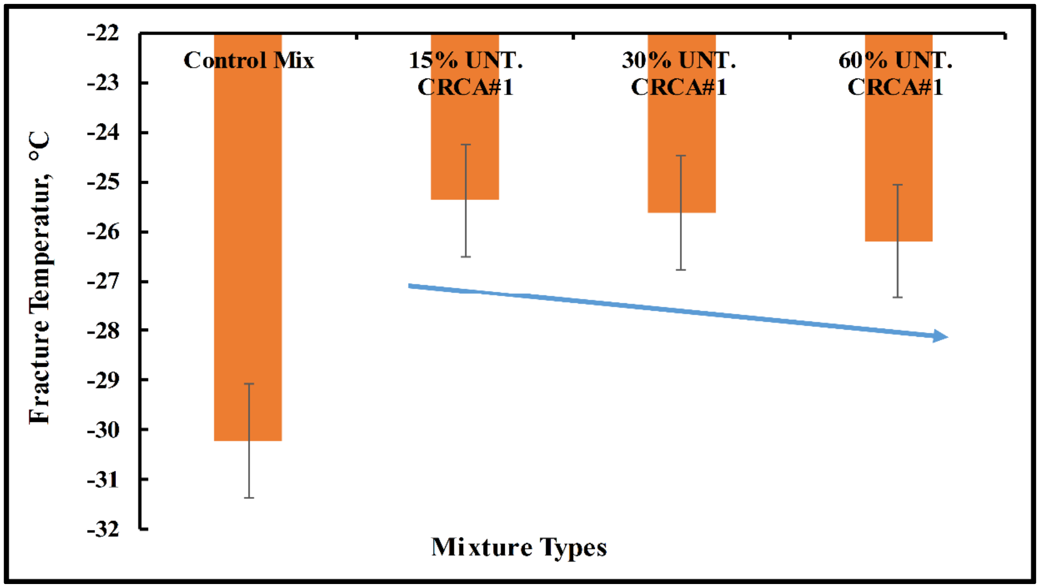


Figure 14.2: Fracture temperature of asphalt mixtures with different CRCA proportions.

14.3.1.2 Effect of CRCA Types on the Fracture Temperature

Figure 14.3 shows the effect of untreated CRCA types with various proportions on the low-temperature performance of HMA mixtures. The outcomes demonstrated that the mixtures that include untreated CRCA for both types have the same trend and behaviour. As the untreated CRCA proportion increases, the fracture temperature of the mixture is slightly decreased. Additionally, the outcomes indicated that the mixtures that included untreated CRCA for both types have a lower low-temperature cracking resistance than the control mix. It is important to note that there is no significant impact for the RCA type on the thermal cracks at low temperatures. While the average fracture temperature of the mixture that included 30% CRCA#1 is (-25.6 °C), the average fracture temperature of the mixture that included the same percentage of CRCA#2 is (-25.4 °C). This is a small difference, approximately negligible, though two different CRCA types were added to the asphalt mixtures. Similar behaviour was registered for asphalt mixtures when the percentage addition of the above-mentioned CRCA types reached 60%. As a result, there is no influence of the type of RCA on the low-temperature cracking of asphalt mixtures. More importantly, the mixtures that included CRCA have an acceptable thermal cracking resistance in cold regions.

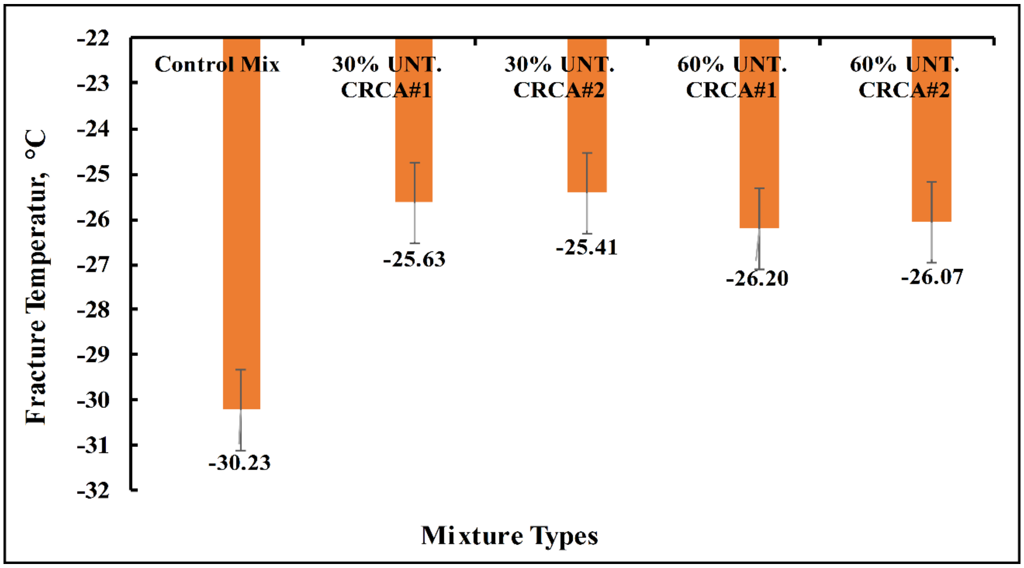


Figure 14.3: Fracture temperature of mixtures that included different CRCA types with various proportions.

14.3.2 Influence of Treated CRCA on the Fracture Temperature

14.3.2.1 Effect of Heat and Mechanical Treatment on the Fracture Temperature

To evaluate the influence of the combination of different treatment methods on the thermal cracks, the average fracture temperatures of different mixtures that included different untreated CRCA types or various treated types: CRCA#1 or CRCA#2 with the same proportion are presented in Figure 14.4. It is interesting to note that the combination of the heat treatment at 300 °C and short mechanical treatment leads to a considerable decrease in the average fracture temperature for both CRCA types. The average fracture temperatures are (-25.6 °C) and (-28.2 °C) for the mixtures that included 30% untreated CRCA#1 and treated CRCA#1 at the same percentage, respectively exhibiting a reduction of 10.2%. Interestingly, this result meets the corresponding low-temperature performance grade, (-28.0 °C), of the respective asphalt binder used. In terms of CRCA#2, the average fracture temperatures for the mixtures that included 30% untreated or treated CRCA#2 are (-25.4 °C) and (-27.2 °C), respectively. This obtained outcome is higher than the corresponding low-temperature performance grade, (-28.0 °C), of the respective asphalt binder used by (0.8 °C). Hence, this treatment type appears to be highly successful for low-temperature regions. However, the low-temperature performance of asphalt mixtures that included treated CRCA#1 seems to be better than the mixtures that included treated CRCA#2 at the same percentage. The reason behind this could be due to the origin of CRCA#1, which appeared to be stronger than CRCA#2, as shown earlier in the results of physical and mechanical properties. Additionally, CRCA#1 registered higher improvement in the surface morphology and mineralogy than CRCA#2. However, the obtained results of physical and mechanical properties and the images of SEM analysis revealed that CRCA#1 had more porosity, adhered mortar, and surface pores than CRCA#2, and showed more roughness with many crushed faces due to more attached adhered mortar.

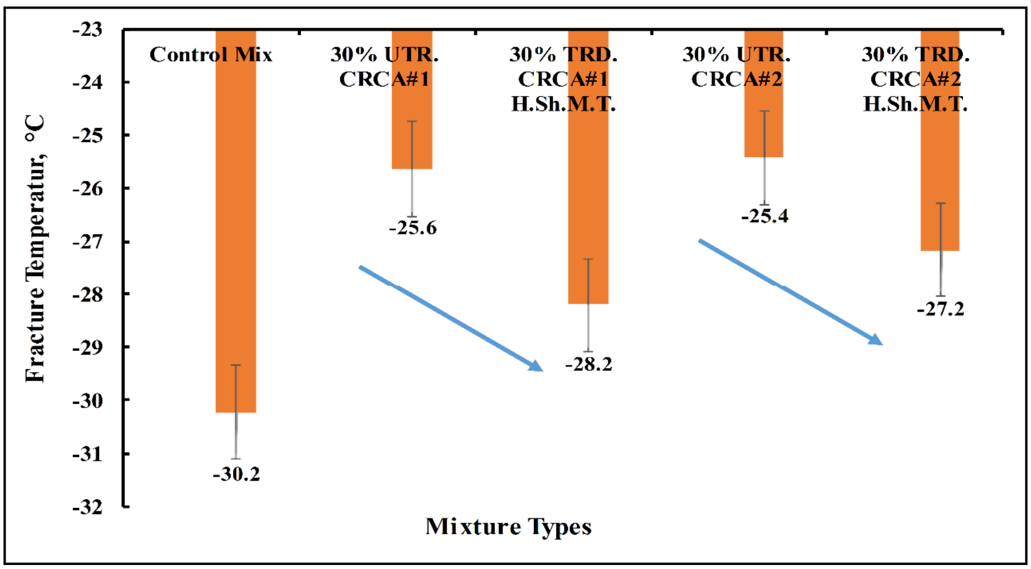


Figure 14.4: Effect of treated CRCA with the combination of heat and short mechanical treatment on the fracture temperature of asphalt mixtures.

14.3.2.2 Effect of Pre-Soaking and Mechanical Treatment on the Fracture Temperature

Figure 14.5 shows the average fracture temperatures of different mixtures that included different treated or untreated CRCA types with the same proportion. It is noteworthy that the combination of pre-soaking in acetic acid and short mechanical treatment leads to an important reduction in the average fracture temperature for both CRCA types. The average fracture temperatures were (-25.6 °C) and (-28.0 °C) for the mixtures that included 30% untreated and treated CRCA#1 respectively, showing a reduction of 9.4%. Interestingly, this result meets the corresponding low-temperature performance grade, (-28.0 °C), of the respective asphalt binder used. Meanwhile, the average fracture temperatures for the mixtures that included 30% untreated CRCA#2 and treated CRCA#2 at the same percentage were (-25.4 °C) and (-26.4 °C), respectively. This outcome is higher than the corresponding low-temperature performance grade, (-28.0 °C), of the respective asphalt binder used by (1.6 °C). Consequently, this combination approach appears to be highly successful for cold regions. However, these results are still higher than the fracture temperature of the control mix. In addition, the low-temperature performance of asphalt mixtures that included treated CRCA#1 seems to be better than the mixtures that included treated CRCA#2 at the same percentage.

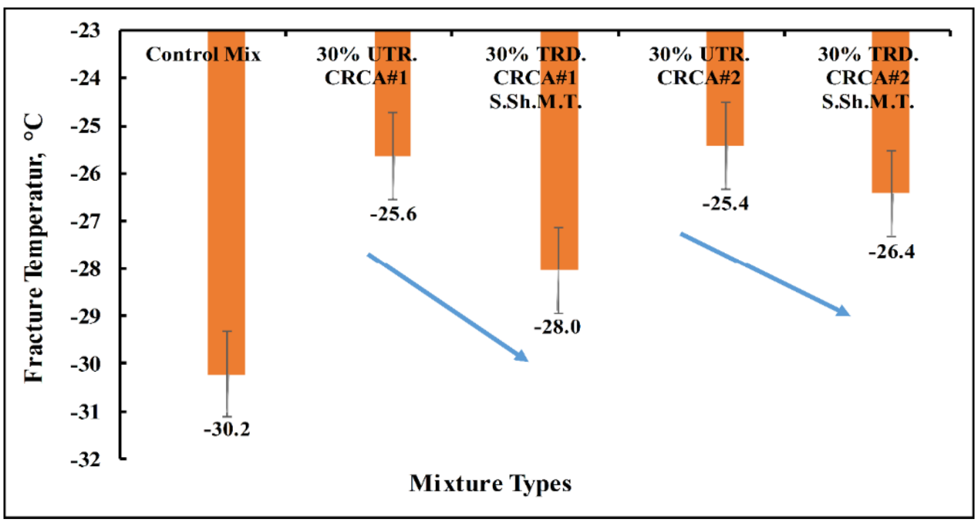


Figure 14.5: Effect of Treated CRCA with the combination of pre-soaking and short mechanical treatment on the Fracture temperature of asphalt mixtures.

