EXPERIMENTAL INVESTIGATIONS ON PERFORMANCE OF RECYCLED CONCRETE AGGREGATES-CONTAINING CONCRETE EXPOSED TO HEATING-COOLING CYCLES

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES

OF

NEAR EAST UNIVERSITY

By

Alhamza Derki

In Partial Fulfilment of the Requirements for

the Degree of Master of Science

in

Civil Engineering

NICOSIA, 2019

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and appreciation to my supervisor Asst. Prof. Dr. Pınar Akpınar for expanding my horizon and guiding me to gain self-confidence in myself and my abilities. Also I would like to express my thankfulness for her support, patience and comments which helped me to accomplish my thesis properly.

Also, I would like to thank my beloved supporting family for believing in me during all my studies, words cannot describe my feelings and gratitude towards them and how lucky I am to have them in my life.

Also I would like to thank the laboratory technician Mustafa Turk for his help and assistance during my experimental work.

I also would like to show my appreciation to all my friends how kept supporting me and stood by my side all the way to accomplish my work.

To my family…

ABSTRACT

As world population is increasing, the need for new construction has increased. Construction industry became larger yielding higher quantity of waste materials like construction and demolition activities. These activities lead to depletion of natural resources since aggregates needed for new concrete are quarried, while landfilling has negative effect on soil.

In this study, concrete mixture including recycled concrete aggregates obtained from 3 years old concretes has been produced in order to investigate possibility of recycling C&D wastes.

Performance of 50% RCA-containing concrete mixtures when exposed to different numbers of heating-cooling cycles were investigated by determining compressive and splitting tensile strength evolution together with their permeability characteristics. Absorption capacity and Los Angeles characteristics of RCA and NA has also been studied in a comparative way in order to provide insight their behavior in new concretes.

Results show that RCA-containing concrete yielded lower splitting tensile strength when they were exposed to more heating-cooling cycles, even though, no strength drop has been observed in their compressive strength compared to NA-containing concrete.

Keywords: Construction and demolition wastes; recycled concrete aggregates; permeability; compressive strength; splitting tensile strength; heating and cooling cycles

ÖZET

Dünya nüfusunun artışıyla, yeni inşaatlara olan ihtiyaç da artmaktadır. İnşaat sektörünün artan aktiviteleri sonucunda da inşaat ve yılular inşaat atıkları artmakta ve ayrıca doğal agrega kaynakları da, eş zamanlı olarak azalmaktadır.

Bu tez çalışnması, inşaat ve yıkım atıklarını elimine etmek amacı ile, üç yıllık betonlardan elde edilen geri dönüşüm agregaları ile yeni beton yapılabilmesini incelemektedir. Yüzde elli geri dönüşüm agregaları içeren betonların farklı ısıtma-soğutma döngülerine maruz bırakıldıktan sonraki basınç ile yarma–çekme dayanımları ve ayrıca geçirgenlik karakteristikleri incelenmiştir.

Geri dönüşüm agregalarının beton içerisindeki davranışlarını daha iyi anlayabilmek için, geri dönüşüm ve doğal agregaların ayrıca emme kapasitesi ve aşınma dayanımları da araştırılmıştır.

Elde edilen sonuçlar, geri dönüşüm agregası içeren betonları ısıtma-soğutma döngüsüne maruz bıraktıktan sonra yarma-çekme dayanımlarında normal agregasi içeren betonlara göre düşüş yaşanıldığını göstermektedir. Geri dönüşüm agrega içeren betonların, içermeyen beton numunelerine göre, basınç dayanımlarında ise belirgin bir düşüş gözlemlenmemiştir.

Anahtar Kelimeler: İnşaat ve yıkım artıkları; geri dönüşüm beton agregaları; geçirgenlik; basınç dayanımı; çekme – yarma dayanımı; ısıtma-soğutma döngüsü etkisi

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LIST OF ABBREVIATIONS

ASTM: American Society for Testing and Materials

BS: British Standard

CH: Calcium Hydrate

C_3S: Tricalcium Silicate

C_2S: Dicalcium Silicate

C_3A: Tricalcium aluminate

C_4AF: Picalcium Aluminate Ferrite

RCA: Recycled Concrete Aggregates

NA: Natural Aggregates

CDWS: Construction & Demolition wastes

ITZ: Interfacial Transition Zone

GGBS: Granulated Ground Blast-furnace Slag

CHAPTER 1
INTRODUCTION

1.1 Overview of Construction and Demolition Wastes

As the quantity of construction activities increases, the consumption of natural resources in order to build new structures poses an environmental threat. These constructed structures could be demolished for various reasons, and if not, eventually their lifetime will end and need to be demolished to construct new structures. After demolishing, the majority of materials used in those structures are moved to landfills, these landfills have negative effect on the surrounding environment. Also for the economical concept, taxes on quarrying and landfilling are becoming larger.

These wastes could be processed in order to be reused again, and this process is called "Recycling". Recycled concrete aggregates "RCA" is a term of preparing old demolished concrete to be used as aggregates to make new concrete, but this type of aggregates needs to be studied in order to avoid any potential problem when being used in new structures.

1.2 Definition of the Problem

Heating-cooling cycles that can be experienced by concrete elements during their service lives are known to cause expansion-contraction on concrete which is a heterogeneous material. In the case of RCA-containing concrete, heterogeneity of the construction material becomes more remarkable, as the concrete element would increase both the new mortar as well as the old mortar attached to old aggregates. In such a case, different responses (i.e. different volume changes) are expected to be yielded by each feature in RCA-containing concrete, when it is exposed to heating-cooling cycles. Knowledge on the performance change of RCA-containing concrete under thermal cycles is essential to ensure an improved concrete mix design practice in the real applications where concrete elements are expected to experience changing heat exposure conditions throughout their service lives.

1.3 Objectives and Scope of the Study

This study aims to study the effect of heating and cooling cycles on both the permeability and the mechanical properties of concrete made with RCA. Two concrete mixtures will be prepared, a control mixture with 100% NA, while the other will have 50% replacement by RCA to be tested under heating and cooling cycles. Temperature cycles varying between ambient to 160^{o} C will be applied for 0, 3, and 6 cycles and then the samples of both mixtures will be tested to observe the change in their permeability, compressive and tensile splitting strength behavior.

1.4 Significance of the Study

Results obtained from this study will provide systematical and experimental information to the related literature on permeability, compressive and splitting tensile strength behavior of samples prepared from RCA-containing concrete in case of exposure to heating-cooling cycles. This information also has the potential to serve to concrete manufacturers in their projects to ensure adequate mix design when RCA is used in their concrete structure where changing heat exposure conditions are expected.

1.5 Structure of the Study

This study consists of five chapters that will be explained in details. An introduction and overview of construction and demolition wastes, as well as a definition of the problem, significant of the study, objective and scope of the study, the structure of the study, and limitation will be presented in chapter one.

Chapter two presents a historical background of the topic, containing information about production of RCA and general information about concrete and its constituents, as well as the related literature of the topic.

Chapter three presents the materials and methodology, will present in details the procedure takes in order to prepare samples and perform experiments.

Chapter four presents the results of the experiments performed with a scientific discussion. Conclusion and future recommendations will be presented in chapter five.

1.6 Limitations of the Study

Obtaining old concrete for real life demolished structure was unavailable. RCA production was obtained in this study from three years old concrete cubes that were tested with the facilities of NEU Civil Engineering Laboratory, considering that using old concrete cubes is widely accepted for related studies. Time and limited resources were limitations that were faced in his study which affected the design of experimental campaign that was carried out.

CHAPTER 2
THEORETICAL BACKGROUND

2.1 General Aspects

Construction materials vary from one region around the globe to another. These variations are due to the availability of local materials and the infrastructure available for adequate production. For some countries like the United States, timber is used extensively, while for other regions like Middle East countries timber is not the most preferred option, and brick is commonly used in around United Kingdom. Steel, however, is adopted as a construction material in special cases fields, like high rise skyscrapers, hangers, or mega structures like stadiums, due to its high mechanical properties, like compression and tensile strengths.

In the list of utilization, there is another construction material that occupies the first position among all types. Concrete is considered the most preferred and utilized construction material all around the world, as it has properties that are lacking in other construction materials that will be previewed further.

2.2 Concrete as a Construction Material

Concrete as mentioned before, has the highest position among all other construction materials; this position is earned because of special properties of concrete that are partially or fully not available in competing construction materials. Concrete is a heterogeneous material and is produced by a reaction between its key constituents. Constituents of concrete are easily available almost everywhere around the globe in each environment. Moreover the availability of its constituents they are relatively cheap when compared with the cost of obtaining other construction materials like steel. Beside the high availability and the relatively cheap price of concrete, it has also other advantageous properties. Concrete can be used in any environment and under any circumstances. Concrete is used beside in building and infrastructure construction in many other fields like airstrips, roadways as subbase layer, pavements, and harbor protection as breakwaters, onshore and offshore structures like harbors and oil platforms, and water distribution is both cases clean and waste as pipes and open channels. In addition, concrete has the ability to be shaped in any desired shape like arches, piers, shells, columns etc. Concrete properties can be tailored according to needs of a case or situation. These properties might include strength, durability etc. Concrete as well has relatively high resistance to physical conditions like high temperature, freezing temperature, or even in case of being in direct contact with fire. Concrete can also withstand wet environment when it is designed accordingly. Members made of concrete can also have multiple functions act like architectural and structural at the same time.

2.3 Concrete Constituents

Concrete is a non-homogeneous material, it has various constituents. These constituent vary from coarse, fine, and in some cases ultrafine material, where the coarse constituents which are aggregates act like the main skeleton and inert fines fill the gaps, while cement and all other cementitious materials with presence of water produce products that fill the remaining gaps and combine everything together as a result of a hydraulic exothermic reaction called cement's hydration reaction.

Table 2.1: General concrete constituents (Neville & Brooks, 2010)

Concrete Constituents					
Water	**Cement**		**Admixtures**	**Aggregates**	
Should not contain harmful compounds	Cement types with no additives	Cement types with mineral additives	Chemical compounds to add special desired properties to concrete mix	Coarse aggregates	Fine aggregates

2.3.1 Water

Water is an essential factor in concrete because without water no hydration reaction can start. Also w/c ratio is also an important factor for determination of resultant concrete properties in both fresh state like workability, as well as in the hardened state porosity which has an effect on strength of resultant concrete mixture. These characteristics affect even durability of concrete. Quality of water used should be considered before utilization in any mixture, thus water used should contain limited quantities of contaminations like salts, ions, etc. These contaminations with high concentrations in mixing water will lead to unwanted reactions, thus deterioration in concrete. Water used in concrete mixture is quality that is suitable for drinking (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

2.3.2 Cement

Cement by itself is not considered as a construction material, while concrete which cement is one of the constituents is. Cement plays the binding role in the concrete's structure where it keeps all other constituents stick together to form the final microstructure of concrete. Cement actually has its constituents also which called compounds, and each one of these compounds has its own role in performing the binding ability and characteristics of cement. These compounds are C_3A, C_3S, C_2S, and C_4AF. Controlling the compounds' proportions in cement produces variations in cement's behavior and properties. These variations lead to multiple types meeting required properties in each case of cement utilization. American society of testing and materials ASTM made a categorization of cement in ASTM C150 based on variation of proportions of its clinkers dividing cement types into 5 main types as following:

- **Type I: Ordinary Portland Cement "OPC":** This type of cement has no special properties, and it is used when no need for special properties of special types of cement. Type I cement is used in general construction operations; it's used in buildings, bridges, concrete pavements and sidewalks. This cement type is used when temperature is moderate and the environment is not aggressive like seaside areas, which makes it the mostly used type of cement (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Type II: Modified Portland Cement:** This type of cement is used in cases where moderate heat generation is required, or in case of no severe sulfate attack is expected. For rate of heat generation, this type occupies the middle place between Type I and Type IV cements. Although this type has lower heat generation than Type I, it still has the same strength gain rate. Type II cement is desired when no need for high reduction of heat generation, or in mass concrete in cases where its heat generation is acceptable (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Type III: High Early Strength Portland Cement:** This type of cement has a higher hardening rate so it hardens faster than other types. This property is gained by maximizing C_3S proportion reaching 70% with a higher fineness of 325 m^2/kg. This type is desired in some special cases where rapid hardening is required like the need of early removing of framework, faster construction progress, or some repairing operations. This

type has a relatively high heat of hydration, so it's desired when working in cold weather. On the other hand, it's not used in case of mass concrete like dams, or when working in hot weather. Although this type has a rapid hardening ability, but its setting time still remains the same as Type I cement (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

- **Type IV: Low Heat Portland Cement:** This cement is used is special cases like huge dams, it develops very low heat of hydration, this reduction is due to minimizing the C_3A and C_3S contents because these two clinkers generate the highest heat when hydrated, but also due to this reduction strength development is slower that's why such type of cement should not have fineness lower than 320 m^2/kg (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Type V: Sulfate Resistant Cement:** Sulfate attack is considered as a huge problem facing a concrete structure; it can come from sea water, ground water, industrial waste water, and soil. This type of cement is specially developed to resist sulfate attack by minimizing the C_3A content, and limiting SO_3 content coming mainly from adding gypsum making a content of C_4AF+2C_3A is limited to 20%. Nevertheless, this type of cement can only minimize formation of secondary ettringite, hence expansion related to it, but not all types of sulfate attacks (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

There are other types of cement than the ordinary ASTM types, these types don't depend on clinkers' proportions variations, but depend on replacing cement by other materials which also have cementitious properties. Cementitious materials are either waste or by-product materials, and properties of these materials could improve properties of cement in some aspects; these materials are Ground Granulated Blast-Furnace Slag, Fly Ash, and Silica Fume. By blending these materials different types of cement are produced, these types are as following:

- **Portland Blast-furnace Slag Cement:** Blast Furnace Slag is a waste material from manufacturing of iron; it has higher fineness as 350 m^2/kg. Cement blended with such material has different properties than ordinary Portland cement types. Spherical particle shape of slag provides lower water demand hence higher workability, and its lower heat generation makes cement blended with slag suitable for use in mass concrete and hot weather. Use of slag blended cement provides denser structure and in case with low alkali slag it makes alkalis less able to move and react with reactive aggregates. Cement replacement with slag leads to less C_3A in total, hence better sulfate attack resistance (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

- **Portland Pozzolan Cement:** Pozzolan materials have cementitious properties. Artificial pozzolans used are Fly Ash which is waste material from exhaust gases of coal powered power plants, while the other is called Silica Fume which is a by-product of manufacturing of silicon and ferrosilicon alloys from quartz and coal. Both Fly Ash and Silica Fume have higher fineness than cement with 600 and 20000 m^2/kg respectively. Cement blended with Pozzolans has better sulfate attack resistance because firstly, lower content of C_3A due to replacement. Secondly Pozzolans mainly react with calcium hydrates CH forming calcium silicate hydrate C-S-H providing better microstructure and lower chance of formation of secondary gypsum in case of sulfate attack. Pozzolan blended cement has also lower heat generation during hydration reaction, so this type of cement is suitable in cases of mass concrete, and casting in hot weather. On the other hand, this type of cement has lower strength development in the early age due to slower hydration, that's why it has relatively longer curing period. Although early strength of concrete made with this type of cement is low, the ultimate strength is high and its value depends on replacement ratio. Pozzolans provide lower cost because they are cheaper than cement they are replaced with. Rice husk and Metakaolin are also Pozzolan materials that could contribute as they have cementitious properties also (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

Figure 2.1: Light brown and dark gray Fly Ash (Pellegrino & Faleschini, 2016)

2.3.3 Admixtures

Admixtures are chemical components that are used to provide or enhance specific properties of concrete instead of using special type of cement. Unlike additives, admixtures are added to concrete during mixing stage, while additives are meant to be added at manufacturing stage. Usually admixtures come in liquid form, while additives have powder form. Admixtures vary according to the function and aim of usage, and ASTM C 494-92 categorized admixtures as accelerators, retarders, and water reducers (plasticizers) or high range water reducers (superplasticizers), also the can be combined in forms like water reducer and retarder, water reducer and accelerator.

- **Accelerators:** Accelerators are used to accelerate hardening of the concrete mixture by playing as catalyst for hydration reaction, and they do not have an influence on setting time, calcium chloride $CaCl_2$ is the most commonly used accelerator. In general accelerators are used when working in very low temperatures, or in case of manufacturing or pre-cast concrete where rapid hardening is a desired property to fasten the manufacturing process. Accelerators also are used when repairing operations take place, or in some cases structure under construction should be brought into service in short time. On the other hand, utilization of accelerations has drawbacks also, because utilization of such admixtures appeared to increase possibility of corrosion in steel reinforcement bars, and amplifying the risk of alkali aggregate reaction in the system in case of reactive aggregates usage. In addition, using accelerators also has a negative effect on resistance of cement to sulfate attack, and obstructs air entraining agents, while increasing creep, and shrinkage. But for erosion and abrasion of concrete, accelerators have positive effect (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Retarders:** This type of admixture is used to obstruct setting process and delay it. They are mainly desired when working in hot weather, and to prevent formation of cold joints when casting. Using retarders also causes a delay in hardening, and has an effect on early strength where using retarders reduces early strength, but ultimate strength is not significantly affected (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

- **Water Reducers:** This type of admixtures required to reduce the excessive water which is not necessary to complete hydration reaction but necessary to maintain reliable workability. Using such admixture has a reduction effect relaying on w/c ratio, as for a fixed w/c ratio using of water reducers lead to higher workability for fresh concrete, while for specifically desired workability, it will reduce w/c ratio leading to better ultimate strength because of dispersing ability which yields better distribution of cement particles, and better durability properties due to lower porosity hence denser microstructure in hardened concrete. Water reducers also play a role in improving workability in fresh concrete with poorly graded aggregates (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **High Range Water Reducers:** They are also known as "Superplasticizers", and their main usage is to produce flowing concrete in case of normal w/c ration, or to produce high strength concrete with acceptable workability in case of very low w/c ratio. The main intense of using such admixture is where no other admixture can provide same desired results like producing Self Compacting Concrete which used in special types of framework or in areas of heavy reinforcements, or in case of producing ultra-high strength concrete (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

2.3.4 Aggregates

Aggregates are fillers which are added to concrete to provide volume stability. Aggregates are granular materials which should be inert and inorganic. Aggregates are added into cement in order to limit its volumetric changes like drying shrinkage, and to maintain cheaper cost for a certain volume of a mixture. Although aggregates are expected to serve as inert fillers, their characteristics are important, and they influence the final characteristics of the concrete mixture them. Despite their characterizations according to their mineralogy, aggregates characteristics can be categorized as following:

- **Gradation:** Gradation of aggregates refers to the size distribution of aggregate particle. Aggregates with good gradation provide better compacting hence lower voids between aggregates and lower cement demand to fill them. Good gradation also leads to more economical mixture, and also affects the workability of the mixture in its fresh state where the poor gradation leads to higher water demand to maintain proper workability; hence strength of concrete will be negatively affected (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

- **Maximum Aggregate Size:** Determining the maximum possible aggregate particle size has some effect on the mixture, whereas the water demand is reduced, hence lower drying shrinkage will occur. Also the mixture will be more economic and generate less heat during hydration process due to lower amount of cement needed. While for fixed cement content and desired workability, w/c ratio will be decreased increasing strength of hardened concrete (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Aggregates Absorption Capacity:** Absorption of aggregate is the ability of an aggregate particle to absorb fluids within, and the absorption capacity refers to the porosity of aggregate particle. Naturally aggregate come in different moisture stages wet, saturated surface dry, air dry and oven dry. Absorption capacity has an effect on workability by absorbing water from the mixture, and it has an effect on the interfacial transition zones then the bonding strength between aggregates and paste (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Aggregates Unit Weight:** This term refers to the weight of aggregates occupying certain volume; this filling is affected by various factors such as particle shape, gradation, degree of compaction and moisture state. Unit weight refers also to how densely aggregates are filling certain volume, so a higher unit weight means denser concrete and though higher strength will be achieved and more durable with longer serviceability lifetime of concrete (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Soundness:** Soundness of aggregates is the ability of aggregate to maintain volumetric stability. Volumetric changes could occur in aggregates during aggressive attacked on embedding concrete such as exposing to freeze-thaw cycles in cold environments or heating-cooling cycles in hot countries or in case of fire (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).
- **Deleterious substances:** Aggregate used in concrete should be relatively clean, in the nature aggregates could contain contamination that are considered harmful to

concrete such as organic impurities that affect the strength and setting time by affecting the hydration process, also fine material such as clay or silt that cover aggregates could be harmful for the bonding between aggregates and paste the are within. Unsound particle if they are more than the limits, could also have deleterious effect on concrete, while salt contaminated aggregates in used will lead to increase corrosion in steel reinforcement bars and emphasis formation of florescence (Neville, 2011; Neville & Brooks, 2010; Shetty, 2006).

2.4 Thermal Properties of Concrete

All materials have their specified physical properties. These properties are what make any material unique, such as weight, density, and specific gravity. Each material according to its specific physical properties shows a specific response to external physical applied conditions, such as electrical and heat conductivity or thermal expansion and contract.

Concrete as a material that has physical properties is not an exception, concrete also has its physical properties, and among these properties are the thermal properties that verify the response of concrete to thermal variations. Concrete has thermal conductivity, expansion, and contract, but as concrete is a heterogeneous material this response varies with different components, studies showed that what controls the thermal response in concrete are two factors, types and specifications of cement and aggregates used to prepare concrete. Concrete that have normal aggregates showed higher conductivity and volumetric changes than concrete with lightweight aggregates, this could be because of the lower density and higher permeability of lightweight aggregates in comparison with normal aggregates. As shown in Table 2.1 (Hein & Eng, 2012; Phan, McAllister, Gross, & Hurley, 2010).

Table 2.2: Coefficient of Thermal Expansion according to aggregate type (Hein & Eng, 2012)

Primary aggregate class	Average CTE (/^{o} C x 10^{-6})
Andesite	7.78
Basalt	7.8
Chert	10.83
Diabase	8.35
Dolomite	8.92
Gabbro	8.0
Gneiss	8.77
Granite	8.5
Limestone	7.8
Quartzite	9.34
Rhyolite	6.91
Sandstone	9.58
Schist	7.98
Siltstone	9.03

2.5 Recycled Concrete Aggregates

2.5.1 General aspects

Using of natural quarries to produce aggregates for new concrete may lead to depletion of natural resources, and damages the environment. Mountains' deteriorations may result a miss-balance in natural life regardless the appearance of eroded mountains' foothills that also has a harmful effect on other economic sectors such as tourism, like the case of Beshparmak Mountain in Northern Cyprus as shown in Figure 2.2.

Figure 2.2: Beshparmak Mountains (Derki, 2019)

The significant increase of population worldwide from 1.5 billion up to 7.5 billion within this century had serious implications on the construction rate as well. Statistics of industry requirements and wastes, it shows that building industry consumes about 25- 40 % of power worldwide, buildings wastes occupy 20 – 40% of cities' waste, and Carbon dioxide emissions produced were 7% of the total CO_2 emissions (Xiao, 2018).

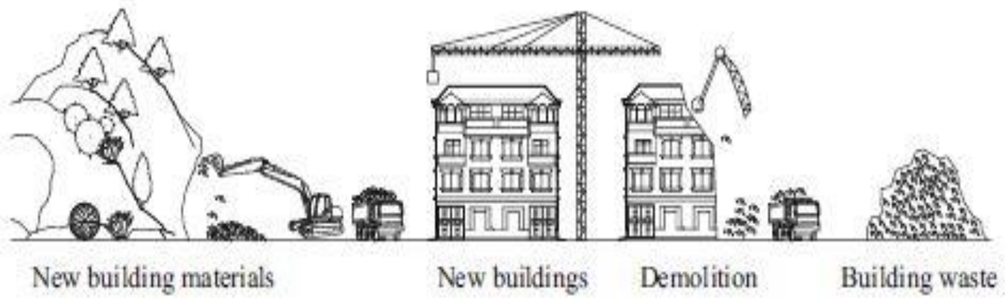

Figure 2.3: Building life cycle (Xiao, 2018)

Recycled Aggregates Concrete "RCA", prefers to the type of concrete mixtures that includes a recycled aggregates, which are made from crushing and reusing waste materials from demolished buildings. Aggregates that have a size of 4.75 mm to 40 mm are considered as coarse aggregates "RCA", and aggregates with size less than 4.75 mm are considered fine aggregates "RFA", these two types are used as partial or full replacement of natural aggregates (Xiao, 2018).

After WW2 the amount of demolished building due to combat was enormous, so a need appeared to have a solution for these materials. Countries like Russia, Germany, Japan, and other countries started researches in order to reuse these materials, in the last century a number of conferences were held to discuss methodologies related (Xiao, 2018).

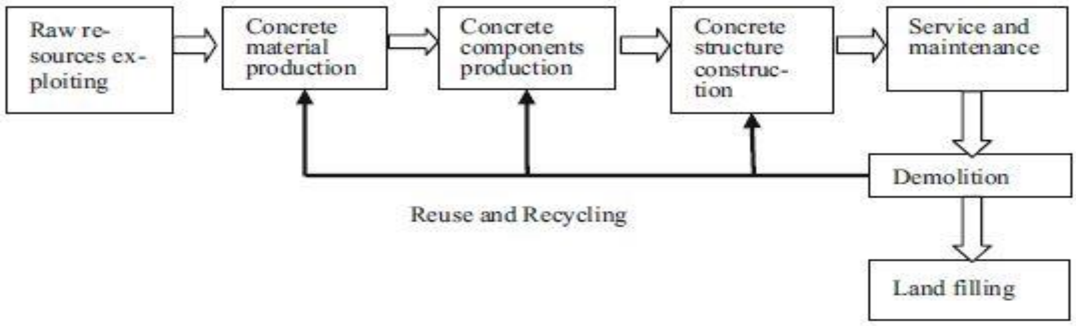

Figure 2.4: General model of recycling life cycle (Xiao, 2018)

As early as 1946, the former Soviet scholar “Gluzhge” made studies of recycling concrete for production of recycled concrete aggregate. At late of 1970’s, about 40 million tons of waste concrete were reused, while, on 1977, the Japanese government made “Specification for use of RA and RC”, and established many plants with production capacity of 100 tons of RCA per hour, while Germany was the world’s pioneer establishing environment improvement institutions (Xiao, 2018).

Since large land resources, China was not threatened by the crisis of raw material decreasing, China’s contribution in researches on RCA started later. However, due to improvement of awareness of environmental issues, from 1990’s many Chinese researchers have participated in studying the RCA (Xiao, 2018).

Other countries like Brazil, and the Nordic countries also started their programs for studying and development of the properties of recycled concrete aggregates, due to increasing of waste materials and the lack of new raw materials and landfills (Pellegrino & Faleschini, 2016; Xiao, 2018).