14.4 Influence of CRCA Addition on the Fracture Stress

Tables 14-1 and 14-2 demonstrate the average of the fracture stress for different asphalt mixtures that include various CRCA types with various proportions of untreated and treated CRCA with different treatment methods. It is known that the higher value of fracture stress corresponds to a significant resistance to thermal cracks and vice versa. The details of the obtained results are explained in the following paragraphs.

14.4.1 Effect of Untreated CRCA on the Fracture Stress

14.4.1.1 Effect of CRCA Proportion on the Fracture Stress

From the perspective of the proportion of CRCA, Figure 14.6 shows the average of fracture stress for HMA mixtures that included different proportions of untreated CRCA#1. The obtained results indicate that the fracture stress levels of the mixtures that included 30% untreated CRCA#1 are higher than the fracture stress of the control mix followed by the mixtures that included 60% untreated CRCA#1. The mentioned mixtures registered an increase by 12.2% and 7% respectively. In addition, it is important to mention that the mixture that included 15% untreated CRCA#1 had a lower fracture stress compared to the control mix. These results indicate that the utilization of RCA in the asphalt mixtures is generally successful (Zhang et al., 2016). However, the obtained findings are inconsistent with the fracture temperature results. Therefore, it can be stated that the outcomes regarding fracture stress appear to be completely opposite compared to the fracture temperature results with respect to the influence of the CRCA proportions.

Figure 14.7 presents the effects of different CRCA types on the fracture stress of HMA mixtures. The mentioned figure demonstrates the outcomes of the effect of untreated CRCA #1 and CRCA#2 with various proportions (30% and 60%) on the fracture stress. For the mixtures that included 30% or 60% untreated CRCA, the outcomes showed that the mixtures that included CRCA#1 exhibit a higher fracture stress compared to the control mix and the mixtures that included untreated CRCA#2 at the same proportions. This indicates that the application of CRCA#1 in the asphalt mixtures is more suitable and preferable than

CRCA#2. These findings confirm the other laboratory results including the tests of physical and mechanical properties and different performance tests such as rutting and tensile strength. This could possibly be as mentioned earlier because of untreated CRCA#1 has a rougher surface with many crushed faces than untreated CRCA#2 due to having more attached mortar on its surface.

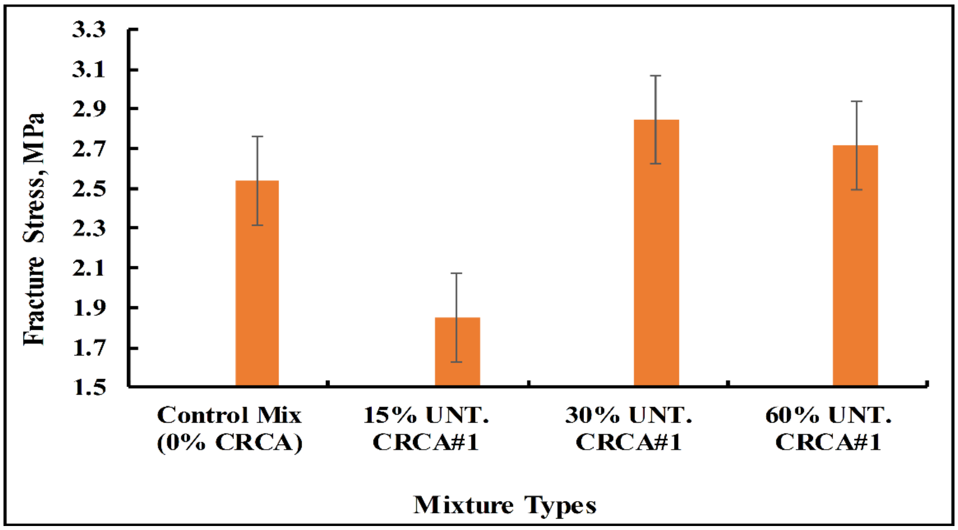


Figure 14.6: Fracture stress of asphalt mixtures that included different proportions of Untreated CRCA#1.

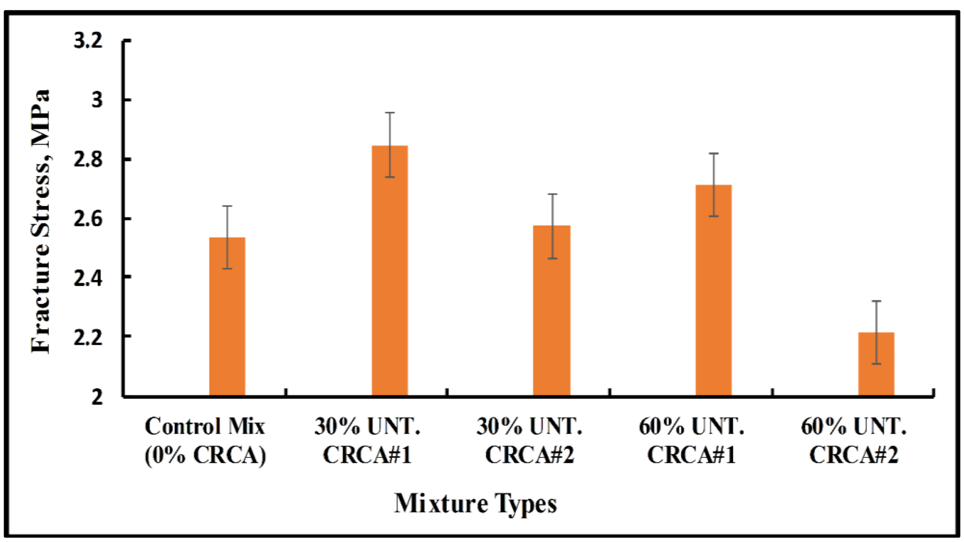


Figure 14.7: Fracture stress of asphalt mixtures included different CRCA types with various proportions.

14.4.2 Influence of Treated CRCA on the Fracture Stress

Figure 14.8 displays the average values of the fracture stress of HMA mixtures that included treated CRCA with a combination of heat treatment at 300 °C and short mechanical treatment. The values of the fracture stress for the mixture that included treated CRCA with this combination approach has a lower fracture stress value compared to the mixture that included untreated CRCA with the same percentage. Similar behaviour is registered for both CRCA types. The mentioned mixtures recorded low reduction percentages with values of (2%) and (8%) for CRCA#1 and CRCA#2, respectively. The obtained values indicate little negative impact for this combination approach on fracture stress. However, the fracture stress value of the mixture that included 30% treated CRCA#1 is still higher than the value of the control mix. In contrast, the value of the mixture that included the same percentage of treated CRCA#2 is slightly lower, showing a reduction of (7%), relative to the value of the control mix. In terms of the application of pre-soaking and short mechanical treatment, the average values of the fracture stress of asphalt mixtures that included treated CRCA with this combination approach is provided in Figure 14.9. The obtained findings indicate that the mixture that included 30% treated CRCA#1 with this approach has a lower fracture stress than the control mix with a reduction value of (5.9%). Interestingly, the mixture that included 30% treated CRCA#2 with the same technique has a similar fracture stress value to the control mix with a value of 2.54 MPa. These results indicate that there is generally no effect for this combination type on enhancing the resistance of fracture stress of asphalt mixtures. In conclusion, the obtained results of fracture stress appear to exhibit a different behavior compared to the fracture temperature for the same mixtures that included similar CRCA types with the same proportions. Additionally, it can be stated that the application of a combination of different treatments had a significant effect on the fracture temperature, whereas it has no impact on the fracture stress of asphalt mixtures.

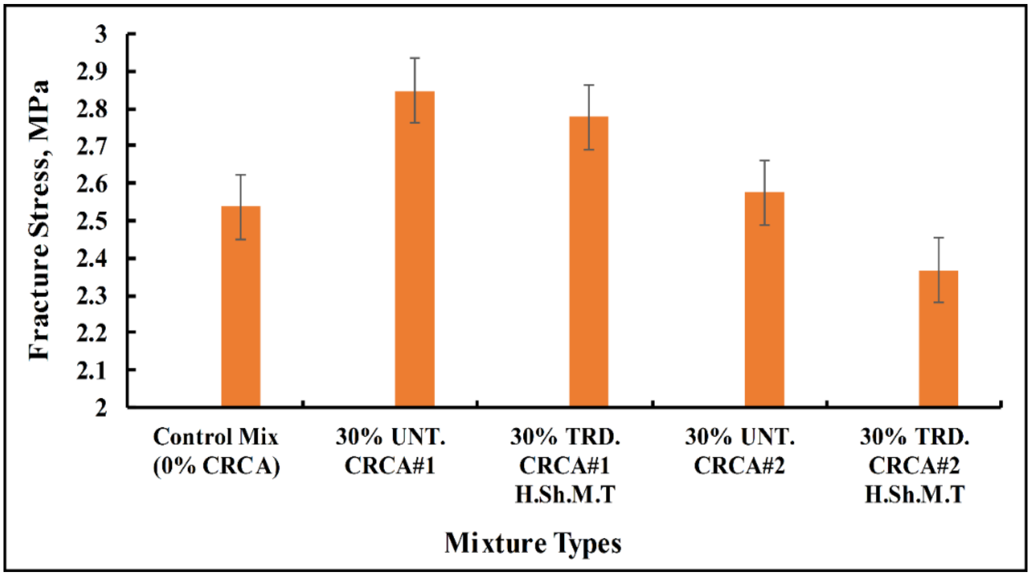


Figure 14.8: Fracture stress of asphalt mixtures that included different types of treated CRCA with heat and short mechanical treatment.

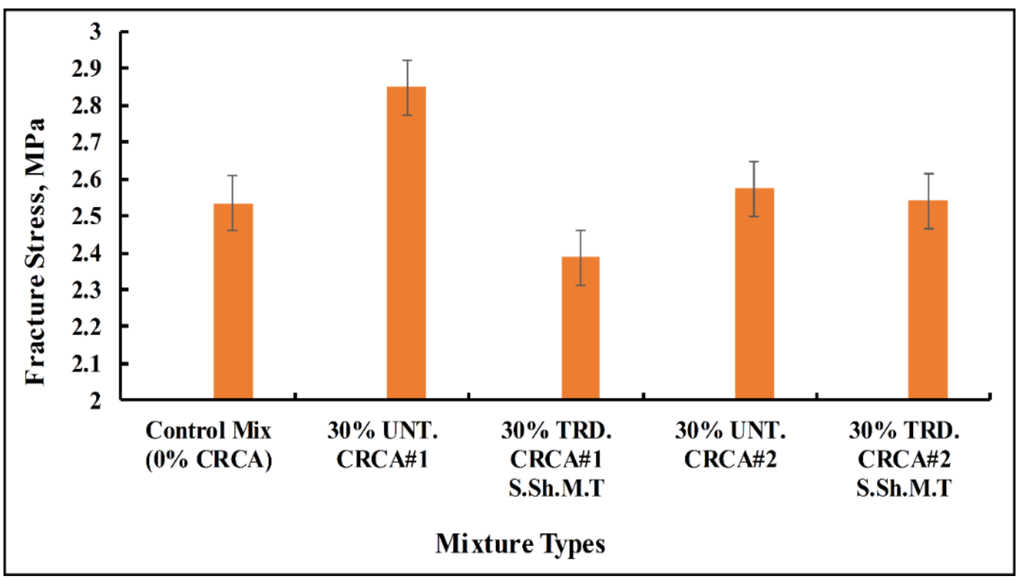


Figure 14.9: Fracture stress of asphalt mixtures that included different types of treated CRCA with pre-soaking and short mechanical treatment.

14.5 Statistical Analysis

Table 14-3 summarizes statistical aspects of fracture temperature and fracture stress including standard deviation and coefficient of variation. In general, the statistical results showed that the coefficients of variation of the fracture stress are much higher values than the coefficients of variation of the fracture temperature. This indicates there is a strong possibility to use the fracture temperature as a parameter to rank the low temperature resistance of asphalt mixtures.