Table 2.3: Waste production of European countries (Pellegrino & Faleschini, 2016)

State	X 1000 tons	State	X 1000 tons
Belgium	22,239	Lithuania	357
Bulgaria	2235	Luxemburg	8867
Czech	9354	Hungary	3072
Denmark	3176	Malta	988
Germany	190,990	Netherlands	78,064
Estonia	436	Austria	9010
Ireland	1610	Poland	20,818
Greece	2086	Portugal	11,071
Spain	37,497	Romania	238
France	260,226	Slovenia	1509
Croatia	8	Slovakia	1786
Italy	59,340	Finland	24,645
Cyprus	1068	Sweden	9381
Norway	1543	UK	105,560

There are different types of recycled aggregate, there variation is due to different original materials, some of them are recycled concrete aggregate which are made by concrete waste from construction and demolition of concrete structures, while ceramic recycled aggregates are produced from corrupted of demolition ceramic facilities such as sinks, toilet chair, etc. (Brito & Saikia, 2013; Pellegrino & Faleschini, 2016; Xiao, 2018). This study will focus only on recycled concrete aggregates.

Figure 2.5: Adhered mortar on RCA (NEU Civil Engineering Laboratory, 2019)

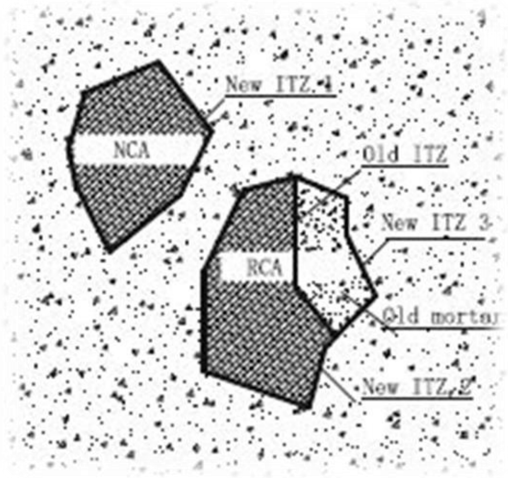

Figure 2.6: Microstructure of RCA and its ITZs (Pellegrino & Faleschini, 2016)

2.5.2 Production

Two types of plants are considered for recycling concrete demolition waste, and reproduce them as recycled aggregates: stationary (fixed) and mobile. Stationary plants are recycling facilities fixed in a specific place authorized to recycle concrete demolition waste, by utilizing fixed equipment, hence cannot provide on-site operations. On the other hand, Mobile recycling plants are machinery and equipment that can be relocated to any place to recycle waste at directly from the source. The same equipment (screens, crushers, magnetic separators, etc.) is furnished by modules, which provide recycling procedures directly on site (Pellegrino & Faleschini, 2016).

For any waste treatment plant, there are two types fixed and mobile plants, which are used according to the needs, but in both types of plants, general steps of recycling process are almost similar, which are defined as (Pellegrino & Faleschini, 2016):

- Separation,
- Crushing,
- Separation of ferrous elements,
- Screening,
- Decontamination and removal of impurity.

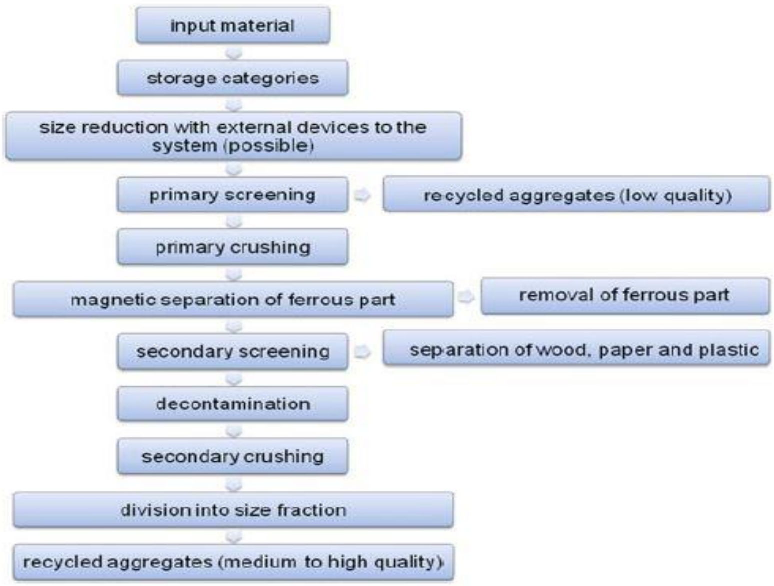

Figure 2.7: Blueprint of a CDWs treatment process (Pellegrino & Faleschini, 2016)

Like any type of manufacturing, there are special combination of equipment that contribute in order to produce special type of products, in case of producing recycled concrete aggregates equipment needed are defined as (Pellegrino & Faleschini, 2016) :

- Vibrating feeders,
- Screening (Trommel, vibrating, rotary),
- Primary crusher,
- Secondary crusher (effector or cone crusher),
- Magnetic separators,
- Conveyor belts,
- Sink-float tank,
- Front-end loader,
- Excavator,
- Concrete Pulverizer,
- Grapples,
- Effect hammers.

Until recently, countries investing in recycling, mostly are developed countries, the amounts of reproduction of concrete varyes from on country to another, Table 2.3 shows the production quantity of construction and demolition waste and recovery in these countries with a percentage of production.

Table 2.4: Waste production and recovery (X1000 tons) (Tam et al., 2018)

Country	Waste	Waste	Recovery
Australia	19.3	12	62.2
China	300	120	40
Hong Kong	24.3	6.8	28
Japan	77	62	80.5
Taiwan	63	58	91
Thailand	10	3.2	32
Belgium	40.2	34.57	86
Denmark	21.7	20.40	94
Finland	20.8	5.4	26
France	342.6	212.4	62
Germany	192.3	165.4	86
Ireland	16.6	13.3	80
Netherlands	25.8	25.28	98
Norway	1.3	0.87	67.3
Portugal	11.4	5.52	48.4
Spain	38.5	5.39	14
Switzerland	7	2	28
UK	114.2	74.23	65
Brazil	101	6.2	6.14
Canada	0.66	0.2	30
USA	534	256.3	48
South Africa	4.7	0.76	16

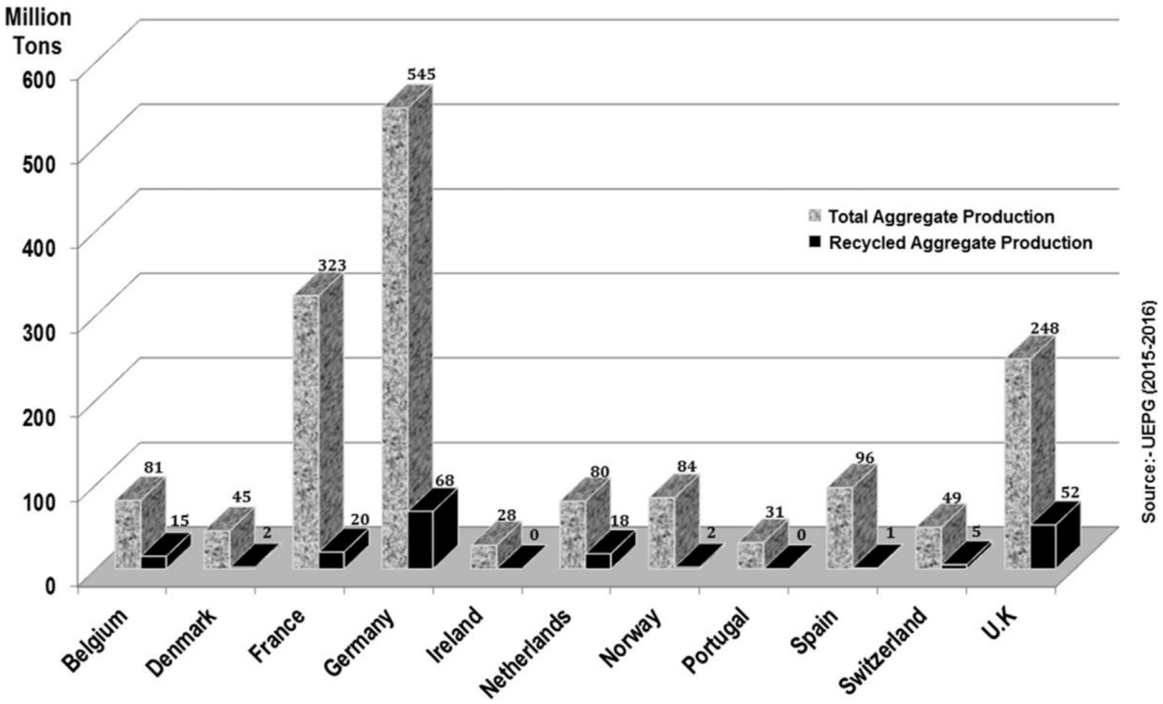

Figure 2.8 Comparison of total aggregate and recycled aggregate production in EU (Tam et al., 2018)

2.5.3 RCA characteristics and properties

Australia: Australia developed two codes for recycled aggregates concrete. These codes are **(HB 155:2002)** and **(AS 1141.6.2)**, categorizing recycled aggregates into two types; first is high and the second is low characteristics. First RCA (Class 1A), having density > 2100 kg/m^3 and allowed water absorption < 6%. For chloride and sulfate content code condition that must be equal to the content of natural aggregates, and limiting size by 4-32 mm with 30% allowed replacement proportion, mixtures to be prepared with recycled aggregates should achieve 40 MPa at 28 days, requiring well graded RCA with no >0.5% brick content, total contaminants <1.0% by weight. Second RCA (Class 1B) with density > 1800 kg/m^3, and allowed water absorption <8%, as the Class 1A, Class 1 B should have chloride and sulfate content equal to natural aggregates, with the same size limitation. For this type full replacement proportion is allowed, and a mixture should achieve 25 MPa at 28 days, allowed contaminants are < 2% by weight and not more 30% crushed bricks content (Brito & Saikia, 2013; Tam et al., 2018; Xiao, 2018).

China: China developed **(DG/TJ 07/008), (GB/T 25,177),** and **(GB/T 25176:2010)** codes, Chinese divided recycled aggregates into recycled concrete aggregates RCA and recycled mixed aggregates RMA. No density limitations are required for both types of aggregates. The allowed water absorption requirement is only applied on RCA with < 10% with allowed chloride and sulfate soluble (0.03-0.25%) and (0.8-1%) respectively. Limited impurities content <2% including Organic matter <0.5% and contaminants <1.0%, and allowing a replacement proportion for RCA and RMA of (95% Plus <5.0% Masonry) and (90% Plus >10.0% Masonry) respectively (Brito & Saikia, 2013; Tam et al., 2018; Xiao, 2018) .

Hong Kong: (CS-3:2013), (HKBD 2009), and **(WBTC-12: 2002)** codes were developed, consisting only recycled concrete aggregates RCA, with limitation of density > 2000 kg/m^3, and water absorption less than 10%, with chloride and sulfate soluble of (<0.05%) and (< 1%) respectively. Codes allow only utilization of coarse aggregates, the division in codes of Hong Kong is specified as allowed replacement proportion is limited by 20% for structural use with mixtures having 25-35 MPa strength at 28 days and full replacement for non-structural use with mixtures having 20 MPa strength at 28 days, contaminants with density lower than water are limited by 0.5%, while other contaminants are limited by 1% (Brito & Saikia, 2013; Tam et al., 2018; Xiao, 2018).

Japan: Japanese developed **(JIS A 5021), (JIS A 5022),** and **(JISA 5023)** codes, these codes define recycled aggregates as 4 categories. First, the RCA coarse aggregates with density higher than 2500 kg/m^3, this category allows water absorption < 3%, with chloride soluble less than 0.04%, due to high quality of this type of aggregates it's allowed to be used in structural concrete. When use with concrete with 45 MPa or less nominal strength no utilization limitations adopted. Second the RCA fine and coarse aggregates with high quality, there is a condition that for fine aggregates density must not be less than 2300 kg/m^3 while for coarse aggregates 2500 kg/m^3, for water absorption it was limited by 3.5% for fine aggregates and 5% for coarse aggregates, acid content for this type only mention the fine aggregates limiting it by maximum 0.04%, this type is allowed to be used in structural system in case of not being exposed to drying , or freezing & thawing such as piles, sub-surface beams, and concrete filled steel tubes. Third type consists of fine and coarse aggregates with medium quality, requiring density higher than 2200 kg/m^3 for fine aggregates without any requirements for coarse aggregates, both fine and coarse aggregates have a limited water absorption by 7%, while for acids content it was not mentioned. This type of aggregates is approved to be used in non-structural systems like backfill concrete, blinding concrete, and concrete used to fill steel tubes. Forth type consist only of fine aggregates with low quality, it has no density or acids content limitations. For water absorption it was limited be 13% maximum. Due to low quality, this type is allowed only in non-structural uses which has no quality requirements (Brito et al., 2016; Tam et al., 2018; Xiao, 2018) .

Belgium: Belgium developed 3 standards (**PTV 406-2003),** (**NEN EN 12620: 2013),** and **(NBN B 11-255)**. Defining two types of recycled aggregates; first recycled concrete aggregates RCA with density not less than 2100 kg/m^3. Water absorption lower than 9%, this type has allowable acids content less than 0.06% for chloride soluble and less than 1% for SO_4, for RCA fine aggregates are not allowed, and should be used only with concrete Class C 30/37 in dry environment. For contaminants they are allowed if non-mineral if less than 1%, and for organic less than 0.5%. Second recycled mixed aggregates RMA with minimum density 1600 kg/m^3, with water absorption allowed of 18% and the same limitations as RCA for acids contents and the use of only coarse aggregates. This type is allowed to be used in dry environments with concrete of class C16/20, with the same non-mineral and organic contaminants limitations (Brito et al., 2016; Tam et al., 2018; Xiao, 2018).