Table 14-3: Statistical Analysis of the Results of TSRST

Mixture Types	Std. dev. for Fracture Temperature	COV for Fracture Temperature (%)	Std. dev. for Fracture Stress	COV for Fracture Stress (%)
Control mix (0% CRCA)	1.52	**-5.02**	0.68	26.92
15% untreated CRCA#1	0.60	**-2.36**	0.15	8.33
30% untreated CRCA#1	0.15	**-0.60**	0.16	5.74
60% untreated CRCA#1	0.22	**-0.82**	0.17	6.34
30% untreated CRCA#2	0.70	**-2.74**	0.05	1.80
60% untreated CRCA#2	1.51	**-5.79**	0.20	9.10
30% treated CRCA#1 H.Sh.M.T.	0.20	**-0.60**	0.30	12.1
30% treated CRCA#2 H.Sh.M.T.	0.18	**-0.67**	0.21	8.98
30% treated CRCA#1 S.Sh.M.T.	1.23	**-4.40**	0.07	3.05
30% treated CRCA#2 S.Sh.M.T.	0.25	**-0.95**	0.15	5.79

A two-way ANOVA analysis was carried out on the different mixture results, representing three replicate specimens of various asphalt mixtures to examine the effect of many parameters on the low-temperature cracks (thermal cracks). The mentioned parameters include different CRCA proportions (0%, 15%, 30%, and 60%); various CRCA types; different treatment types: heat treatment at 300°C followed by short mechanical treatment and pre-soaking in acetic acid solution followed by short mechanical treatment; and the type of evaluated factor: fracture temperature and fracture stress. The ANOVA analysis was carried out with a probability of 95%. In the analysis of the two-way ANOVA, the major impact could possibly be determined from the variables as well as their significance. A higher value of the sum of the squares typically relates to which of the variables has the main effect. When there is a significant interaction between two different variables, the major impact cannot be determined.

The obtained results showed that there is a statistically insignificant effect of CRCA type and its proportion on the fracture temperature of asphalt mixtures, with F_{actual} (0.085) < $F_{critical}$ (5.318) and F_{actual} (1.06) < $F_{critical}$ (5.318) and p-values of (0.778) and (0.334), respectively. However, the effects of CRCA type and its proportion are acting independently due to an insignificant interaction between the mentioned variables, with Factual (0.005) < Fcritical (5.3177) and a p-value of (0.948). Interestingly, the statistical analysis results demonstrated that the CRCA proportion has a greater impact on the fracture temperature of asphalt mixtures than the type of CRCA.
In terms of the influence of CRCA type and its proportion on the fracture stress, the statistical ANOVA analysis revealed that the type of CRCA has a significant effect on the fracture stress with Factual (11.98) > Fcritical (5.32) and a p-value of (0.009). Meanwhile, the obtained findings indicated that there is a statistically insignificant effect of CRCA proportion on the fracture stress of asphalt mixtures, with Factual (4.89) < Fcritical (5.32) and a p-value of (0.06). Thus, a variation in the CRCA type will lead to a higher impact on the value of fracture stress of asphalt mixtures than its proportion. Hence, the mentioned parameters demonstrated an opposite behavior compared to their impact on the fracture temperature of HMA mixtures.

In terms of studying the statistical interaction between the CRCA type and treatment methods for both fracture temperature and fracture stress, the obtained findings showed the effects of these variables are acting independently for both fracture temperature and fracture stress due to an insignificant interaction between the mentioned variables with p-values of (0.289) and (0.134), respectively. Interestingly, the CRCA type and treatment methods have a significant impact on the fracture temperature with p-values of (0.018) and (0.000), respectively. The higher value of (SS) is registered for the type of treatment methods, with a value of (15.56), which is higher than the value of (SS) based on the type of CRCA. This indicates that the type of treatment method statistically has the main impact on the fracture temperature of the HMA mixtures rather than the type of CRCA. Meanwhile, the statistical analysis showed that there is a statistically insignificant effect of both the type of CRCA and the type of treatment method on the fracture stress of asphalt mixtures. The effects of these parameters are acting independently due to an insignificant interaction between the mentioned parameters. Heterogeneity of CRCA and its inferior properties such as the surface texture, porosity, and density could possibly have an impact on the fracture stress of different asphalt mixtures. The obtained results of a two-way ANOVA analysis are numerically tabulated in Table 14.4.

Table 14-4: Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of Fracture Temperature and Fracture Stress

Source of Variation		Fracture Temperature	Fracture Stress
CRCA type	P-value	0.7777	< 0.0086
	SS	0.0906	0.4454
	F	0.0852	11.9764
	F- critical	5.3177	5.31766
CRCA%	P-value	0.3333	0.0580
	SS	1.1269	0.1817
	F	1.0603	4.8858
	F- critical	5.3177	5.3177
Interaction	P-value	0.9477	0.3392
	SS	0.0049	0.0384
	F	0.0046	1.033
	F- critical	5.3177	5.3177
CRCA type	P-value	< 0.0175	0.1316
	SS	4.0980	0.1405
	F	7.5827	2.6184
	F- critical	4.7472	4.7472
Treatment methods	P-value	< 0.0006	0.2233
	SS	15.5636	0.1826
	F	14.3990	1.7033
	F- critical	3.8853	3.8853
Interaction	P-value	0.2891	0.1337
	SS	1.4899	0.2565
	F	1.3785	2.3905
	F- critical	3.8853	3.8853

14.6 Summary of This Chapter

This chapter investigated the influence of CRCA addition on the thermal cracks of Ontario Superpave mixtures. Based on the obtained results, the main points of this chapter can be summarized as follows:

- The outcomes indicated that the variation in the CRCA proportions has an impact on the fracture thermal stress and the fracture temperature.
- Compared to the control mix, 0% CRCA, it is noted that the average fracture temperature increases due to the untreated CRCA addition and there is no significant impact for the type of RCA on the thermal cracks at low temperatures.
- While the application of the combination of various treatments leads to a significant reduction in the average fracture temperature, there is no impact of these techniques on the fracture stress of the asphalt mixtures.
- The combination of heat at 300 °C and short mechanical treatments has a considerable effect on the fracture temperature of asphalt mixtures, more so than the combination of pre-soaking in weak acid and short mechanical treatment.
- The combination of heat at 300 °C and short mechanical treatment leads to obtaining a fracture temperature of -28.2 °C and -27.2 °C, registering a reduction of 10.2% and 7.1% for the mixtures that included 30% treated CRCA#1 and CRCA#2 respectively compared to the fracture temperature of the mixtures that included 30% untreated CRCA types.
- The combination of pre-soaking in acetic acid and short mechanical treatment leads to an important reduction in the average fracture temperature for both CRCA types. The average fracture temperatures were -28.0 °C and -26.2 °C, registering a reduction of 9.4% and 4% for the mixtures that included 30% treated CRCA#1 and CRCA#2 respectively compared to the mixtures that included untreated CRCA types.
- It can be stated that the mixtures that included treated CRCA#1 have more resistance to low temperature cracking than the mixtures that included treated CRCA#2.
- The mixtures that included different types of untreated CRCA with various percentages have higher fracture stress values than the control mix, whereas the fracture temperature exhibits an opposite behaviour.

- The mixtures that included treated CRCA have a lower fracture stress than the mixtures that included the same percentage of untreated CRCA. This behavior was registered for different treatment approaches.
- The results of the statistical analysis demonstrated that the fracture temperature can be used to rank the low-temperature resistance of different asphalt mixtures.
- From the outcomes of the ANOVA analysis, the effect of CRCA type and its proportion are acting independently on the fracture temperature, due to an insignificant interaction between the mentioned variables. However, the CRCA proportion has the higher impact on the fracture temperature of asphalt mixtures compared to the type of CRCA.
- The findings of ANOVA indicated that both the type of treatment method and the type of CRCA have a considerable effect on the fracture temperature of asphalt mixtures. Nevertheless, the type of treatment method has the higher impact compared to the type of CRCA.
- The obtained results of ANOVA analysis showed that both the type of treatment method and the type of CRCA have an insignificant effect on the fracture stress of asphalt mixtures.

CHAPTER 15

COST ANALYSIS

In this chapter, the obtained results of CRCA#1 have been published in the Resources, Conservation & Recycling Journal (Al-Bayati et al., 2018).

15.1 Economic Cost Analysis

For a pavement construction project, a large portion of the project cost is due to raw material procurement and production. Thus, reduced need for virgin aggregate in HMA mixtures by incorporating CRCA into asphalt mixtures is an approach that could not only reduce pavement environmental impact but also the economic cost. For the comparative economic evaluation of HMA mix designs, cost savings include a comparison of the cost of various mix designs that included different proportions of untreated CRCA compared to the control mix design with 0% CRCA. To obtain a better evaluation of the balance comparison, the cost of heat and pre-soaking treatments is estimated for 1 m^3 of mixture. This leads to the evaluation of savings offset by the additional cost of the above-mentioned treatments for the respective mixtures. Table 15-1 summarizes the required material weight in kilograms for preparing 1 m^3 of various asphalt mixtures that were analyzed in this study.

Table 15-1: Material Content of Components in 1 m^3 of HMA Mix Design Blends

	Control Mix, Kg	15% untreated CRCA, Kg	30% untreated CRCA, Kg	30% treated CRCA heat & Sh.M.T, Kg	30% treated CRCA soaking & Sh.M.T, Kg	60% untreated CRCA, Kg
Percentage of CRCA (%)	0	15	30	30	30	60
Heat treatment				√		
Acid soaking treatment					√	
Asphalt binder (PG 64-28)	141.23	143.28	155.26	155.26	155.26	166.96
CA#1 HL8 stone	1113.11	903.48	678.34	678.34	678.34	297.76
CA#2 1/4 Chip	333.93	318.63	387.62	387.62	387.62	303.27
FA#1 Manufactured sand	987.88	970.63	841.70	841.70	841.70	879.50
FA#2 Blend sand	278.28	292.47	332.25	332.25	332.25	330.84
Dust plant	69.57	72.99	85.83	85.83	85.83	85.47
CRCA	0.00	222.23	443.00	443.00	443.00	860.20

* Sh.M.T = Short mechanical treatment.

15.1.1 Cost of Materials

The cost of materials required for this research was obtained based on domestic communications with several asphalt concrete producers. However, the material costs were validated using a specific search for material prices in both industrial and agency websites. The price of NA ranged from $18/tonne to $26/tonne. In the present study, NA consists of two main sizes of coarse and fine aggregates. While coarse aggregate includes two different types, namely, CA#1 and CA#2, there are also two fine aggregate types; FA#1 and FA#2. For asphalt concrete producers, it is known that Dust plant is a by-product material with a very low price; approximately negligible. Therefore, it is considered that Dust plant has no cost compared to other materials. For RCA, the price ranged between $7.50/tonne and $8.00/tonne, implying an average price of $7.75/tonne, fluctuating ±25 cents from its average. To evaluate the influence of this variation on the total cost, this uncertainty is considered in the sensitivity analysis. It is generally known that the cost of asphalt binder varies with fluctuations in crude oil prices. In Canada, the most recent price was between $834.51/tonne and $719.51/tonne (Province of Nova Scotia, 2017; Wessel et al., 2016). The sensitivity of the total cost of asphalt mixture designs to the variation in the asphalt binder price was also considered.

15.1.2 Cost of Treatment of CRCA

The cost analysis for various treatment methods of CRCA to produce 1 m^3 of an asphalt mixture with 30% CRCA is evaluated. As mentioned earlier, two different treatments for improving CRCA quality; namely, heat and pre-soaking with acetic acid were investigated. For the heat treatment, CRCA was heated in an oven, Lindberg Blue M laboratory, for 1 h with an average energy consumption of 1.8 kWh/h. Based on the current time-of-use rate of electricity in Ontario, the energy cost is estimated at approximately 9.5 cents per kWh (Waterloo North Hydro, 2017). By applying simple calculations, the cost of heat treatment of CRCA to produce 1 m^3 of the asphalt mixture with 30% CRCA is very reasonable, approximately $0.17. For pre-soaking treatment, CRCA was soaked with 0.1 M acetic acid solution. Based on the manufacturer's website, the cost of acetic acid is $11.76 for a container of volume 2.5 l. During acid treatment, only 5.74 ml of acetic acid was mixed with distilled water to prepare 1 l acidic solution with a concentration of 0.1 M. Considering the above-mentioned information, the cost of acid treatment of CRCA for the production of 1 m^3 of asphalt mixture with 30% CRCA is approximately $0.03. It is concluded that the cost of both heat and pre-soaking treatment is quite reasonable. This amounts to noticeable economic benefits and indicates that these treatments could be applicable. However, more research is required from the technical point of view, especially, large-scale application.