Denmark: Danish developed **(DS 2426 – EN 206-1)**, and **(DS EN 12620: 2013)** codes. Codes divide recycled aggregates into three categories not testes RCA, tested RCA, and RMA. First, recycled concrete aggregates with no tests have density limitation with minimum 2200 kg/m^3, on the other hand no limitations of water absorption, nor acids content were provided, but for this type it was conditioned that 95% of recycled aggregates must come from clean resources such as concrete, masonry, or roofing tiles, size was conditioned with 4-32 mm coarse aggregates. Second, tested recycled concrete aggregates, this type has few limitations due to testing processes, which provide better quality than the not-tested once, density must not be less than 2200 kg/m^3. No limitations for water absorption, or acids content, with allow ability for fine recycled aggregates engagement, it leads to a wider sizes allowed 0-32 mm conditioning quality control. At last, recycled mixed aggregates, this type has a density condition of minimum 1800 kg/m^3, with no limitations of water absorption, or acids content, this type can contain a proportion of fine aggregates not more than 20%, with sizes allowed of 0-32 mm (Brito & Saikia, 2013; Tam et al., 2018).

Finland: Finland has two codes for recycled aggregates **(By-43-2008)** and **(SFS EN 12620)**, defining recycled aggregates as recycled concrete aggregates RCA1 and RCA2, and recycled mixed aggregates RMA. For recycled concrete aggregates types RCA1 and RCA2, there are no limitations for density, acids content, and replacement proportions, or application conditions. Limitations were restricted in water absorption 10% and 12% respectively, and the contaminants as bricks 0% and other materials 0.5% for RCA1, and maximum 10% of bricks or 1% of other materials for RCA2. While for recycled mixed aggregates RMA, limitations are: for density 2550-2650 kg/m^3, with maximum water absorption of 12%, with contaminants allowed of 10% bricks and 1% other materials, for RMA as for RCA with their 2 types, no limitation for acids content, sizes allowable, or application condition are provided (Tam et al., 2018) .

Germany: Germany is the most developed country is Europe in utilization of recycled aggregates, developing **(DIN 4226-100: 2002), (DIN 12620: 2015/pr EN 12620:2015), (DafStb-2010)** codes, which specify recycled aggregates into four types. First, recycled concrete aggregates RCA from concrete waste, with minimum density of 2000 kg/m^3, and allowed water absorption of 10% maximum. For acids content, chloride acid soluble Cl less than0.04%, and sulfate SO_4 less than 0.8% are allowed, authorizing them to participate in structural concrete, with Aggregate more than 90% containing Bricks and Sandstone less than 10% proportions, contaminants allowed are maximum 2% for mineral materials, 0.2% maximum for non-mineral, and a maximum of 0.5% asphalt. Second, recycled concrete aggregates RCA from construction wastes. This type shares with the first type with limitation of density, acid contents, contaminants proportions, and the authorization for structural utilization, on the other hand. It has a water absorption limit of 15% maximum and allowed recycled aggregates used with 70% aggregate containing bricks and sandstone not more than30%. Third, the recycled brick aggregates RBA, which has a minimum density limitation of 1800 kg/m^3, with allowable water absorption of 20%, and acids content of chloride Cl 0.04%. This type of aggregates is allowed to contain aggregate with 20%, bricks with 80%, and sandstone with 5% proportions, although contaminants proportions are the same with RCA types, but this type is for non-structural use. Fourth, this type is the recycled mixed aggregates RMA, with density not less than 1500 kg/m^3, and allowed acids content of chloride soluble 0.15% maximum. No water absorption limitation provided, with allowing aggregate, bricks, and sandstone more than 80% , with limitations of contaminants of 20% for mineral and asphalt, and less than 1% of non-mineral contaminants (Brito et al., 2016; Tam et al., 2018; Xiao, 2018).

Italy: Italy adopted two codes **(NTC – 2008) and (UNI EN 12620: 2013)**, defining two types of recycled aggregates, recycled concrete aggregates RCA, and recycled mixed aggregates. Both types don't have limitations for density, water absorption, and acids content, claiming that source of aggregates must be specified with limiting replacement proportions of 30% and 60% for use with 30MPa and 25MPa concretes respectively. Also allowing full replacement for RMA with 10 MPa concrete (Pellegrino & Faleschini, 2016; Tam et al., 2018).

Netherlands: Developed **(NEN 5942, 5921, 5930)** and **(NEN EN 12620:2013)** codes, providing two types of recycled aggregates. A recycled concrete aggregates RCA allowing to be used in structural activities when achieving density not less than 2100 kg/m^3, with a replacement proportion not exceeding 20% by volume, and used with 45MPa concrete. Also recycled mixed aggregates RMA with minimum density of 2000 kg/m^3. Both types have no limitations for water absorption ratios. Dutch codes are very detailed in acids and contaminants contents, allowed acids content are for RCC chloride Cl less than 0.1% for < 4mm, and less than 0.05% for > 4 mm). For sulfates SO_4 less than1.0%, for equal or finer than 4 mm, with no requirement of SO4 for coarser than 4 mm for RCA, while for RMA PC = Cl <1.0% for all sizes ,and for RCC Cl (0.1% for <4 mm & 0.05% for >4 mm), while for Pre-stressed Cl (<0.015% for <4.0 mm), & (0.007% for >4.0 mm) SO_4 (<1.0%) for less or equal to 4 mm. Contaminants, however, are limited in RCA with 0.5% non-minerals for sizes less or equal 4mm, and 0.1% for coarser than 4mm with calcium carbonate allowed content of 25% for finer than 4mm and 10% for coarser than 4mm.

While in RMA are limited with 0,1% in finer than 4mm aggregates for non-mineral contaminants.(Brito et al., 2016; Tam et al., 2018)

Norway: Norway adopted **(NS EN 12620:2008)** code, categorizing recycled aggregates as recycled concrete aggregates RCA, and recycled mixed aggregates RMA. For the RCA limitations were minimum density of 2000 kg/m^3 and maximum water absorption of 10%, without mentioning acids content, replacement proportions, or application limits. For contaminants of RCA in case of more than 94% of crushed concrete and natural aggregates, limits are 5.0% for Non-minerals, 1.0% for Organic materials, and 0.1% for Crushed asphalt. Contaminants of RMA in case of higher than 90% crushed concrete and crushed bricks, limits are 2.5% for Non-minerals, 0.5% for Organic materials, and 1% for Crushed asphalt (Brito & Saikia, 2013; Tam et al., 2018).

Portugal: (LNEC- E471) code has been developed, defining recycled aggregates as two types of recycled concrete aggregates and one type of recycled mixed aggregates. RCA1 and RCA2 are sharing limits of density with minimum of 2200 kg/m^3, water absorption of 7%, and acids content of 0.8% sulfate content. On the other hand for allowed replacement proportions are 20% for RCA1 and 25% for RCA2, while RCA1 can be used with Class C 35/45 concrete, RCA2 can be used with Class C 40/50. Contaminants in RCA1 are limited with 10% masonry, 1% lightweight, and 0.2% non-mineral materials, while for RCA2 30% masonry, 1% lightweight, and 0.5% non-mineral materials are allowed. The other type RMA has the same limitations for water absorption and acids content, and requiring 2000 kg/m^3 as minimum density. Lightweight contaminants are limited with 1.0%, while Non-mineral components, and material with density <1000 kg/m^3 are limited with 1.0% (Brito & Saikia, 2013; Pellegrino & Faleschini, 2016; Tam et al., 2018).

Russia: Russia has no obvious code for recycled materials, but they use coarse recycled mixed aggregates RMA in with concretes with strengths of 15-20 MPa. Recycled concrete aggregates are not allowed to be used in pre-stressed concrete due to high shrinkage and creep (Brito & Saikia, 2013).

Spain: Spain adopted two codes **(EHE 08-2000)** and **(UNE EN 12620:2003)**, with only one type of recycled aggregates, which is recycled concrete aggregates RCA, limiting density with equal or denser than 2000 kg/m^3, with allowed water absorption not exceeding 5%. For acids content chloride water soluble was limited by 0.05%, while sulfate acid soluble by 0.08%, concrete with recycled aggregates can be used in structural activities with 40 MPa concrete except for pre-stressed concrete using a replacement proportion not exceeding 20%. For contaminants, they were limited by 1% for non-mineral material, 1% for lightweight materials, and 5% as sand content (Brito & Saikia, 2013; Pellegrino & Faleschini, 2016; Tam et al., 2018; Xiao, 2018).

Switzerland: (IT 70085:2006), **(SIA 430:1994)**, and **(SN EN 12620:2003)** codes were adopted, dividing recycled aggregates into RCA and RMA. For RCA and RMA, no limitations for density or water absorption were defined, but for RCA a limitation for acids content were specified as 0.03% and 0.12% for chloride in case of reinforced and non-reinforced concrete respectively, with a 0.4% sulfate content. RCA are allowed for utilization in reinforced concrete and for pre-stressed concrete with additional tests, a 100% replacement proportion of fine aggregates is allowed, and also for coarse aggregates. In condition of complying with SIA 162/4, and could be used in indoor C30/37 & C 20/30, outdoor C25/30, and minor C 15/20 with cement content of 150-230 kg/m^3. Contaminants are allowed if were 1% maximum, while for mixed material should not exceed 3%, and bituminous materials are not allowed. On the other hand, for RMA, acids content limits are determined for sulfate SO_4 by 1%, RMA are not allowed for structural use, and cement content in the mixture should not exceed 150 kg/m^3 in case or full replacement (Brito & Saikia, 2013; Tam et al., 2018).

United Kingdom: UK developed 3 codes **(BS 8500-2)**, **(BS EN 12620:2013**), and **(BS EN 206:2013)**. British recycled aggregates should not contribute in reinforced concrete, and provide no limitations for density or water absorption. For the first type which is recycled concrete aggregates, acid content is limited for sulfate SO_3 by 1%, and could be externally on internally in condition of not exposed to Cl^- or deicing salts, with a replacement proportion not exceeding 20%. It can be used in concrete with classes C20/25 and C40/50, for contaminants they are limited by 5% for masonry and fine materials, and 0.5% for non-mineral materials. The second type is recycled mixed aggregate RMA, which has no appropriate limits for acids content, and could be used only with concrete with class C16/20, and for contaminations the are limited by 3% fine materials, and 1% non-mineral materials, while masonry has no limits (Brito & Saikia, 2013; Tam et al., 2018).

Brazil: Brazilians developed **(NBR 15.116)** code; this code divides two types of recycled concrete aggregates, with two types of recycled mixed aggregates, all types have no density limitations for fine aggregates while having 2300kg/m^3 for coarse aggregates and are not used in structural activities. For RCA and RMA coarse aggregates and acids content limitations for both Cl water soluble and SO_4 1 %. For RCA types the first type has both fine and coarse aggregates with water absorption limitation of 7%, allowing 20% as replacement proportion, for contaminants non-minerals and clay lumps are limited with 2% and 10% for materials finer than 75 microns. Second RCA type is recycled fine aggregates with water absorption limited to 12%, and contaminants material finer than 75 microns are limited with 15%. For RMA fine and coarse aggregates have water absorption limits of 12% and 7% respectively. For contaminants consisting of materials finer than 75 microns limits are 20% and 10% respectively (Brito & Saikia, 2013; Tam et al., 2018; Xiao, 2018).

USA and Canada: (ACI E-701. 2007) is adopted allowing use of recycled aggregates for non-structural uses, at replacement proportions up to 100% limiting content of foreign materials with 2% (Pellegrino & Faleschini, 2016; Tam et al., 2018).

RILEM: is the International Union of Laboratories and Experts in Construction Materials, divided recycled aggregates into three types RCA1, RCA2, and RMA, all types have acids content limitation of 1% for SO_4 water soluble, and require ARS testing in case of using in Exposure Classes 2a & 4a. RCA1 requires minimum density of 2000 kg/m^3, and water absorption is limited to 10%. Replacement proportion can reach a 100% for aggregates coarser than 4mm, to be used with concrete with class C 50/50 when aggregates are from concrete rubble. While RCA2 requires minimum density of 1500 kg/m^3, and water absorption is limited to 20%, replacement proportion can reach a 100% for aggregates coarser than 4mm, to be used with concrete with class C 16/20 when aggregates are from demolished masonry. RMA, however, limits minimum density with 2400 kg/m^3, and water absorption is limited to3%, replacement proportion can reach 20% for aggregates coarser than 4mm, with no condition for concrete class (Brito & Saikia, 2013; Tam et al., 2018; Xiao, 2018).

2.6 Recent Studies and Literature Review

As concrete is a heterogeneous material, formed by a combination of various materials, this made researchers study concrete as a three phase material. These phases are aggregates, cement paste, and the interfacial transition zone ITZ between them. Among the interfacial transition zone the bonding forces that make concrete stand still take place. Interfacial transition zones in concrete as considered being the weakest phase among the three phases. Some researches were held to study the effect of the bonding strength between aggregates and paste on properties of concrete, regarding effect of properties of aggregates and paste on this strength, while fewer researches were held to study the bonding strength in case of contribution of recycled concrete aggregates.

In a study of the response of high strength concrete in case of exposed to high temperatures, and for that prepared samples using two grades of ordinary Portland cement grade 30 and 40, adopted three w/c ratios 0.3, 0.35, and 0.4. For aggregates, researchers used limestone aggregates with maximum size of 12.5 mm, and river sand with specific gravity of 2.7. Additives were Pozzolan, specifically Silica Fume with two replacement proportions 6% and 10%, while for obtaining desired workability polycarboxilate High Range Water Reducer was adopted. Also polypropylene “PP” fibers were used in some samples, then gradually heated to 100, 200, 400, 600, and 800 C^o, then measuring the residual strength according to compressive strength and splitting tensile strength tests, reporting that polypropylene fiber addition yields better heat resistance up to 100 C^o, and the best percentage is 2% by volume. For bonding strength between aggregates and paste, researchers reported that heating negatively affect bonding strength, also smoothness of aggregates’ surface has an effect on bonding strength. Researchers also reported that for predicting tensile splitting strength from compressive strength as mentioned in ACI 363 is valid when heating up to 300 C^o only. Finishing than normal strength concrete has better heat resistance than high strength concrete due to higher porosity microstructure (Behnood & Ghandehari, 2009).