15.2 Results and Discussion

15.2.1 Total Cost of Asphalt Mixtures

As mentioned earlier, Table 15-1 shows the required materials for preparing 1 m^3 of asphalt mixture with various proportions of CRCA. The cost of materials required for the mentioned volume of various asphalt mixtures was calculated. With the addition of CRCA treatment cost, the total cost of the production of 1 m^3 of various asphalt mixtures was obtained. Due to the fluctuation in the price of both binder asphalt and CRCA, various total costs of various asphalt mixtures were calculated and presented in Table 15-2. The obtained results indicate that the total cost of asphalt mixture generally increases as the CRCA proportion is increased for fluctuating prices. It is noteworthy that the mixture with 15% CRCA has a lower cost in comparison to the control mixture. Interestingly, this outcome is noticeable for various fluctuations. Though there is a considerable addition; 60%; of CRCA to the asphalt mixture, an insignificant cost difference is registered for this mixture compared to the control asphalt mixture. For various CRCA prices, this cost difference is estimated at approximately $5 and $8 for the lowest and highest price of asphalt binder, respectively. With various price fluctuations, it is interesting to note that the total cost of mixtures that included 30% treated CRCA is very comparable, with an approximately negligible difference of less than $1 compared to the cost of mixtures that included 30% untreated CRCA. Though various treatment approaches were applied for treating and improving CRCA quality, the same negligible difference is observed. In comparison to the cost savings of the control mixture, the cost savings for producing 1 m^3 of various asphalt mixtures are presented in Figure 15.1. Among various mixtures, the asphalt mixture with 15% CRCA has a positive cost saving. More precisely, there is a cost saving of approximately $2 for the asphalt mixture with 15% untreated CRCA while a negative cost saving of approximately $-3.00 and $-5.00 registered for the mixtures with 30% and 60% untreated CRCA, respectively. For various fluctuations, the cost savings of mixtures that included 30% treated CRCA is very similar, approximately equal to the cost savings of mixtures that included 30% untreated CRCA. Based on this, it seems that there is no influence, approximately negligible, of the cost of CRCA treatment on the cost saving whereas the cost savings are highly influenced by the percentage of untreated CRCA addition. From an economic perspective, the obtained findings of various treatment applications for CRCA are very promising and highly useful for asphalt industry companies and related agencies. Nevertheless, more research into the environmental impact and practical application of various treatment methods is still required to optimize their utilization.

Table 15-2: Sensitivity Analysis of CRCA Price and Asphalt Binder Price on the Total Cost of HMA Mix Design Blends Production

	Control Mix	15% untreated CRCA	30% untreated CRCA	30% treated CRCA heat & Sh.M.T	30% treated CRCA soaking & Sh.M.T	60% untreated CRCA	
Percentage of CRCA (%)	**0**	**15**	**30**	**30**	**30**	**60**	
CRCA price 1 ($7.75/t)	$159.38	$157.42	$162.54	$162.71	$162.57	$164.24	Binder 1[a]
	$175.68	$173.95	$180.46	$180.63	$180.49	$183.51	Binder 2[a]
CRCA price 2 ($7.5/t)	$159.38	$157.36	$162.43	$162.60	$162.46	$164.02	Binder 1
	$175.68	$173.95	$180.46	$180.63	$180.49	$183.51	Binder 2
CRCA price 3 ($8.0/t)	$159.38	$157.47	$162.65	$162.82	$162.68	$164.45	Binder 1
	$175.68	$174.01	$180.57	$180.74	$180.60	$183.72	Binder 2

***** Sh.M.T = Short mechanical treatment.

a Binder 1 and Binder 2 represent PG 64-28 highest $834.51/tonne and lowest $719.51 prices posted in Canada for 2017.

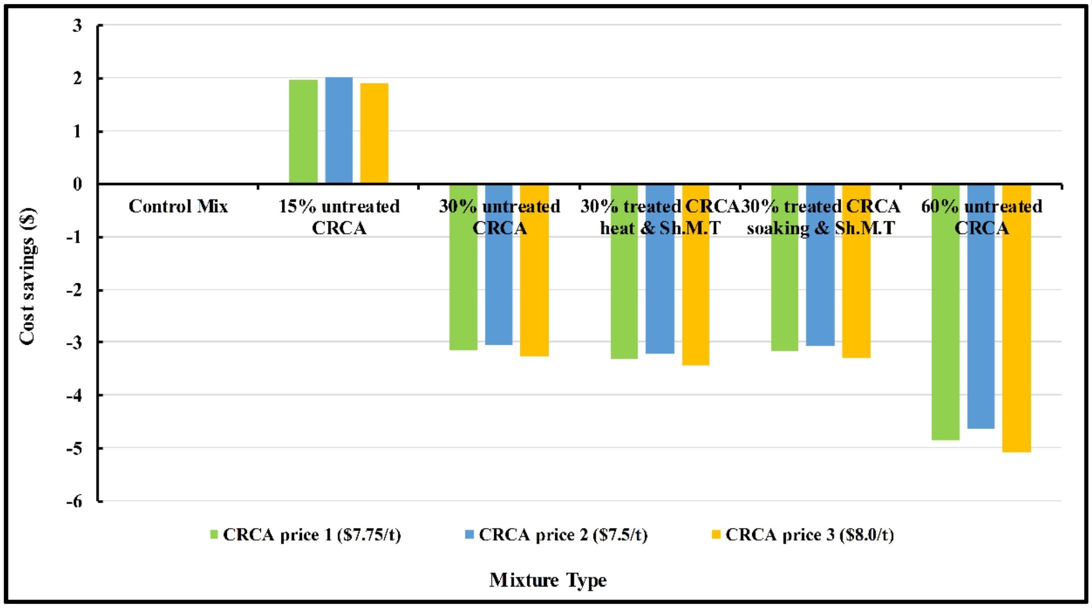


Figure 15.1: Cost savings of asphalt mixtures that included both treated and untreated CRCA for producing a volume of 1 m^3.

CHAPTER 16

CONCLUSIONS, RECOMMENDATIONS, AND FUTURE RESEARCH

16.1 Conclusions

The conclusions are presented based on the sequence of thesis chapters.

16.1.1 Impact of Various Treatment Methods on Improving Characteristics of CRCA

Based on the experimental results related to the comparison of various treatment methods for the enhancement of CRCA characteristics, the following conclusions can be drawn:

- With respect to the type of RCA, a significant difference is registered between types of untreated RCA in terms of physical and mechanical properties. This variation could be attributed to the original source of RCA and the amount of adhered mortar.
- The use of various techniques of heat treatment and pre-soaking treatment methods is highly successful methods for improving various physical and mechanical properties of RCA.
- Separately, among different treatment methods, heat treatment type at 350 °C has a maximum influence for enhancing various physical and mechanical properties of CRCA including water absorption, specific gravity, porosity, and abrasion loss.
- The use of heat treatment method is successful in improving various physical properties including water absorption, specific gravity, porosity and freezing, and thawing. However, it is recommended to use this method at temperatures between 300 °C and 350 °C because of the noticeable negative effects of higher temperatures on CRCA characteristics. The aggregate suffers from thermal expansion followed by internal stresses due to exposure to a high temperature between 400 °C and 600 °C. Whereas there is serious microcracking of

the cement matrix when the material is exposed to a higher temperature range between 600 °C and 800 °C resulting in degradation, breakdown and mass loss of aggregate.

- It is highly recommended to use heat treatment type at temperatures between 300 °C-350 °C because of noticeable negative effects of higher temperatures on different physical and mechanical CRCA characteristics.
- The acid treatment at low concentration is an effective technique to enhance the physical and mechanical characteristics of CRCA depending on the acid type due to the corrosive influence on the attached mortar. However, it is interesting to conclude that using weak acid is more effective than strong acid to enhance mechanical properties in terms of abrasion loss and adhered mortar loss, whereas acid treatment with strong acid appears to be more efficient in improving water absorption and porosity.
- Physical properties of CRCA, namely, porosity and water absorption are strongly correlated with durability characteristics in terms of resistance to freezing and thawing and abrasion resistance under influence of heat treatment.
- A strong correlation is observed between different durability characteristics including resistance to freezing and thawing, abrasion resistance, and adhered mortar loss under the influence of heat treatment.

16.1.2 Influence of the Combination of Various Treatments on the Properties of CRCA

According to the laboratory experiments related to the combination of various treatments on the properties of CRCA, the main conclusions are presented as follows:

- The utilization of combination method between different treatment types is a highly successful technique for improving physical and mechanical characteristics of CRCA compared with separate (single) treatments due to a considerable difference in the findings of the present study with the results of related literature.
- The laboratory results demonstrated that there is a negative impact for the heat treatment combined with/without mechanical treatment at the high temperatures ranging between (350 °C-750 °C) on the physical and mechanical properties of RCA.

- The outcomes revealed that the type of short mechanical treatment, with/without steel balls, has a considerable impact on the adhered mortar loss.
- The obtained findings indicate a strong relationship between different physical properties, physical and mechanical characteristics, and various mechanical properties due to obtaining considerable regressions.
- Among various treatments, the combination of both heat treatment at 300 °C and pre-soaking with weak acid treatment with short mechanical treatment (without balls) exhibits the best performance; therefore, these methods are chosen to be further used with a short mechanical treatment (with balls) to achieve further improvement in the CRCA properties for asphalt mixture applications.

16.1.3 Influence of Treatment Methods on Surface Characterization of CRCA

Based on the comparison of various treatment methods for the enhancement of the surface characteristics for CRCA, the major conclusions can be provided as shown below:

- The observations of SEM tests indicated that the surface morphology of untreated CRCA was a rough and heterogeneous surface and highly porous structure, whereas the surface of treated CRCA was more homogeneous and had less adhered mortar depending on treatment type. However, there was evident damage on the CRCA surface due to the effect of the strong acid attack.
- A significant enhancement of CRCA microstructure was obtained under the influence of various treatment types. However, improved microstructure mainly includes increased density, increased surface homogeneity and reduced Ca/Si ratio. Besides this, there is a strong possibility for increasing the strength of CRCA in other ways.
- Strong relations with a significant correlation are obtained for mineralogical characteristics of CRCA in terms of Ca/Si ratio with durable and mechanical properties including abrasion loss and adhered mortar loss under the impact of heat treatment.
- The acid treatment at low concentration is an effective technique to enhance the quality of CRCA depending on the acid type due to corrosive influence on the attached mortar. However, it is concluded that using weak acid is more efficient than the strong acid to

decrease the influence of acid attacks on the CRCA surface as demonstrated by the characterization images.

16.1.4 Effect of Various Treatment Methods on Microstructure Properties of CRCA

The main conclusions based on the obtained results are displayed as follows:

- Heat treatment at temperatures ranging between (0-350 °C) has a strong positive influence on pore size reduction due to the dramatic decrease of pore volume values, whereas there is a significant negative impact of heat treatment within a temperature range of (350-500 °C) due to a considerable increase of pore size compared with untreated CRCA.
- A successful acid treatment is recorded for both types: strong and weak acid for decreasing pore size of CRCA. However, the treatment method using strong acid seems to be more effective due to a slight difference compared with a weak acid.
- Heat treatment has a negative effect on the properties of the matrix cracks including width and length on the mortar surface. This influence is considerably increased at temperatures that ranged between (350-500 °C).
- It is concluded that the impact of both acid treatments on the properties of matrix cracks including width and length is similar to the influence of heat treatment at temperatures between (0-350 °C).
- Crack density on the mortar side is strongly correlated with properties of matrix cracks including width and length due to a significant regression. However, a considerable difference in the behavior is clearly observed between properties of matrix cracks and crack density.