This study adopted a method for clarifying bonding strength, the method is by applying engine oil and painting on aggregates by soaking for 96 and 48 hour respectively. Ordinary Portland cement was used without utilization of any type of additives or admixtures. Natural crushed stones with maximum size of 19 mm was used as coarse aggregates, with sand with fineness modulus of 2.7 were used as fines. Two w/c ratios of 0.4 and 0.5 were adopted. Compressive and splitting tensile strength test were made, and a formula was presented to estimate bonding strength concluding that bonding strength is effected by characteristics of interfacial transition one ITZ, and bonding strength is related to smoothness of aggregates surface, while excessive water could negatively affect bonding. For predicting failure causes, researcher depended on presented formula and by the ratio of estimated bond to splitting tensile strength it could be determined that the failure is caused by lack of bond strength or because stresses in interfacial transition zone exceeded its strength (Al-Attar, 2013).

In another study, researchers adopted three grades of concrete 30, 60, and 90 MPa, and for that, three w/c ratios were adopted 0.26, 0.44, and 0.55. Four different types of aggregates crushed quartz, crushed granite, limestone, and marble were used with maximum size of 20 mm to determine effect of aggregate properties on bonding strength. For fine aggregates river sand with fineness modulus of 2.85 adopted. Ordinary Portland cement used with a replacement of 30% by Granulated Ground Blast-furnace Slag with fineness 600 m^2/kg. A sulphonated naphthalene formaldehyde superplasticizer used to obtain desired workability. Tests adopted were compressive strength, splitting tensile strength, modulus of elasticity, fracture energy, and characteristic length. Results showed that high strength concrete showed better bonding strength due to higher strength paste, and failure if occurred in interfacial transition zone would be due to difference in strength between aggregates and paste, also concluding that splitting tensile strength and properties of interfacial transition zone are not directly related to strength or type of aggregates, but related to w/c ratio adopted (Wu et al., 2001).

In a study on effect of aggregate type of performance, researchers prepared two different mixtures using two different types of aggregates that are limestone and granite as coarse aggregates, while used sand as fine aggregates. For both mixtures fixed w/c ratio of 0.45

was adopted. Silica Fume was used as additive, while to obtain desirable workability a superplasticizer was added. Tests adopted were compressive strength, tensile splitting, and pull apart. Results showed that limestone showed better performance in pull apart test due to chemical reaction with paste, and aggregates surface roughness is not related to bonding strength. Addition of Silica Fume showed better results for bonding by 50% higher results in Pull Apart test, and 25% higher in Tensile splitting test. But Tensile Splitting test showed different results than Pull Apart test, and in some cases interfacial transition zone was not the weakest point (Almahdi Bahalul & Ahmed Deiaf, 2016).

Researchers prepared 4 concrete mixtures; Ordinary Portland Cement was used without additives, and fixed w/c ratio adopted of 0.35. Four types of coarse aggregates are Calcareous limestone, Dolomitic limestone, Quarzitic limestone, and artificial aggregates of slag; all coarse aggregates have a maximum size of 19 mm, while dune sand with bulk specific gravity of 2.54 used as fines. Naphthalene-based superplasticizer was used to obtain desired workability. Tests adopted were compressive strength, tensile splitting strength, and elastic modulus. After testing researchers found that in high strength concrete the weakest point is aggregates because of denser and high strength interfacial zones and paste. Limestone aggregates showed better bonding due to chemical reacting with paste, and bonding has an effect on elastic modulus more than compressive strength. Type of aggregates has an effect on the properties of concrete as slag showed better performance even in the same mixing conditions (Beshr et al., 2003).

In order of studying the effect of leaching on the bonding strength between aggregates and paste, type II cement with grade of 32.5 was used as a binder. A w/c ratio of 0.5 was adopted for preparing the paste. A limestone block with dimensions of 10 x 10 x 10 mm ± 0.05 mm was prepared. Accelerated leaching was applied by soaking samples in ammonium nitrate solution with concentration of 480 g/L. Tests adopted for this study were direct shear and direct tensile. For direct tensile it was concluded that the bonding strength is affected by leaching due to the degradation of strength by time although paste firstly didn’t strength loss, while for direct shear it showed a direct loss of strength since the beginning of leaching process, while strength development lead to decreasing friction angles, and for aggregate-paste interphase it showed a higher loss due to higher porosity and calcium hydrate CH decomposition (Jebli et al., 2018).

In order to study the effect of bonding strength between aggregates and mortar and aggregates and cement on the mechanical properties of concrete containing lightweight aggregates. For this study KC cement with grade of 32.5 was used with a w/c ratio of 0.5. No admixtures or additives were used. As coarse aggregates, Deistic tuff lightweight aggregates with maximum size of 16 mm was used, while for fine aggregates, lightweight sand with size smaller than 4 mm. In this study tests adopted were compressive strength, modulus of elasticity, and flexural strength. After tests, results have been analyzed, it was concluded that aggregates type and characteristics are essential for bonding strength and better bonding leads to better concrete properties. This conclusion was after noticing that the bonding strength between aggregates and paste is better in lightweight aggregates than ordinary aggregates, while that was not the case in aggregate-mortar bond; also it was noticed that the high variation of strength between aggregates and mortar will increase stresses in the interfacial transition zone (Husem, 2003).

In order of illustrating mechanical and physical response of high strength concrete that contains 100% replacement of NA by RCA at elevated temperatures. For this study Ordinary Portland Cement with grade 42.5 N was used, with a low w/c ratio of 0.32. Naphthalene based superplastizer was used as an admixture to maintain desirable workability. Densified Silica Fume as an additive was adopted. For coarse aggregates, two types of aggregates were used, a natural limestone and lab-prepared recycled concrete aggregates with maximum size of 12.5 mm, while as fine aggregates, natural sand with fineness modulus of 2.79 was adopted. Two testing methods were adopted in this study residual strength and unstressed methods. Samples were exposed to gradually elevated temperature of 100, 200, 400, 600, and 800 C^o, then splitting tensile strength; compressive strength, scanning electron microscope “SEM”, stress-strain curves, elastic modulus, and mass loss measurements were applied. Results showed that recycled concrete aggregates showed lower characteristics at room temperature but showed better initial bonding strength due to its roughness and surface texture. Recycled concrete aggregates also showed better strength retention after heating than natural aggregates. Even after 400 C^o

recycled concrete aggregates showed better response especially in stress-strain response curves and bonding even though calcium silica hydrate C-S-H starts to decompose. Recycled concrete aggregate showed lower elastic modulus at room temperature and better retention after heating with less microstructure damage. Higher porosity and better bonding of recycled concrete aggregates provides better heating resistance than natural aggregates (Khaliq & Taimur, 2018).

In this study, researchers adopted two types of cement General Use “GU” and General Use Limestone “GUL” in order to detect the effect of new paste volume on performance of structural concrete using quality controlled coarse and granular RCA. For that prepared several mixtures with two w/c ratios of 0.4 and 0.47 using 10, 20, and 30% replacement of coarse aggregates with maximum size range of 7-20 mm in three of them, while using 10 and 20% replacement of granular recycled concrete aggregates with size range of 0-20 mm for two others in addition to a control mixture. Ground Granulated Blast-furnace Slag GBBS adopted as additive with 35% replacement proportion, and high range water reducer and air entraining as chemical admixtures. Tests applied were slump, measured air, compressive strength, splitting tensile strength, flexural strength, linear drying shrinkage, rapid chloride permeability, and resistance of freezing and thawing. Tests showed that in case of controlled quality coarse recycled concrete aggregates there were similar quality and bond behavior with natural aggregates up to 40 MPa, while failure is limited to the strength of concrete that aggregates originally made with. Also showed that new paste content has essential effect of new concrete properties made with recycled concrete aggregates, and replacement up to 30% keeps drying shrinkage within acceptable limits, and bond between adhered and new pastes is critical. For case on granular recycled concrete aggregates, it was shown that fines included lead to obstruct formation of proper interfacial zones around aggregates. For durability it was concluded that with absence of both admixtures and additives, high replacement of natural aggregates will increase possibility of having durability issues (Sucic & Lotfy, 2016).

This study aimed to assess technological and economical side of using recycled concrete aggregate to determine the strength characteristic of recycled aggregates, which will give a better understanding on the properties of concrete with recycled aggregates as an alternative material to coarse aggregate in structural concrete by cost. The study intended to prepare 3 concrete mixtures M20, M25, and M30, for preparation of these mixtures, ASTM type I cement with grade 52, natural and recycled sand with diameter < 5 mm, natural basalt rocks with size of 5-20 mm. Same size recycled aggregates with proportions of 0, 20, 40, 60, 80, and 100 % were adopted, with w/c ratios 0.55, 0.5, and 0.45 respectively, tests considered were modulus of elasticity, and split strength. Researchers came out with a conclusion that cost decrease due to reduction in natural aggregates, split strength increases when natural aggregates replaced by recycled coarse aggregates by 40%, but modulus of elasticity decreases with replacement of natural aggregates (Vyas, 2012).

In order of studying the effect of amount of recycled coarse aggregates on mechanical properties of concrete; this study prepared multiple mixtures prepared with Ordinary Portland Cement as a binder without additives replacement, and Glenium C313 superplasticizer as chemical admixture. For coarse aggregates, four replacement ratios where adopted 0, 25, 50, and 100%, with three different sizes of aggregates 4/10, 10/16, and 16/25 mm. Limestone sand adopted as fine aggregates, and mixtures had three different w/c ratios as 0.4, 0.5, and 0.55. It was observed that for recycled aggregates size of 10/25, adhered mortar had a proportion of 20%, while for size of 4/10 it was 40%. Tests adopted were Compressive strength and Splitting Tensile strength. After tests it was concluded that low absorption capacity with high humidity for recycled aggregates is essential, but full saturation of recycled aggregates yields lower bonding strength between aggregates and paste, also concrete made with recycled aggregates needs more cement to meet same compressive strength as conventional concrete. Old concrete strength which the recycled concrete made of is critical in case of 45-60 MPa concrete because the aggregates in this case are the weakest point and not the interfacial zones. Also it was observed that concrete made with recycled aggregates yielded lower elastic modulus which is an indicator to more ductile behavior. Researchers also recommended that recycled aggregates should be used only in case of 20-45 MPa concretes due to the effect of adhered mortars strength (Etxeberria et al., 2007).

Several batches were made for studying the failure mechanism of concrete made with recycled concrete aggregates. For that, researchers imported recycled concrete aggregates from two different sources 55MPa high strength concrete, and 30MPa medium strength concrete, in addition of granite crushed stones for control mix. Sizes also varied by using 15% of 6-12 mm, 70% of 6-20 mm, and 15% 10-30 mm nominal sizes. For fines siliceous river sand was used, with utilizing of blended cement, and naphthalene based superplasticizer as admixture to maintain desired workability. Tests applied on concrete were compressive strength and splitting tensile strength, while on aggregates density, water absorption (24 h), Los Angeles abrasion, point load strength index were applied. Results lead to conclude that concrete made with recycled aggregates generally has lower strengths, and lower fracture zone size, but the splitting strength was higher due to better bond that leads to more brittle behavior. Also concluded that fracture is related to compatibility between aggregates and paste, and on the fracture surfaces, a reduction of meandering and branching of cracks was observed. For the elastic modulus it was observed that the reduction was greater that the reduction in compressive strength, while the tensile to compressive strength ratio decreased as strength increase (Casuccio et al., 2008).

For studying the effect of microstructure of interfacial transition zone ITZ on properties of concrete in case of using recycled concrete aggregates. Researchers used two types of recycled concrete aggregates brought from high strength concrete and normal strength concrete with natural aggregates for control mix; these aggregates have sizes of 10-20 mm, and used natural river sand with fineness modulus of 2.1 as fine aggregates. For the binder Ordinary Portland Cement was used with fixed w/c ratio of 0.5. Neither additives nor admixtures of any type were used. Tests were adopted on both aggregates and concrete, for aggregates crushing value, density, water absorption, as-received water content, porosity and pore size distribution, chemical soluble in RCA, while for concrete compressive strength at 7, 28, and 90 days, microstructure using Scanning Electron Microscope (SEM) together with an Energy Depressive X-ray Analyzer (EDXA). After tests researchers made conclusions that recycled concrete aggregates brought from high strength concrete showed better quality than those brought from normal concrete. Strength development of concrete made with recycled aggregates with high strength concrete origin overlapped the conventional concrete after 90 days. Difference in strength development between the two types of recycled aggregates was due to better bonding and ITZ microstructure in case of high strength origin aggregates, and the microstructure of interfacial zones in concrete made with recycled aggregates from high strength concrete was denser. Also higher porosity and absorption capacity of aggregates lead to higher porosity in the interfacial zones, hence, enhancing the surface quality of aggregates will lead to better microstructure and bonding quality (Poon et al., 2004).

This study declared that if recycled concrete aggregates are used from old concrete structures,and these structures' elements has been carbonated. This means that the samples to be assessed must be labratorial carbonated, not only using a non-carbonated or low carbonated labratory made crushed concrete spiecmens. So researchers imported an old (1.5 years old) spiecmens and new spiecmens, then they applied carbonation treatment on them with different pressures 0.1 bars and 5 bars. Spiecmens where involved in making new concrete with a varity of replacment between 0% and 100%, aggregates used where coarse with diammeters of 5-10 mm and 10-20 mm. Same diameters for natural aggregates, natural fine aggregates with diameter < 5 mm were used, with a w/c ratio of 0.55, while mixing apolymer-based superplasticizer (RHEOBUILD 1100) at 1.0% was added with a ASTM Type I cement. After hardening and curing test were made at 56 days and 112 days, these tests were deformation caused by drying shrinkage, bulk electrical conductivity, water absorption, with chloride and gas permeability. By checking tests' results, researchers concluded that carbonated RCA showed better properties than non-carbonated ones, so CO_2 treatment could be innovative method of enhancment of properties of RCA (Xuan et al., 2017).