16.1.5 Effect of Different Treatments on the ITZ Zone Microstructure of CRCA

According to the obtained findings, the major conclusions are presented as follows:

- The heat treatment method is highly successful in improving the properties of microcracks in the ITZ including width and length of microcracks. It is concluded that there is an inverse relationship between microcrack properties, including width and length and increasing temperatures. However, heat treatment at high temperature (500 °C) has very little influence on microcrack width due to a slight increase compared with microcrack width at 350 °C.

- Acid treatment is an effective technique for lowering width and length of microcracks in the ITZ. However, treatment using weak acid appears to be more successful than strong acid due to a slight difference in the obtained results for both types of acid treatment.
- Heat treatment at 250 °C exhibits the best performance by considerably decreasing the Ca atoms and greatly increasing the Si atoms for the mortar side compared with the aggregate surface, resulting in a considerable decrease in the Ca/Si ratio, which indicates significant enhancement for the ITZ zone. However, there is a negative impact for heat treatment at higher temperatures between (350-500 °C) on the atomic Ca/Si ratio for both aggregate and the mortar side of the ITZ.
- Utilization of acetic acid treatment leads to a significant reduction of the Ca/Si ratio for the aggregate side compared with HCl acid treatment, whereas HCl treatment seems to be more successful for lowering the Ca/Si ratio on the mortar side.
- The best performance of transformation to the CSH phase was observed at 250 °C for the aggregate side of the ITZ, whereas the mortar side improvement through CSH transformation is recorded at 350 °C as an optimum behaviour.
- It is concluded that the use of acetic acid treatment is more successful for CSH transformation for the mortar side of the ITZ, whereas HCl acid treatment seems to be highly effective for CSH transformation on the aggregate side of the ITZ.

16.1.6 Evaluation of ITZ Improvement

The main conclusions based on the obtained results are presented as follows:

- The use of heat treatment method is highly successful in improving the ITZ region. It is concluded that heat treatment at high temperature (500 °C) has no influence on the ITZ region. However, it is seen that cracks form in the mortar of CRCA at high temperature (500 °C), indicating a negative impact on mortar properties. Therefore, it is recommended to use this method at temperatures between 300 °C and 350 °C.

- Acid treatment is an effective technique for enhancing the ITZ region. However, treatment using weak acid appears to be more successful and effective than strong acid due to a significant difference in the obtained results for both types of acid treatment.
- This study clearly indicates the increase of both CSH compounds for different treatment types. However, a significant increase was observed for acetic acid treatment type compared to other treatment approaches.
- In terms of CSH compounds, the acetic acid treatment type exhibits the best performance for increasing tobermorite and jennite compared to other treatment types. However, there is a significant difference in the obtained results for both types of acid treatment in terms of jennite, indicating a specific sensitivity to the HCl acid environment.

16.1.7 Effect of Various Filler Proportion in HMA

Based on the laboratory experiments related to the application of various filler proportion in HMA mixtures, the following conclusions can be drawn:

- The OAC decreases when the filler percentage is increased. However, a significant decrease in the optimum asphalt binder content is observed when filler content is increased from 2.5% to 3%.
- It is seen that an increase in filler content decreases the VMA of the mixture. Compared to MTO specifications, the obtained results are higher than the required proportion.
- VFA values are proportionally reduced depending on the increase in the filler content. Based on MTO requirements, it is indicated that the study findings are higher than the lower limit.
- Compared to other volumetric properties, Dp proportion behaves inversely; Dp proportion increases when the filler content is increased. The obtained values of Dp for the mix design with a 2% filler content are unacceptable due to lower values, whereas the experimental values of Dp for mix design with filler contents of 2.5% and 3% were acceptable based on MTO specifications.

- Similar behaviour for the G_{mm} and G_{mb} properties with respect to various proportions is observed. When the filler percentage increased, the values of G_{mm} and G_{mb} increased.

- The addition of filler of 2.5% was very successful as it satisfied all MTO requirements for volumetric properties of HMA. Based on MTO specifications, the addition of 2.0% filler appears to be unsuccessful due to lowering the dust to asphalt binder ratio. Mix design with 3.0% filler was also unsuccessful because of the lower value of OAC meaning that the mix is dry and there is insufficient asphalt binder to coat the aggregate particles.

16.1.8 Effect of Various CRCA Types with Different Proportions on the Volumetric Properties of HMA

Depending on the experiments related to the application of untreated CRCA and treated CRCA with different treatment techniques in HMA, the main conclusions are provided as below:

- For lower proportions of CRCA addition; namely, 0% and 15%, one trial was needed for achieving MTO requirements, whereas it was performed using two trials for CRCA#1 addition of 30% and 60%. The mix blend included 30% treated CRCA with both heat treatment and soaking in weak acid solution, then followed by a short mechanical treatment and was similar to the satisfied mix blend involving 30% untreated CRCA.

- The percentage of increase in OAC is affected by the original source and proportions for RCA.

- The NA replacement by different CRCA types CRCA leads to increase the OAC for the
- mixtures. For both types, there was a considerable reduction in OAC for mixtures included with 30% of treated CRCA with various treatment approaches compared to the mixture with 30% untreated CRCA. However, a significant difference between various treatment methods is observed; resulting in soaking with acetic acid solution approach seems to be more efficient and favourable.

- The increase in CRCA percentage leads to absorption of some of the asphalt in the mixture due to the porosity of the CRCA surface, resulting in a reduction of the effective asphalt content, and therefore, the VMA is reduced. Compared to the mixture with 30% untreated CRCA, a reasonable improvement in the VMA value is obtained for mixtures with 30% treated CRCA with different treatment types. However, no considerable difference between various treatment methods is found.

- Compared to the behaviour of the VMA property, a comparable behaviour is observed for the VFA characteristic. For both types, a very small improvement in the VFA value is registered for mixtures that included 30% treated CRCA with different treatment approaches compared to the mixture with 30% untreated CRCA. This indicates that there is no significant influence of various treatment approaches on this volumetric property.
- As the proportion of CRCA addition increases, both G_{mb} and G_{mm} of the mixes are decreased for both CRCA types. Compared to the mixture with 30% untreated CRCA, it is found that an insignificant increase in both G_{mb} and G_{mm} properties is obtained for mixtures that included 30% treated CRCA with various treatment approaches.
- Laboratory findings demonstrated that the Dp value for the mixture with 60% untreated CRCA#1 is comparable to the control mix, registering a negative influence for the higher percentages on this characteristic. For CRCA#2, the results showed that there is a gradual increase in Dp value when CRCA proportion was increased to 60%.
- It is also found that there is no influence of various treatment approaches on this volumetric property. However, the Dp values are within the acceptable range of MTO standards.
- With CRCA addition to mixtures, the findings indicated that the values of volumetric properties including G_{mm} $N_{initial}$ (%), G_{mm} N_{des}. (%), and G_{mm} N_{max} (%) are completely satisfied in relation to the MTO requirements. It is found that there is no impact of CRCA types and different treatment methods on these volumetric properties.
- The CRCA addition with different types and proportions seems to be completely successful for both untreated and treated CRCA due to achieving all MTO requirements for volumetric properties of HMA. However, CRCA treated with different treatment methods is more successful than untreated CRCA applications. The obtained findings

widely open RCA applications and relieve the severe hesitation about the possibility of using RCA in HMA.

16.1.9 Investigation of the Effect of RCA on Rutting and Stiffness Characteristics of HMA

According to the obtained results, the main conclusions are presented as shown below:

- The mixtures that included different types of untreated CRCA in various proportions have higher rutting resistance, higher stiffness modulus, and a higher rutting parameter than the control mix (0% CRCA). This indicates that the application of untreated CRCA is highly successful for improving resistance to permanent deformation.
- From the perspective of the type of CRCA, the addition of untreated CRCA#1 up to 30% leads to a higher rutting resistance, higher stiffness modulus, and a higher rutting parameter compared to the addition of untreated CRCA#2. This indicates that the CRCA type has an impact on the rutting characteristics of asphalt mixtures.
- The application of treated CRCA#2 with heat treatment and short mechanical treatment leads to an increase in the rutting resistance, decrease in the total rut depth, a slight increase in the stiffness modulus, and an increase in the rutting parameter of asphalt mixtures compared to the mixtures that included the same proportion of untreated CRCA#2. This indicates a successful application of the combination technique of different treatment methods.
- The mixture that included 30% treated CRCA#1 with pre-soaking method and short mechanical treatment had a higher stiffness than the mixtures that included the same proportion of untreated CRCA#1. For the same treatment approach, the mixtures that included 30% treated CRCA#2 had a higher rutting factor compared to the mixtures that the same proportion of untreated CRCA#2.
- From the perspective of total rut depth, HWRT rut depth, and shear upheave height, the rutting resistance increased for the mixtures that included untreated CRCA for both CRCA types compared to the control mixture. Additionally, the mixture that included

30% untreated CRCA for both CRCA types had more resistance to rutting than the mixtures that included 15% and 60% untreated CRCA.

- The utilization of different types of CRCA in various forms: treated and untreated in the HMA mixtures, points to a successful application of RCA in these mixtures. The results are highly encouraging with respect to using more RCA applications in asphalt pavements.
- The results of ANOVA statistical analysis showed that the variation of the results was statistically significant, indicating that an increase in the CRCA percentage, the CRCA type, and treatment method have a high influence on the stiffness and rutting of HMA.

16.1.10 Effect of Coarse Recycled Concrete Aggregate on the Moisture Susceptibility of HMA

Based on the experimental results, the major conclusions are displayed as follows:

- In the perspective of ITS, the findings showed that unconditioned and conditioned samples that included different untreated CRCA types with various proportions have higher values than the control mix, indicating a highly successful performance for these mixtures that included CRCA.
- The mixtures that included untreated CRCA#1 or CRCA#2 have the same behavior trend in terms of ITS for both conditioned and unconditioned states. Generally, when CRCA increases, the ITS decreases. However, the mixtures that included untreated CRCA#2 up to 60% exhibited a better tensile strength for both ITS conditioned and unconditioned states, registering a higher tensile strength than the mixtures that included the same proportion of untreated CRCA#1.
- A reasonable improvement in the ITS values for both conditioned and unconditioned states was obtained for the mixtures that included 30% treated CRCA with different treatment techniques compared to the mixture that included 30% untreated CRCA. However, the combination of heat and short mechanical treatment had the best performance for improving ITS values for CRCA#1, whereas the combination of pre-

soaking and short mechanical treatment had the best performance for improving ITS values for CRCA#2.

- The laboratory outcomes revealed that all TSR values for mixtures that included different untreated CRCA types with various percentages are higher than the minimum required value of MTO specifications. This indicates a successful application for the CRCA addition in these mixtures.
- From the perspective of the type of CRCA, the mixtures that included untreated CRCA#1 or CRCA#2 exhibited different behaviour trends in terms of TSR. Additionally, the mixtures that included untreated CRCA#1 up to 60% exhibited a better moisture resistance and registered a higher tensile strength ratio than the mixtures that included the same proportion of untreated CRCA#2.
- The use of a combination technique of pre-soaking method with weak acid followed by a short mechanical treatment method is a highly successful method for enhancing the moisture resistance of HMA, whereas a small improvement in the TSR values is registered for mixtures that included 30% treated CRCA with heat and short mechanical treatment techniques. However, the obtained results are much higher than the minimum required TSR value for MTO specifications.
- The results of a two-way ANOVA analysis showed that the type of CRCA had a significant effect on the unconditioned ITS, indicating that a variation in the RCA type will impact the tensile strength of unconditioned ITS. Additionally, there is a statistically significant effect of CRCA percentage on the conditioned ITS. Surprisingly, the type of CRCA has a greater effect on both conditioned and unconditioned ITS of HMA mixtures than the CRCA percentage.
- The results of an ANOVA analysis also demonstrated that the CRCA type is the main factor that impacts the ITS value of asphalt mixtures for both conditioned and unconditioned states as compared to the type of treatment method.
- From the perspective of TSR, the results of the ANOVA analysis showed that there is a statistically insignificant effect of CRCA type, proportion, and treatment method on the

TSR. However, the type of CRCA and the treatment methods have a higher effect on the results of TSR compared to the CRCA percentage.