For studying influence of curing condition in case of aggressive enviroment such as marine enviroment. Researchers adopted adopting compressive strength, tensile splitting, relative density, absorption coefficient, porosity, water penetraion, oxygen permeability, and Accelerated chloride penetration tests. Number of spiecmens were prepared using ASTM type I 52,5N/SR cement, with w/c ratios varing from 0.4 to 0.75. After testing, it was concluded that for marine enviroment the higher cement content the lower durabilty performance occurred. The control and recycled concretes with high w/c ratios present similar properties comparing standard and marine environments 20% substitution provided similar properties to control concrete in marine enviroment RCA showed better properties than control mix with high w/c ratio (Thomas et al., 2018).

For studying the effect of curing on mechanical and durability properties of concrete containing recycled concrete aggregates. Researchers prepared 75 x 100 mm cylindrical samples using Ordinary Portland cement as a binder, with w/c ratio of 0.41, and with an addition of superplasticizer to maintain desired workability. For aggregates it was combination between crushed granite and recycled concrete aggregates with 60% replacement and a maximum size of 20 mm, while for fines it was river sand with maximum size of 5 mm. Tests made were compressive strength, flexural strength, water absorption, intrinsic air permeability, porosity, and chloride penetration. Results led to a conclusion that enhancing surface texture of RCA leads to better performance especially for durability, also treated RCA showed chloride concentration lower than 0.4% that meets standards (Ismail et al., 2017).

Researchers also analyzed the effects of the incorporation of recycled aggregates (RA) and densified Silica Fume (SF) on the durability of High Performance Concrete (HPC). This study was prepared by using CEM I 52.5 R blended with fly ash 10% and densified silica fume of proportions of 0%, 5% and 10% as a binder, while a 2% superplasticizer to maintain desired workability. Siliceous sands and fine recycled concrete aggregates as fine aggregates with maximum diameter of 5 mm, while for coarse aggregates it was crushed limestone and coarse recycled concrete aggregates with maximum diameter of 16 mm. Coarse and fine recycled aggregates had various replacement proportions (FRA/ CRA) of 50/50%, 0/100% , and 100/100%. Test made on the specimens were particle size distribution, Los Angeles test, Resistance to carbonation, Resistance to chloride penetration, Permeability to oxygen. Results of tests lead to conclude that used recycled aggregates of both types met the related European standards, also it was found that by full replacement of natural aggregates water absorption by immersion was increased by 80%, while for carbonation there was no effect observed because all samples did not exceed 1mm carbonation depth, also specimens prepared with recycled aggregates showed only 36-45% loss in performance, on the other hand, specimens containing recycled aggregates showed a 6 times higher oxygen permeability compared with natural aggregates (Pedro et al., 2018).

CHAPTER 3
MATERIALS AND METHODOLOGY

3.1 General Aspects

Using RCA reduces consumption of quarries which will reserves environment. Conserves landfill space, reduces the need for new landfills. Concrete while being crushed into smaller particles a large amount of carbon dioxide is absorbed. This reduces the amount of CO_2 in the atmosphere. Cost reduction – few research studies have shown a significant reduction in construction costs if RAC is used, by reduction of costs like quarrying, transporting, etc... Also creates more employment opportunities by employing new labor to be involved in the recycling industry. (Bravo, de Brito, Evangelista, & Pacheco, 2018; Brito & Saikia, 2013; Thomas et al., 2018a; Vyas, 2012; Xiao, 2018; Xuan et al., 2017).

This study will check the change of permeability properties and mechanical properties like compressive strength and tensile splitting strength with and without exposure to heating and cooling cycles varying from ambient to 160^{o} C as illustrated in Table 3.1

Table 3.1: Concrete samples properties and applied thermal cycles

	Applied Heating-Cooling Cycles		
	0 Cycles	**3 Cycles**	**6 Cycles**
Mix-1 (100%NA)	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile
Mix-2 (50%RCA& 50%NA)	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile	3 cubes for permeability 3 cubes for compressive 3 cylinders for split-tensile

3.2 Materials

3.2.1 Cement

The cement used according to **EN 197-1** is **CEM II/B-S 42.5 N**, which is slag cement that is normally used in North Cyprus because it provides lower heat of hydration and improved resistance for attacks caused by the sea environment. This cement's chemical and physical properties are illustrated in Table 3.2 and Table 3.3

Table 3.2: Chemical composition of used cement

Chemical Composition								
Compound	SO_3	SiO_2	CaO	CaO Free	MgO	Al_2O_3	Fe_2O_3	Cl
Content (%)	2.67	18.22	65.43	1.1	2.28	3.14	2.54	0.0

Table 3.3: Physical properties of used cement

Physical Properties	
Properties	**Result analysis**
Specific Gravity (g/cm^3)	3
Blaine (cm^2/g)	3548
Water to Cement (%)	29.1
Le Chatellier (mm)	0
Compressive strength (MPa) 2 days	22.45
7 days	37.12
28 days	52.89

3.2.2 Natural aggregates

Natural aggregates, which are used in this study, where supplied by Tufekci ready mix company. Aggregates were extracted from quarries of Beshparmak mountain in North Cyprus , sizes applied were separated into two size ranges 4.75-12.5 mm and 12.5-19 mm. Fine aggregates used in this study are natural sand with size range of < 5 mm.

3.2.3 Recycled aggregates

Recycled aggregates were prepared using old concrete cubes that were tested in NEU Civil Engineering Laboratory. Only coarse recycled concrete aggregates will be used in this study, in order of studying the bonding between RCA and new mortar this decision came because the use of fine recycled aggregates is not much favorable. Two size ranges where adopted for this study 5-12.5 mm and 12.5-19 mm. Natural sand with size < 5 mm was used as fine aggregates in mixing stage.

3.2.4 Water

Water is an essential factor in concrete because without water hydration process will not initiate. Water used in this study was of drinking to make sure that the quality of produced concrete, as defined in **EN 1008**.

3.3 Methodology

3.3.1 Recycled aggregates preparation

Majority of studies in literature are using freshly casted samples or laboratory tested concrete samples as a source of RCA. Validity of these is being determined, but this application is widely accepted. Concrete samples tested for compressive strength performance over years in NEU civil engineering laboratory was used as a source of RCA for this study. Samples were first separated according to their age, strength values, and source. Specific samples were selected to be used in this study according as they have the same source, all are 3 years age, and achieve C25 compressive strength at 28 days. Cubes were further cracked by using the compressive strength machine as shown in Figure 3.1.

Figure 3.1: Cubes further cracking by compressive strength machine (NEU Civil Engineering Laboratory, 2019)

After further cracking the cubes by using compressive strength machine, they were crushed using a hammer as shown in Figure 3.2.

Figure 3.2: Crushing Cubes using hammer (NEU Civil Engineering Laboratory, 2019)

The third stage was to reduce the sizes of crushed concrete to sizes that are able to be sieved using Los Angeles machine as shown in Figure 3.3 and Figure 3.4.

Figure 3.3: Los Angeles machine (NEU Civil Engineering Laboratory, 2019)

Figure 3.4: Samples crushed in Los Angeles machine with steel balls
(NEU Civil Engineering Laboratory, 2019)

After 200 rounds the machine was stopped and the samples where extracted. After extracting samples big parts where separated by hand in preparation for the second sub stage which is named “secondary grinding” as shown in Figure 3.5. After separation the big parts were added again to the machine with also 11 steel balls and the machine was set into another 200 rounds.

Figure 3.5: Separation after Initial grinding (NEU Civil Engineering Laboratory, 2019)

The last stage was to extract the wanted size ranges, for this stage a mechanical sieving machine was used as in Figure 3.6. As only coarse recycled aggregates were chosen to be used in this study, sieves used were 4.75, 12.5, and 19 mm, so aggregates with sizes smaller than 4.75 mm and larger than 19 mm where eliminated.

Figure 3.6: Sieving process (NEU Civil Engineering Laboratory, 2019)

3.3.2 Concrete mix design

For this study, the mix design was aiming to achieve C25; the mix was designed according to American Concrete Institute **ACI 211.1** (Dixon et al., 1997), this mix design was applied to both natural and recycled batches with proportions illustrated in Table 3.4. Replacement ratio of natural aggregates was adopted to be 50%. Both aggregates have same sizes for both 4.75-12.5 mm and 12.5-19 mm size ranges. This mix design was designed to achieve slump of 50-80 mm. The mix that consisted of natural aggregates was named “Mix 1”, while the mix that including recycled aggregates as a replacement was names “Mix 2”; three groups of each mix were prepared. Each group from each mix will be tested under certain circumstances.

Table 3.4: Mix proportions of both RCA and NA batches

Constituents	**Proportions (Kg/m^3)**	
	Mix 1	**Mix 2**
	NA	**RCA**
Cement	363	363
Natural Fine Aggregates	711	711
Natural coarse aggregates (12.5-19 mm)	549	274.5
Natural coarse aggregates (4.75-12.5mm)	549	274.5
Recycled coarse aggregates (12.5-19 mm)	-	274.5
Recycled coarse aggregates (4.75-12.5 mm)	-	274.5
Water	200	200
Water Cement ratio W/C	0.55	0.55

3.3.3 Casting and curing

Both types of mixes were prepared with the same mixing and casting procedure according to **ASTM C31** using a machined mixer. Cement and aggregates with all sizes were added, then water was added and the mixer was started, the mixing period was 120 second from the moment of water addition, then the mixture was ready to be casted. Six cubic and three cylindrical molds were cleaned and colored with a thin layer of oil. Each mold was filled by filling one third at a time, after each one third filling a tamping rod was used with 25 tamps, then tapping by a small rubber hummer 4 times on each side of the mold to achieve compaction and maximum bulk-density. After each mold was filled a trowel was used to make the surface leveled. After finishing filling process, samples were left 24 hours for setting to be demolded as in Figure 3.7.

Figure 3.7: Casting of samples (NEU Civil Engineering Laboratory, 2019)

Curing is essential to ensure proper hydration process. Water curing was adopted. For this study, after 24 hours in the molds, samples were demolded and marked, then they were placed in a curing tank, the tank was filled with drinkable water until all samples were fully submerged. Samples were kept submerged until testing age as in Figure 3.8.

Figure 3.8: Curing of samples (NEU Civil Engineering Laboratory, 2019)

3.3.4 Thermal cycles

Temperature chosen to be 160 C^{o} after checking (Ramakrishnan, Shafai, & Wu, 1991) and other related literature with checking the available equipment in NEU Civil Engineering Laboratory. Each cycle consisted of 2 hours of heating and 1 hour cooling to room temperature. Oven used is a dry-air heating oven as shown in Figure 3.9. Samples were aimed to be tested after different heating and cooling cycles; normal 0 cycles, 3 cycles, and 6 cycles as mentioned in Table 3.1.

Figure 3.9: Samples placed in Dry-air oven (NEU Civil Engineering Laboratory, 2019)

3.4 Tests on Aggregates

3.4.1 Absorption capacity test on coarse aggregates

Absorption capacity of coarse aggregates is an essential property especially for RCA because it has an influence of the water demand to determine w/c ratio in order to grant desired workability. Test procedures were performed according to **ASTM C127-04** for coarse aggregates.

Absorption capacity test is used to determine the amount of mixture's water that will be absorbed by aggregates because it has an effect of concrete mixture's workability.

Coarse aggregates were weighed and placed into the oven for 24 h at 105^{o}C. After drying, coarse aggregates were placed in a tray and soaked in water for 24 h. The SSD aggregates were weighed again. Calculations of water absorption were performed as following:

A: Weigh of the dry aggregate
B: Weight of saturated surface dry aggregate (SSD)
Applied formula : Water absorption = [(A – B)/B] x 100%.

3.4.2 Los Angeles abrasion test

Los Angeles abrasion test was done to determine the abrasion resistance of coarse aggregates. Aggregates from the same size distribution were added to the test machine then sieved in 1.7 mm sieve to determine the abrasion value.

Test procedure for both ranges (5-12) mm and (12-20) mm were performed for both types of aggregates according to **ASTM C31**.

Abrasion resistance test is used to determine the toughness of aggregates and their ability to resist applied abrasive mechanical actions such as in concrete pavements.

Test procedures:

- 5000 g form (4-12) mm and (12-19) mm of natural and recycled aggregate were weighted,
- Weighted aggregates were washed carefully,
- Washed aggregates were put into the oven for 24 h at 110^{o} C ± 5,
- Oven-dried aggregates were taken out from oven and left until cooled down,
- Aggregates were put into Los Angeles abrasion machine,
- According to the standard 11 balls were added to the machine,
- The machine rotated for 500 rounds,
- Aggregates were taken out from Los Angeles machine and put into a tray,
- The aggregates were sieved from 1.7 mm sieving,
- The weight of retained in sieve 1.7 mm is determined,
- Result was calculated as follow:

  Original weight of both types of aggregate samples NA and RCA is W1 in grams

  The weight of both NA and RC aggregate samples retained is W2 in grams

  Weight passing IS 1.7 mm sieve = W1 – W2 g

  Abrasion Value = (W1 – W2) / W1 X 100

3.5 Tests on Concrete

3.5.1 Compressive strength

Compressive strength is the most widely used test to determine hardened concrete performance. **EN 12390-3** was used to determine compressive strength. Three cubes with dimensions of 150 x 150 x 150 mm were used to determine the compressive strength of samples with 0, 3, and 6 thermal cycles as shown in Figure 3.10.