16.1.11 Investigation of the Influence of CRCA Application on the Low-Temperature Cracking of Asphalt Mixtures

Based on the laboratory results, the following conclusions can be drawn:

- The findings indicate that the average fracture temperature is reduced due to CRCA addition compared to the control mix. However, there is no significant influence for the RCA type on thermal cracks at low temperatures.
- The application of the combination of various treatments results in a considerable reduction of the fracture temperature, indicating a successful application of treated CRCA in HMA mixtures in cold regions. However, the combination of heat at 300 °C and short mechanical treatments has a considerable effect on the fracture temperature of asphalt mixtures more so than the combination of pre-soaking in weak acid and short mechanical treatment.
- The fracture stress of the mixtures that included different untreated CRCA types with various proportions is generally higher than the fracture stress of the control mix, whereas the fracture temperature exhibited an opposite behaviour.
- The obtained results of ANOVA analysis revealed that the CRCA percentage has the higher effect on the fracture temperature of asphalt mixtures compared to the type of CRCA.
- The obtained results statistically revealed that both the type of treatment method and the type of CRCA have a significant impact on the fracture temperature of asphalt mixtures. However, the type of treatment method exhibited a higher effect compared to the type of CRCA.
- The findings of statistical analysis indicated that both the type of treatment method and the type of CRCA have an insignificant effect on the fracture stress of HMA mixtures.

16.1.12 Cost Analysis of the CRCA Application in the Asphalt Mixtures

According to the obtained findings, the main conclusions are provided as below:

- It is concluded that the cost of both heat and pre-soaking treatment is quite reasonable. This amounts to noticeable economic benefits and indicates that these treatments could be applicable.
- The obtained results indicate that the total cost of the asphalt mixture generally increases as the CRCA proportion is increased for fluctuating prices. It is noteworthy that the mixture with 15% CRCA has a lower cost in comparison to the control mixture.

16.2 Expected Contributions

This study includes a number of important contributions. The most important contribution is that the study provides a better understanding of the topic of RCA and removes the hesitation related to RCA usage in various applications. One of the main contributions is the introduction of a deep understanding of how RCA characterization, in terms of physical and mechanical properties, can be effectively measured and quantified. The study also contributes to providing more knowledge related to microstructure surface properties of RCA through the evaluation of various aspects: surface morphology, surface mineralogy, mortar microcracks, ITZ microcracks, etc. Additionally, the current research will provide good knowledge about the relationship between microstructure improvement of RCA and its behaviour. Moreover, the study will encourage different sectors towards the addition of more RCA in typical Ontario HMA mixtures because its addition is feasible through the application of RCA treatment methods. In terms of natural resources, the study will aid in decreasing NA usage through encouraging the construction industry, transportation sector, and related private companies to replace NA with RCA. Furthermore, the current study can participate in reducing the pressure on landfill sites of C & D waste by offering more RCA applications, resulting in various health and environmental benefits. Finally, the study will provide guidelines on how RCA should be treated and how it can be utilized effectively in typical Ontario/Canadian HMA mixtures.

16.3 Recommendations and Guideline for RCA Application

Based on the outcomes of this research, the following is a beneficial list of recommendations that would be helpful in the utilization of RCA in HMA pavement.

- It is important to know the origin of RCA, whether from weak or strong old structures.
- ACV test is suitable to test the strength of RCA before being used.
- Utilization of SEM and EDAX techniques are capable of accurately identifying the morphological and mineralogical properties of CRCA. Therefore, the use of this equipment is highly recommended.
- The use of various treatment techniques can improve the physical, mechanical and microstructural properties of RCA. Therefore, it is highly recommended to treat RCA before its application in asphalt mixtures.
- Investigation of the volumetric properties of HMA mixtures that include RCA is highly recommended. It is important to note that the mixtures must meet all the specification requirements before examination of the performance properties.
- Utilization of untreated RCA in HMA pavements up to 60% is highly successful in hot regions and regions where the temperatures could drop to (-25 °C) with low and moderate traffic as a binder layer.
- Depending on the RCA types, the utilization of treated RCA in HMA pavements up to 30% is highly successful in the regions where the temperatures could drop to be between (-27 °C) and (-28 °C) with low and moderate traffic as a binder layer.
- The performance grade (PG) of asphalt binder plays a significant role in the performance of HMA mixtures that include RCA.
- Finally, the type and proportion of RCA play an important role in the performance of HMA mixtures.

16.4 Future Research

Based on the obtained findings of this study, the following points are offered as a guide for future research that could explore a deeper understanding of RCA properties and its utilization in HMA mixtures.

- Explore and examine an additional type of RCA produced from crushing a different type of C&D waste.

- Investigate and test the effect of higher proportions of CRCA up to 100% on the HMA mixture's performance.
- Examine the effect of a combination of heat treatment at 300 °C and acetic acid of a higher percentage than 30% on the physical, mechanical, and microstructural properties of CRCA and HMA mixture performance.
- Investigate CRCA properties with various concentrations of acetic acid solution higher than 0.1 to select the best percentage that can lead to the best improvement in CRCA properties.
- Study the role of various types and proportions of fine recycled concrete aggregate on HMA performance.
- Investigate the effect of asphalt binder grade on the performance of asphalt mixtures that include RCA.
- Examine the influence of different NA types on the performance of asphalt mixtures that include RCA.
- Study the effect of enhancing adhered mortar quality on HMA performance.
- Investigate the flexural fatigue properties of HMA mixtures that include RCA.
- Apply a case study of the utilization of treated and untreated CRCA in HMA pavement to obtain field data.

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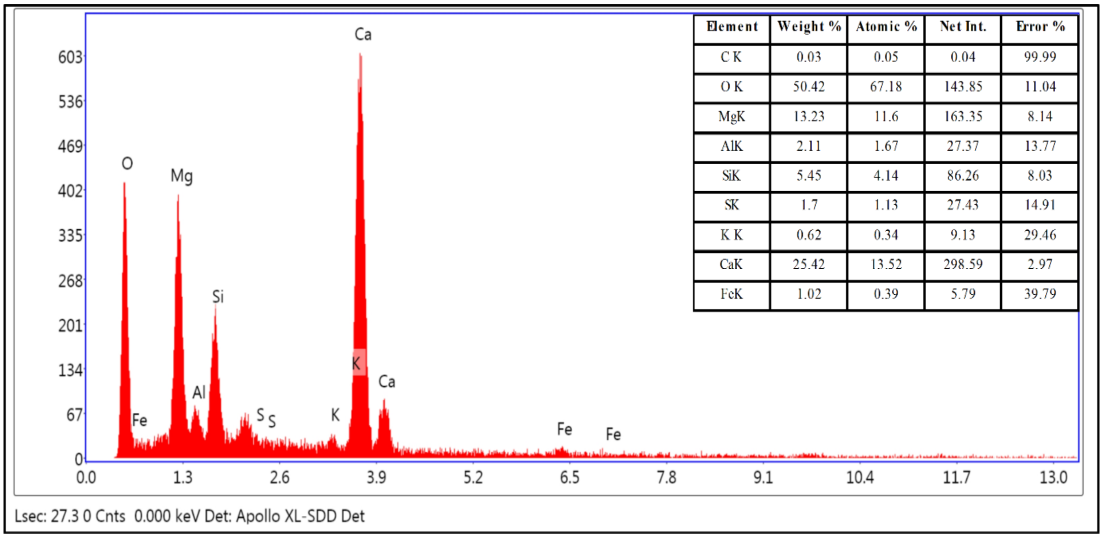
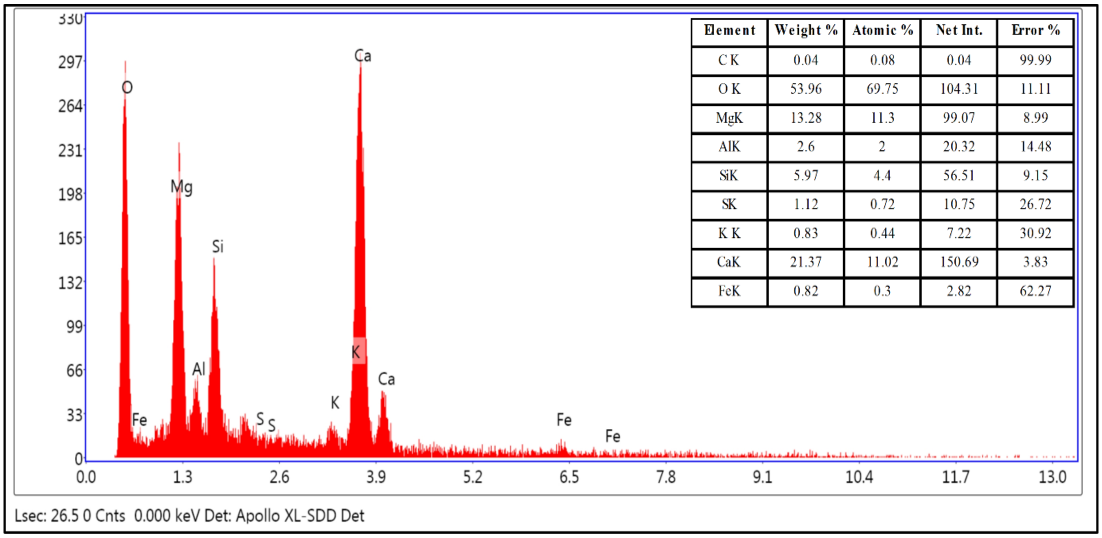
Appendix A

The obtained results of EDAX analysis for aggregate and mortar surface, RCA#2



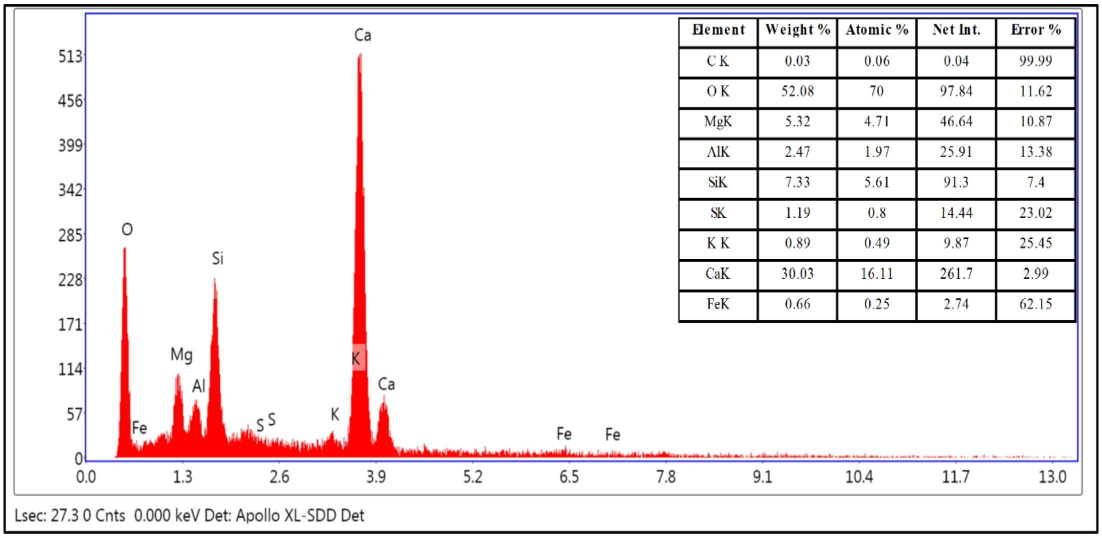
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.03	0.05	0.04	99.99
O K	50.42	67.18	143.85	11.04
MgK	13.23	11.6	163.35	8.14
AlK	2.11	1.67	27.37	13.77
SiK	5.45	4.14	86.26	8.03
SK	1.7	1.13	27.43	14.91
K K	0.62	0.34	9.13	29.46
CaK	25.42	13.52	298.59	2.97
FeK	1.02	0.39	5.79	39.79

Figure A1-a: EDAX of untreated aggregate surface.