Figure 3.10: Compressive strength test (NEU Civil Engineering Laboratory, 2019)

3.5.2 Splitting tensile strength

Splitting tensile strength test is used as an indicator of quality of concrete beside compressive strength. **EN 12390-6** procedures were followed in this study to determine splitting tensile strength of samples. Three cylinder samples were used with dimensions of 150 x 300 mm. Splitting tensile strength test was applied to samples in 0, 3, and 6 thermal cycles as shown in Figure 3.11.

Figure 3.11: Splitting tensile strength (NEU Civil Engineering Laboratory, 2019)

3.5.3 Concrete permeability

Lower permeability in hardened concrete shows more sufficient durability performance in most cases due to higher microstructure density that reduces the penetrability and movability of harmful elements such as acids, carbon dioxide, sulfate, chlorides, etc.. **EN 12390-8** procedures were adopted to determine permeability of concrete mixtures. All natural and RCA-containing concrete samples will be tested after being exposed to various numbers of heating and cooling cycles. All samples will be tested in the age of 28 days. This test is performed by placing 3 cubes in the machine that is connected to compressor to provide 5 bars of pressure as illustrated in Figure 3.12.

Figure 3.12: Concrete permeability test (NEU Civil Engineering Laboratory, 2019)

After samples were subjected to the pressure for 72 hours, samples were split in the half, then by using a marker pen. The water penetration contour was marked, then by using Vernier Caliper the maximum penetration depth was measured for all samples for 0, 3, and 6 cycles as shown in Figure 3.13.

Figure 3.13: Maximum penetration depth measuring (NEU Civil Engineering Laboratory, 2019)

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 General Aspects

In this study, both types of aggregates NA and RCA were tested for absorption capacity and abrasion resistance. Fifty four concrete samples were prepared. Compressive strength, splitting tensile strength, and concrete permeability tests were applied. Heating and cooling cycles were applied ranging between ambient and 160^{o} C for 0, 3, and 6 cycles.

4.2 Aggregates Tests

4.2.1 Absorption capacity

Aggregates absorption capacity has an effect on determination of water demand in the concrete mixture in order to maintain desired workability. Results in Table 4.1 show the absorption capacity for both RCA and NA.

Table 4.1: Aggregates tests

	Los Angeles abrasion value (%)	Absorption Capacity (%)	
		(5-12) mm	(12-19) mm
RCA	41.2	4.8	3.7
NA	34	0.7	0.5

It is known that RCA have higher water absorption capacity than NA due to presence of attached mortar that increases the water absorption due to its higher porosity, which was also reported by (Etxeberria et al., 2007) to be 4.5% for size (5-12) mm and reported by (Poon et al., 2004) to be 8.82 % for size (5-12) mm and 7.9% for size (12-20) mm. and (Thomas et al., 2013) reported 5.3% for (6-20) mm. This makes produced RCA in this study to have acceptable absorption capacity.

In this study, absorption capacity in RCA was not significantly higher than NA. However, this increasing should be taken in consideration when designing a mixture for its effect on workability of RCA-containing concrete.

4.2.2 Abrasion resistance

Both types NA and RCA aggregates showed relatively low abrasion resistance as shown in Table 4.1. RCA did not satisfy the maximum allowed mass loss limit due to abrasion which is determined by ASTM standard as 40%. RCA showed higher mass loss with 7.2% than NA. (Pedro et al., 2018) Reported a mass loss of RCA by 33%, while (Casuccio et al ., 2008) found that the loss 39% when the RCA were produced from normal strength concrete and 32% when RCA produced from high strength concrete. Also (Thomas et al., 2018a) found the mass loss of RCA as 42%. Amount of adhered mortar and properties of original concrete have an effect on properties of produced RCA. Produced RCA in this study are not recommended for use in case of concrete possible exposure to abrasion.

4.3 Concrete Tests

4.3.1 Compressive Strength

Table 4.2: Compressive strength performance with respect to number of cycles

	Number of cycles	**Compressive Strength (MPa)**				
		Sample 1	**Sample 2**	**Sample 3**	**Average**	**Standard Deviation**
Mix 1	0	36.1	36.3	37.5	36.63	0.62
Mix 1	3	35.7	36.7	40.2	37.53	1.93
Mix 1	6	36.6	37.4	41.3	38.43	2.05
Mix 2	0	48.1	50.5	52.5	50.37	1.80
Mix 2	3	34.1	36.3	36.7	35.7	1.14
Mix 2	6	36.4	36.8	37.4	36.87	0.41

Table 4.2 illustrates the results for compressive strength performance of both types NA and RCA concretes. In case of the control mixture “Mix 1” with 100% NA, it was observed that there was slight increase in compressive strength performance as the number of thermal cycles increased as shown in Figure 4.1.

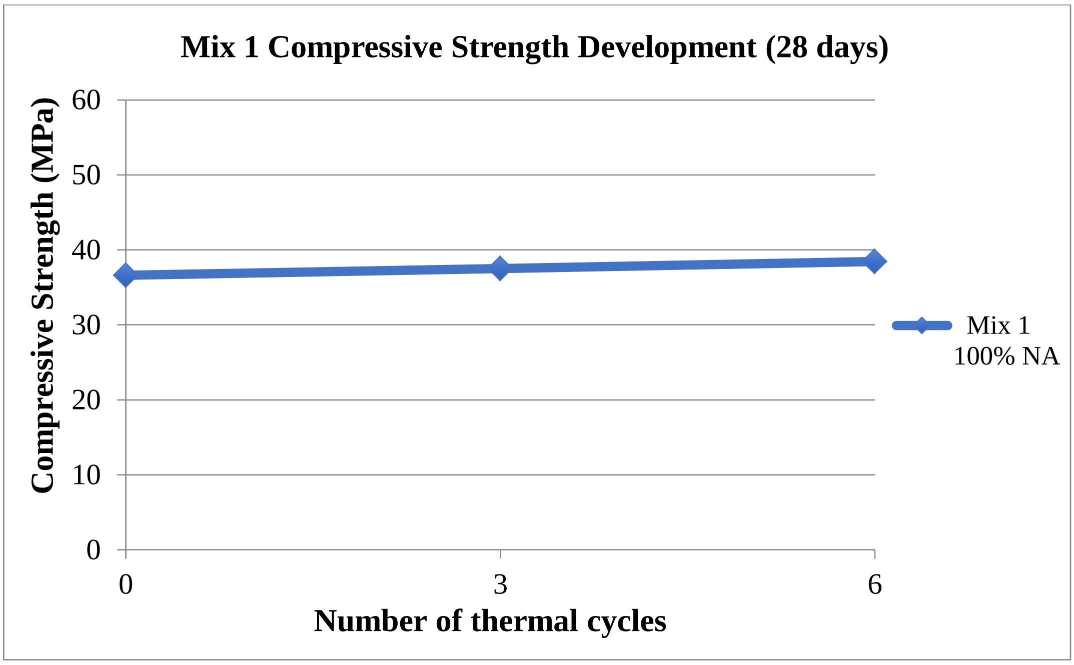

Figure 4.1: Mix 1 with 100% NA compressive strength performance development as exposed to thermal cycles

(Siddique & Kaur, 2012) prepared a study containing concrete samples produced using GGBS cement exposed to various temperature ranges with single thermal cycle, concluding that in some cases concrete that exposed to temperature reaching 100-200^{o} C showed increasing compressive strength performance and reported that this behavior could be due to using GGBS cement. Furthermore, (Khaliq & Taimur, 2018) prepared concrete samples with natural aggregates using cement containing Silica Fume and exposed to various temperature ranges with single thermal cycle finding a drop in compressive strength performance when exposed to temperature reaching 100-200^{o} C and reported that it could be due to dehydration of C-S-H gel. In this study, compressive strength performance showed slight increase in compressive strength performance after exposure to thermal cycles. More experiments are needed to determine the exact reason for this behavior.

In case of “Mix 2” containing 50% RCA, a drop of strength was observed after exposure to thermal cycles as shown in Figure 4.2. (Khaliq & Taimur, 2018) prepared samples with 100% RCA exposed to various temperature ranges for a single thermal cycle reporting a drop of compressive strength performance due to exposure to heat, declaring that this drop in compressive strength performance could be due to dehydration of C-S-H gel.

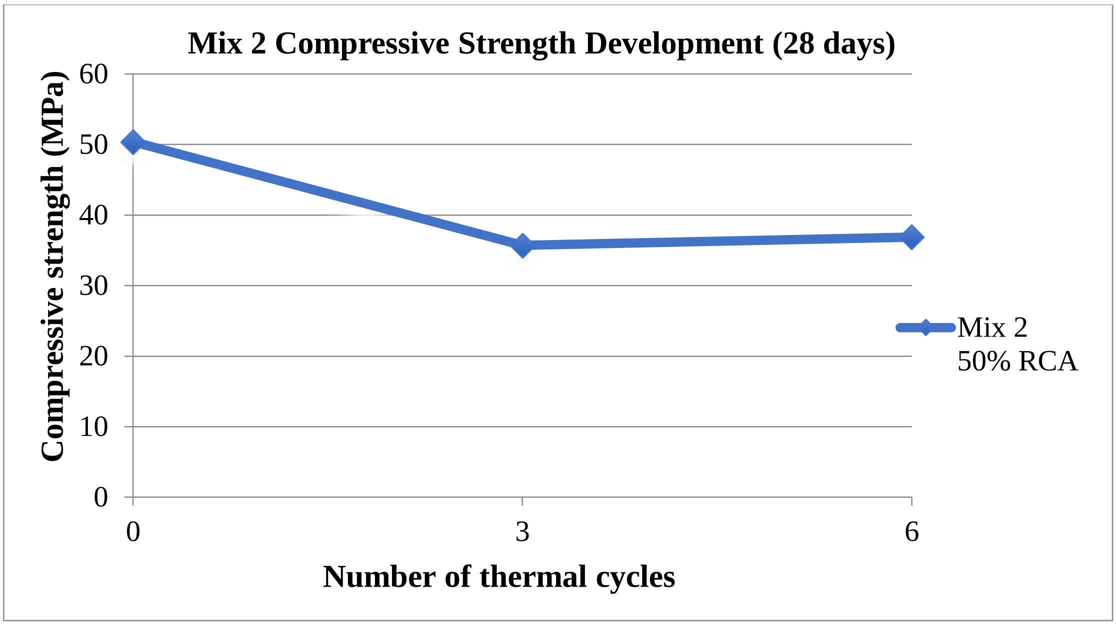

Figure 4.2 Mix 2 with 50% RCA compressive strength performance development as exposed to thermal cycles

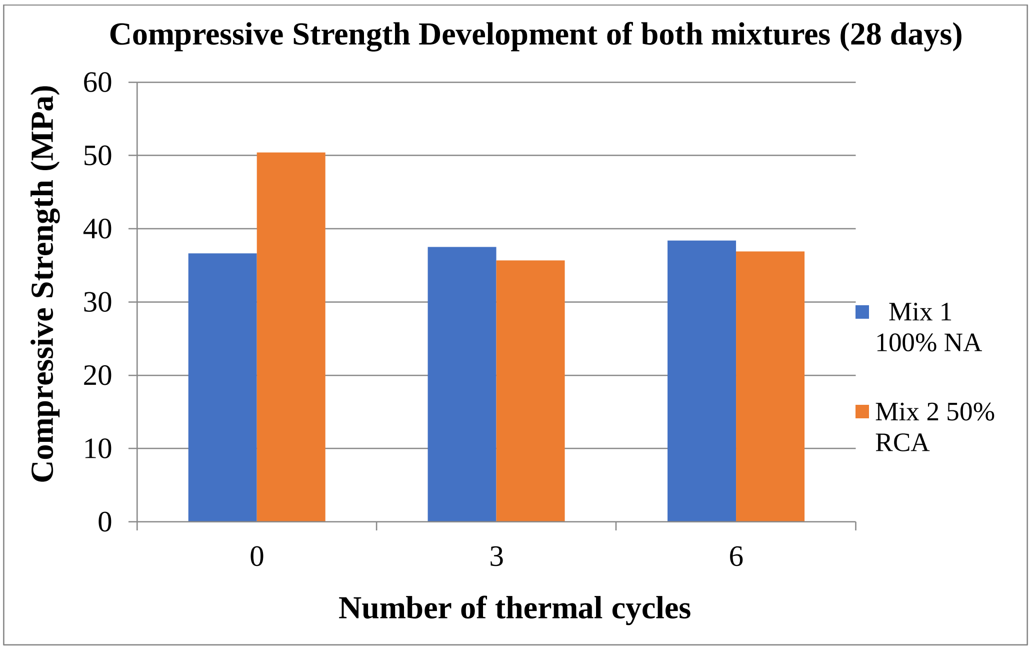

Figure 4.3: Compressive strength performance comparison of both mixtures with respect to number of thermal cycles

Figure 4.3 illustrates the comparison in compressive strength performance development for all heating and cooling cycles' cases for both NA and RCA mixtures.

In case of compressive strength performance with no thermal cycles, a noticeable higher compressive strength performance was observed for "Mix 2" with 50% RCA than "Mix 1"with 100% NA. (Xuan et al. 2017) prepared samples with carbonated RCA reporting that compressive strength behavior of concrete containing carbonated RCA was noticeably improved comparing to non-carbonated RCA. Also it could be due to denser microstructure or RCA-containing mixture.

After exposure to heating-cooling cycles, it was observed that "Mix 1" showed an improvement in compressive strength performance as thermal cycles increased, while "Mix 2" containing 50% RCA showed a drastically drop in compressive strength performance. This drastically drop in compressive strength performance after exposure to thermal cycles could be due to higher cracking in in the RCA-containing mixture "Mix 2" that have denser microstructure. (Khaliq & Taimur, 2018) made a comparison of concrete containing 100% NA and 100% RCA after exposure to single thermal cycles in various temperature ranges reporting that the drop in compressive strength performance of RCA-containing concrete was higher than natural aggregate concrete. More experiments with higher temperature or number of cycles might be needed to verify the exact reason behind the observed behavior.