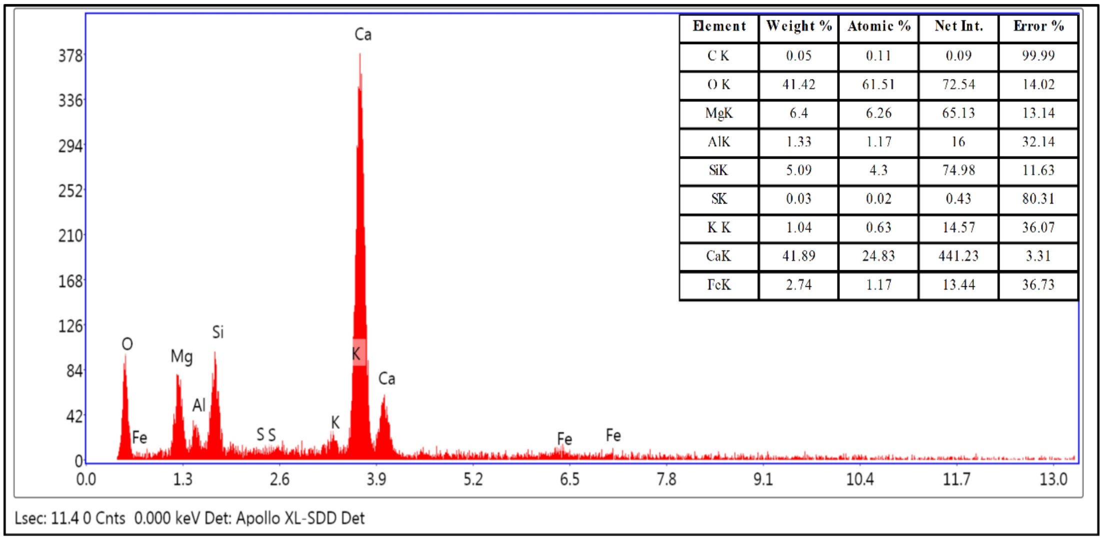
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.04	0.08	0.04	99.99
O K	53.96	69.75	104.31	11.11
MgK	13.28	11.3	99.07	8.99
AlK	2.6	2	20.32	14.48
SiK	5.97	4.4	56.51	9.15
SK	1.12	0.72	10.75	26.72
K K	0.83	0.44	7.22	30.92
CaK	21.37	11.02	150.69	3.83
FeK	0.82	0.3	2.82	62.27

Figure A1-b: EDAX of aggregate surface at 250 °C.



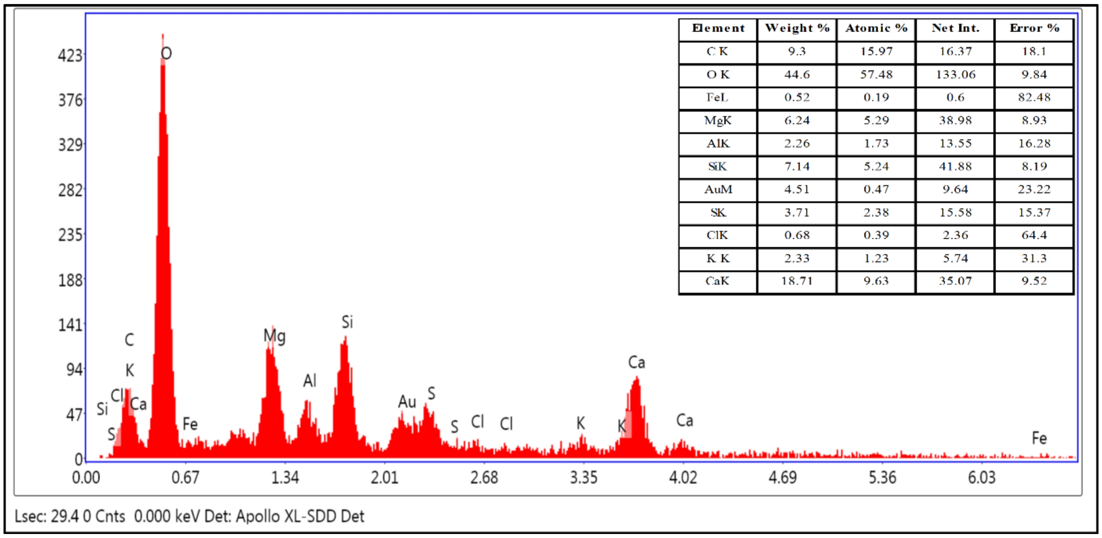
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.03	0.06	0.04	99.99
O K	52.08	70	97.84	11.62
MgK	5.32	4.71	46.64	10.87
AlK	2.47	1.97	25.91	13.38
SiK	7.33	5.61	91.3	7.4
SK	1.19	0.8	14.44	23.02
K K	0.89	0.49	9.87	25.45
CaK	30.03	16.11	261.7	2.99
FeK	0.66	0.25	2.74	62.15

Figure A1-c: EDAX of aggregate surface at 350 °C.



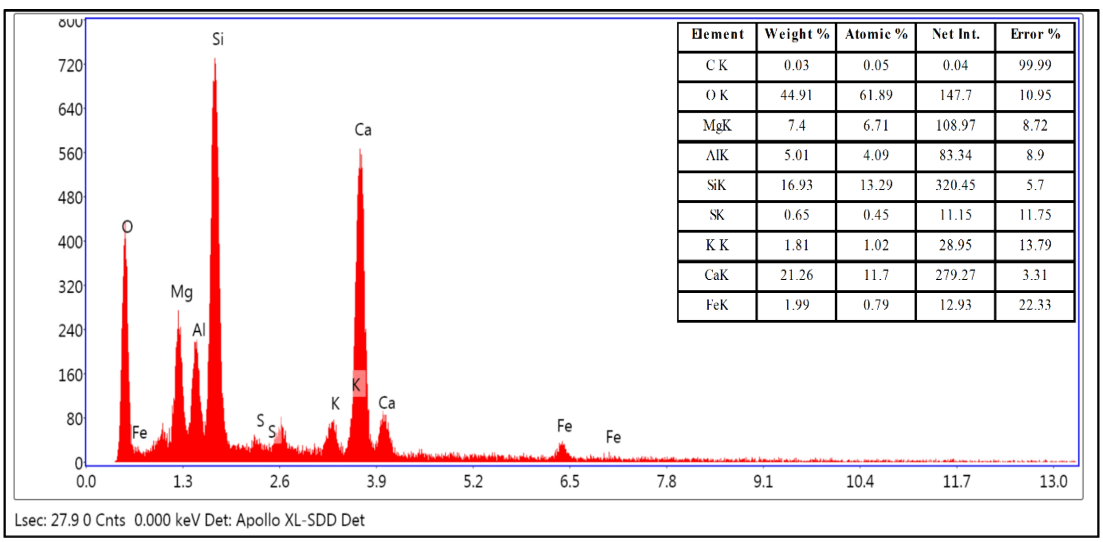
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.05	0.11	0.09	99.99
O K	41.42	61.51	72.54	14.02
MgK	6.4	6.26	65.13	13.14
AlK	1.33	1.17	16	32.14
SiK	5.09	4.3	74.98	11.63
SK	0.03	0.02	0.43	80.31
K K	1.04	0.63	14.57	36.07
CaK	41.89	24.83	441.23	3.31
FeK	2.74	1.17	13.44	36.73

Figure A1-d: EDAX of aggregate surface at 500 °C.



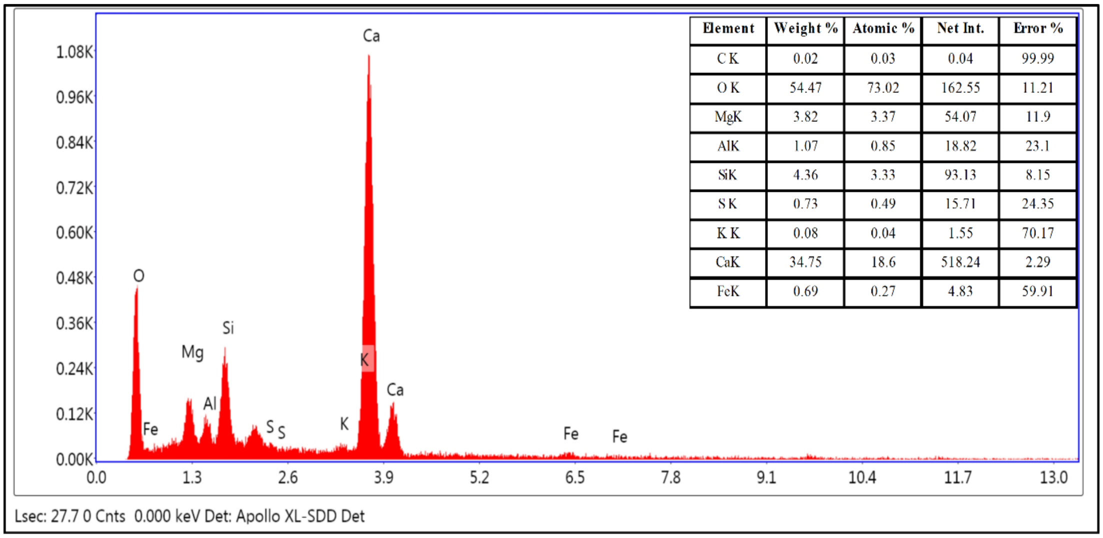
Element	Weight %	Atomic %	Net Int.	Error %
C K	9.3	15.97	16.37	18.1
O K	44.6	57.48	133.06	9.84
FeL	0.52	0.19	0.6	82.48
MgK	6.24	5.29	38.98	8.93
AlK	2.26	1.73	13.55	16.28
SiK	7.14	5.24	41.88	8.19
AuM	4.51	0.47	9.64	23.22
SK	3.71	2.38	15.58	15.37
ClK	0.68	0.39	2.36	64.4
K K	2.33	1.23	5.74	31.3
CaK	18.71	9.63	35.07	9.52

Figure A1-e: EDAX aggregate surface HCl treatment.



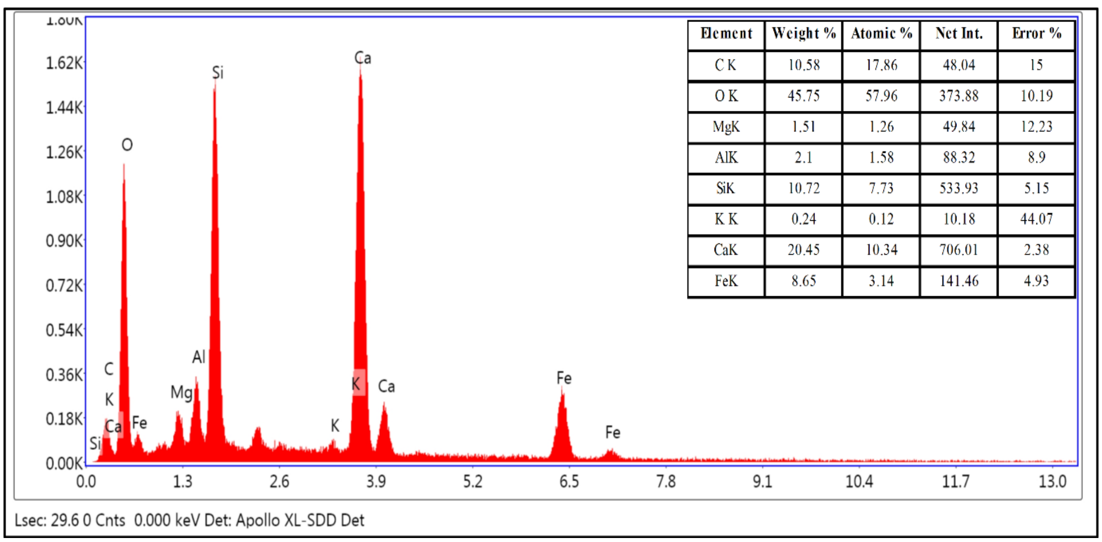
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.03	0.05	0.04	99.99
O K	44.91	61.89	147.7	10.95
MgK	7.4	6.71	108.97	8.72
AlK	5.01	4.09	83.34	8.9
SiK	16.93	13.29	320.45	5.7
SK	0.65	0.45	11.15	11.75
K K	1.81	1.02	28.95	13.79
CaK	21.26	11.7	279.27	3.31
FeK	1.99	0.79	12.93	22.33

Figure A1-f: EDAX aggregate surface acetic treatment.



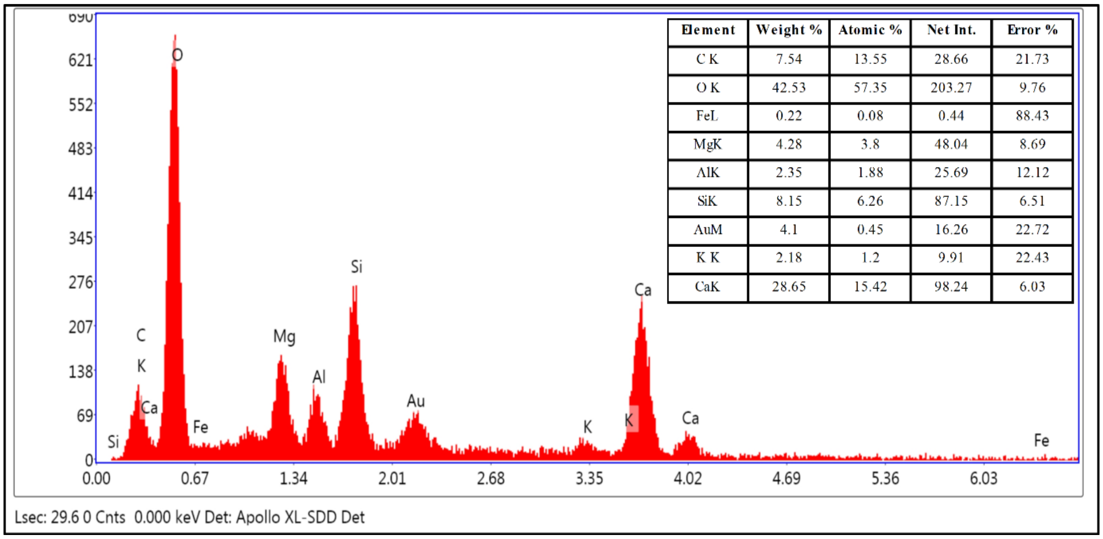
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.02	0.03	0.04	99.99
O K	54.47	73.02	162.55	11.21
MgK	3.82	3.37	54.07	11.9
AlK	1.07	0.85	18.82	23.1
SiK	4.36	3.33	93.13	8.15
S K	0.73	0.49	15.71	24.35
K K	0.08	0.04	1.55	70.17
CaK	34.75	18.6	518.24	2.29
FeK	0.69	0.27	4.83	59.91

Figure A2-a: EDAX of untreated mortar surface.



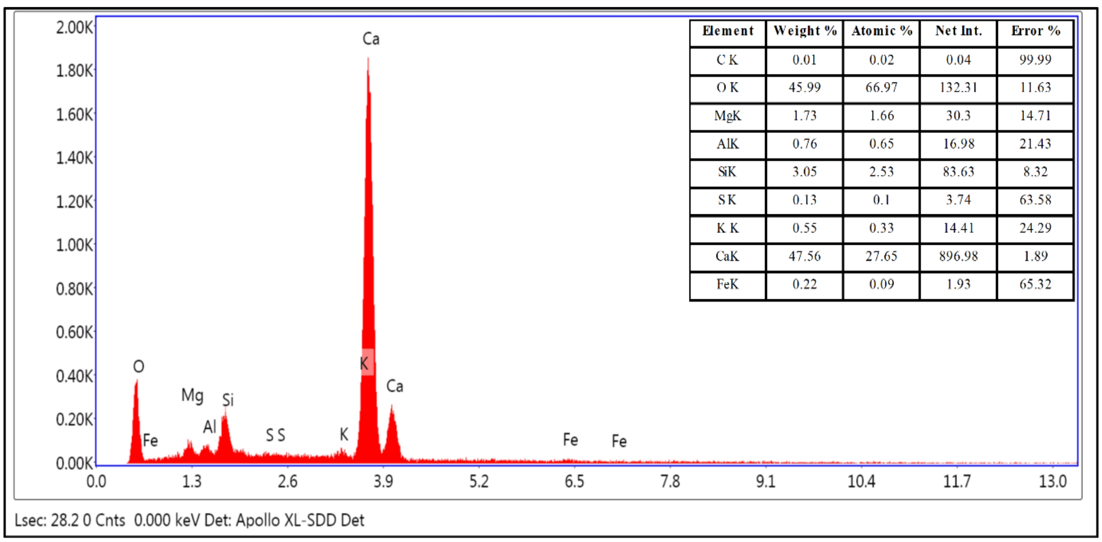
Element	Weight %	Atomic %	Net Int.	Error %
C K	10.58	17.86	48.04	15
O K	45.75	57.96	373.88	10.19
MgK	1.51	1.26	49.84	12.23
AlK	2.1	1.58	88.32	8.9
SiK	10.72	7.73	533.93	5.15
K K	0.24	0.12	10.18	44.07
CaK	20.45	10.34	706.01	2.38
FeK	8.65	3.14	141.46	4.93

Figure A2-b: EDAX of mortar surface at 250 °C.



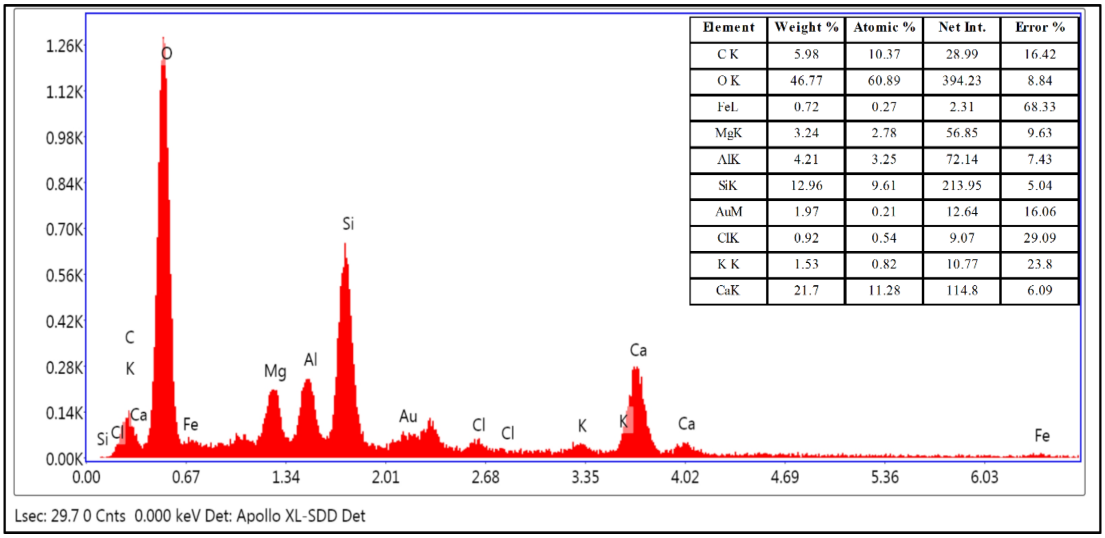
Element	Weight %	Atomic %	Net Int.	Error %
C K	7.54	13.55	28.66	21.73
O K	42.53	57.35	203.27	9.76
FeL	0.22	0.08	0.44	88.43
MgK	4.28	3.8	48.04	8.69
AlK	2.35	1.88	25.69	12.12
SiK	8.15	6.26	87.15	6.51
AuM	4.1	0.45	16.26	22.72
K K	2.18	1.2	9.91	22.43
CaK	28.65	15.42	98.24	6.03

Figure A2-c: EDAX of mortar surface at 350 °C.



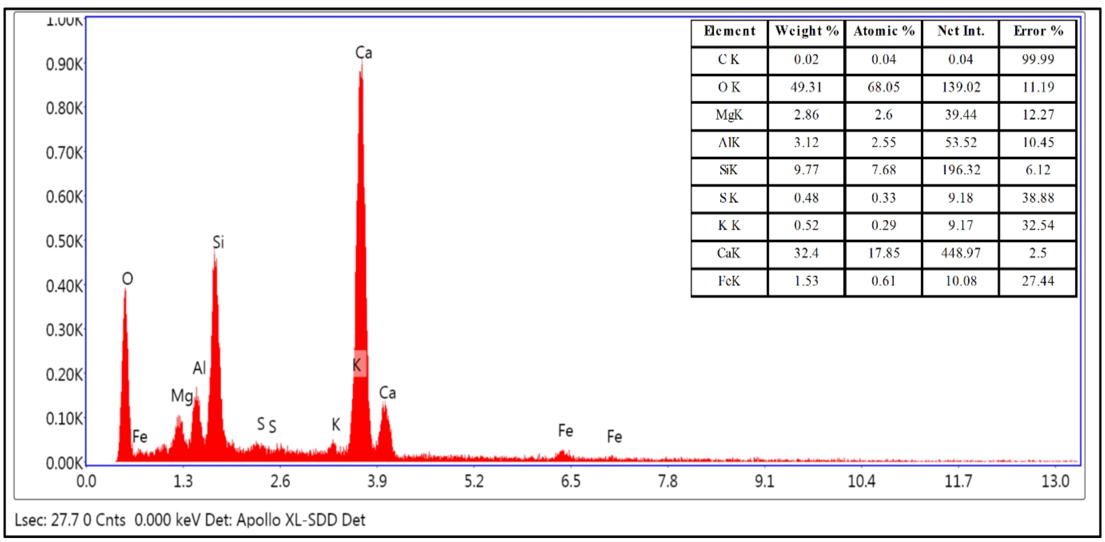
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.01	0.02	0.04	99.99
O K	45.99	66.97	132.31	11.63
MgK	1.73	1.66	30.3	14.71
AlK	0.76	0.65	16.98	21.43
SiK	3.05	2.53	83.63	8.32
S K	0.13	0.1	3.74	63.58
K K	0.55	0.33	14.41	24.29
CaK	47.56	27.65	896.98	1.89
FeK	0.22	0.09	1.93	65.32

Figure A2-d: EDAX of mortar surface at 500 °C.



Element	Weight %	Atomic %	Net Int.	Error %
C K	5.98	10.37	28.99	16.42
O K	46.77	60.89	394.23	8.84
FeL	0.72	0.27	2.31	68.33
MgK	3.24	2.78	56.85	9.63
AlK	4.21	3.25	72.14	7.43
SiK	12.96	9.61	213.95	5.04
AuM	1.97	0.21	12.64	16.06
ClK	0.92	0.54	9.07	29.09
K K	1.53	0.82	10.77	23.8
CaK	21.7	11.28	114.8	6.09

Figure A2-e: EDAX mortar surface HCl treatment.



Element	Weight %	Atomic %	Net Int.	Error %
C K	0.02	0.04	0.04	99.99
O K	49.31	68.05	139.02	11.19
MgK	2.86	2.6	39.44	12.27
AlK	3.12	2.55	53.52	10.45
SiK	9.77	7.68	196.32	6.12
S K	0.48	0.33	9.18	38.88
K K	0.52	0.29	9.17	32.54
CaK	32.4	17.85	448.97	2.5
FeK	1.53	0.61	10.08	27.44

Figure A2-f: EDAX mortar surface acetic treatment.