4.3.2 Tensile Splitting Strength

Table 4.3 illustrates the results for splitting tensile strength for both types "Mix 1" with 100% NA and "Mix 2" with 50% RCA.

Table 4.3: Splitting Tensile strength performance with respect to number of thermal cycles

	Number of cycles	**Splitting tensile strength (MPa)**				
		Sample 1	**Sample 2**	**Sample 3**	**Average**	**Standard Deviation**
Mix 1	0	2.81	2.82	2.84	2.82	0.012
Mix 1	3	2.63	2.61	2.64	2.63	0.012
Mix 1	6	2.41	2.32	2.42	2.38	0.045
Mix 2	0	2.63	2.65	2.61	2.63	0.016
Mix 2	3	2.26	2.34	2.44	2.35	0.074
Mix 2	6	2.32	2.42	2.51	2.42	0.078

In case of "Mix 1" containing 100% NA, the tensile splitting strength behavior showed a reduction of strength performance as heating and cooling cycles increased as shown in Figure 4.4. (Siddique & Kaur, 2012) prepared a study containing concrete samples prepared using GGBS cement exposed to various temperature ranges with single thermal cycle, concluding that in some cases concrete exposed to temperature in range of 100-200^{o} C, observing a drop of splitting tensile strength due to exposure to heat and reporting that using GGBS cement does not have an effect of splitting tensile strength behavior when exposed to heat. (Khaliq & Taimur, 2018) also reported a drop in splitting tensile strength behavior after exposing samples to various temperature ranges including heating to 100-200^{o} C for a single thermal cycle.

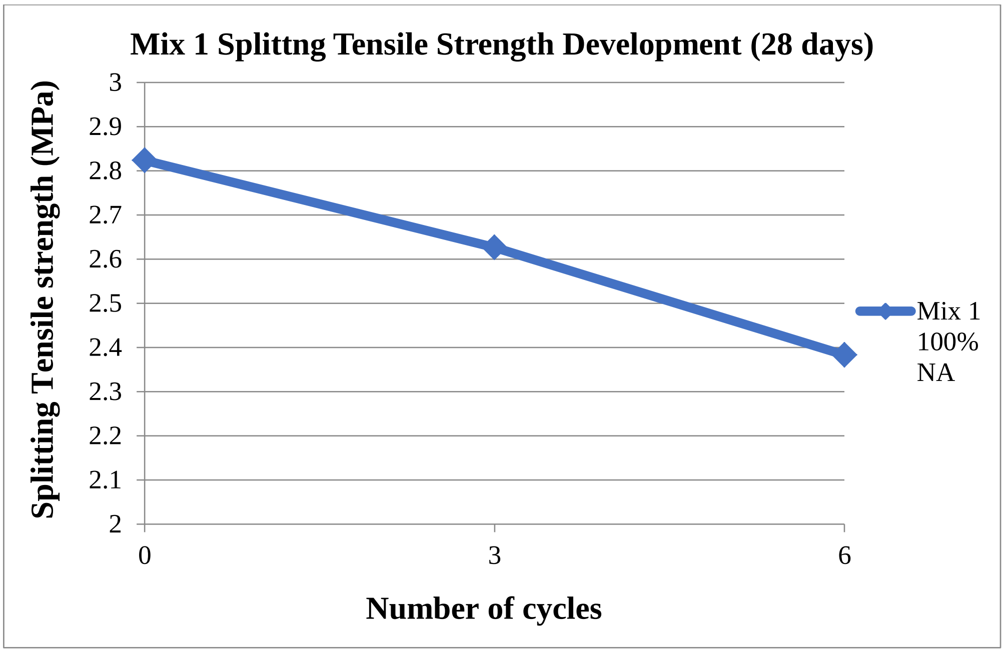

Figure 4.4: Mix 1 with 100% NA splitting tensile strength performance development as exposed to thermal cycles

Also in case of "Mix 2" containing 50% replacement of RCA the splitting tensile strength response for heating and cooling cycles was also reduction of splitting tensile strength performance as shown in Figure 4.5.

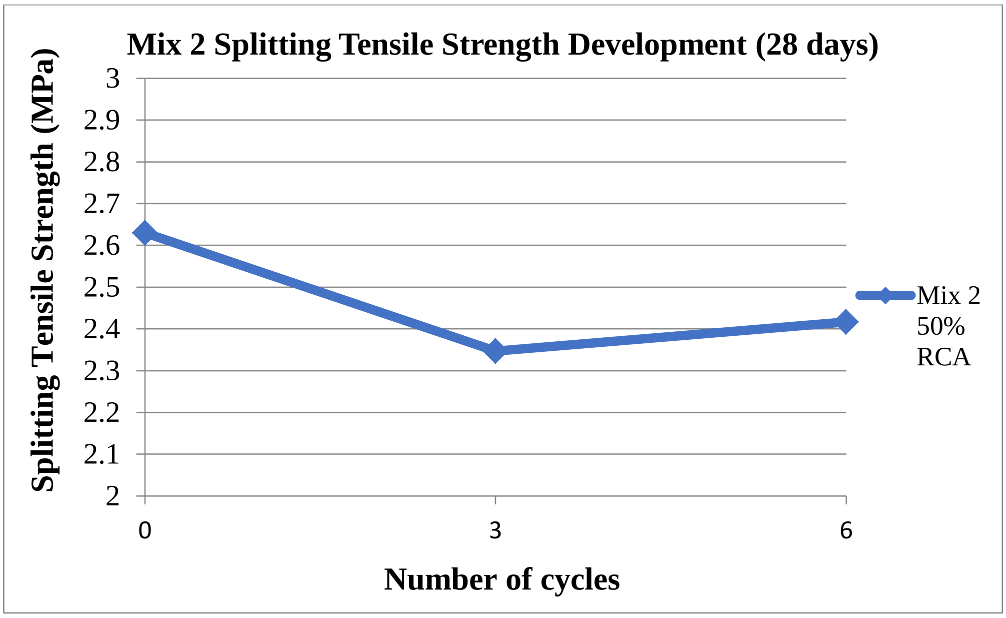

Figure 4.5: Mix 2 with 50% RCA splitting tensile strength performance development as exposed to thermal cycles

(Khaliq & Taimur, 2018) prepared samples with 100% RCA and testing them for splitting tensile strength performance after exposure to single thermal cycles for various temperature ranges including heating to 100-200^{o} C reporting that a drop of splitting tensile strength performance was also observed after exposure to heat.

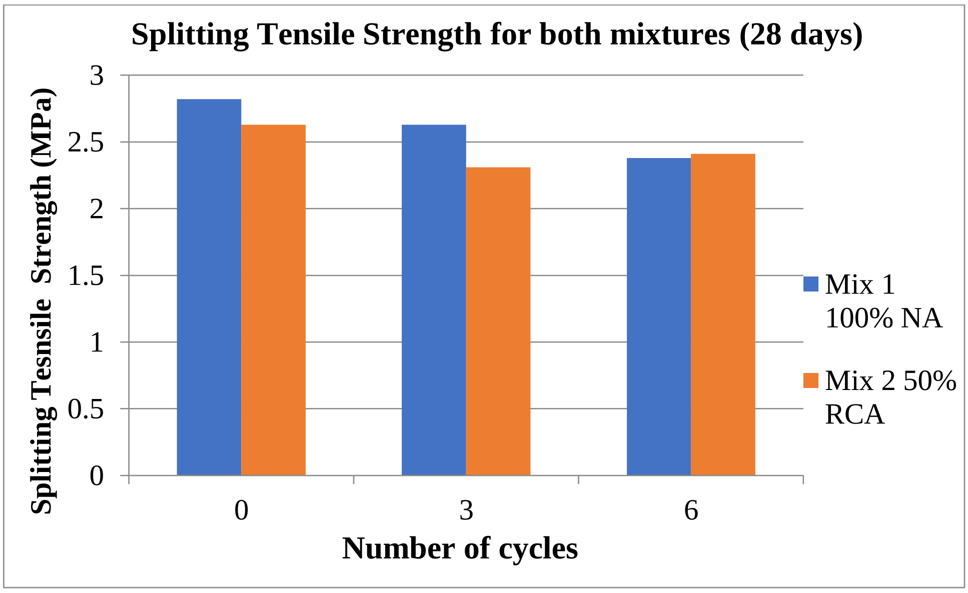

Figure 4.6: Splitting tensile strength performance comparison of both mixtures with respect of number of thermal cycles

Testing results of tensile splitting strength performance are illustrated in Figure 4.6 for both "Mix 1" with 100% NA and "Mix 2" which has a 50% replacement of RCA after 28 days and with exposure to various thermal cycles. Results show that both mixtures showed splitting tensile strength performance reduction after exposure to heat. Lower performance of splitting tensile strength performance was observed of "Mix 2" for cases of 0 and 3 cycles by 7% and 10% respectively, while in case of 6 cycles, "Mix 2" showed slightly higher performance by 2%. The use of slag cement does not have an influence on the splitting tensile strength as observed in compressive strength performance as reported by (Siddique & Kaur, 2012). Furthermore, the observed reduction caused by the heating could be caused by formation of cracks in the microstructure of concrete and the lack of cohesive properties of C-S-H gel due to dehydration as reported by (Khaliq & Taimur, 2018) who prepared a study about RCA-containing concrete exposed to various temperatures . For no heat cycles "Mix 2" samples showed lower splitting tensile strength than "Mix 1" samples. (Dimitriou et al., 2018) prepared samples with 50% and 100% RCA reporting that RCA-containing concrete showed lower splitting tensile strength performance and reported that this reduction could be caused by mineral additives in cement. (Abdel-Hay, 2017; Paul, 2017) prepared RCA-containing concrete with several RCA replacement ratios and after testing for splitting tensile strength performance reported that an increased reduction of splitting tensile strength performance in comparison with natural aggregates concrete was observed as the replacement ratio by RCA increased. Heat cycles with defined temperature and number of cycles seemed to cause a slight reduction in splitting tensile strength for both mixtures. Splitting tensile strength performance observation yielded more adequate information than compressive strength performance about the performance of both concrete types when exposed to thermal cycles. However, having more number of cycles or increasing temperature might be needed to observe further effect on strength and verify the exact reason for observed behavior.

4.3.3 Concrete Permeability

Permeability is considered as a good indicator of concrete durability performance. Concrete with Lower permeability yields lower ability for harmful chemicals to penetrate within concrete. In this study concrete permeability is determined by water penetration depth under pressure, and all measurements were rounded to the nearest mm.

Table 4.4: Concrete permeability for both types with respect to number of cycles

	Number of cycles	Water penetration depth (mm)				
		Sample 1	**Sample 2**	**Sample 3**	**Average**	**Standard Deviation**
Mix 1	0	24	25	26	25	1.00
Mix 1	3	32	29	30	30	1.53
Mix 1	6	39	42	43	41	2.08
Mix 2	0	15	17	16	16	1.00
Mix 2	3	20	22	25	22	2.52
Mix 2	6	26	31	35	31	4.51

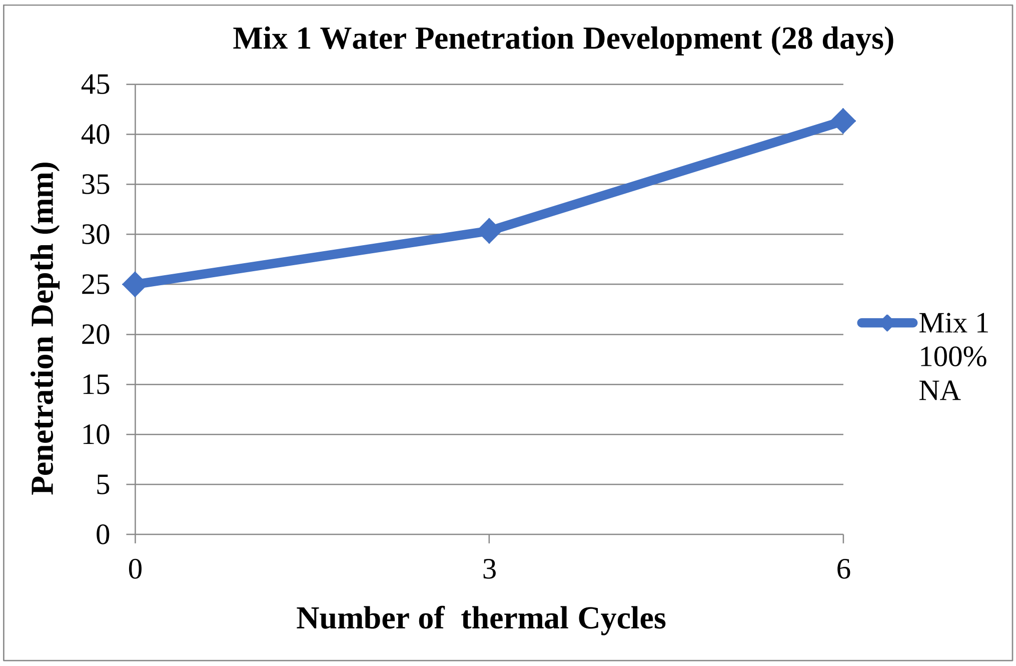

Figure 4.7: Mix 1 with 100% NA water penetration depth development as exposed to thermal cycles

Permeability test results for both types of concrete are illustrated in Table 4.4. In case of "Mix 1" prepared with natural aggregates, it was shown that by exposure to thermal cycles concrete samples' permeability increased by 21% and 65% for 3 and 6 heating and cooling cycles respectively as shown in Figure 4.7.

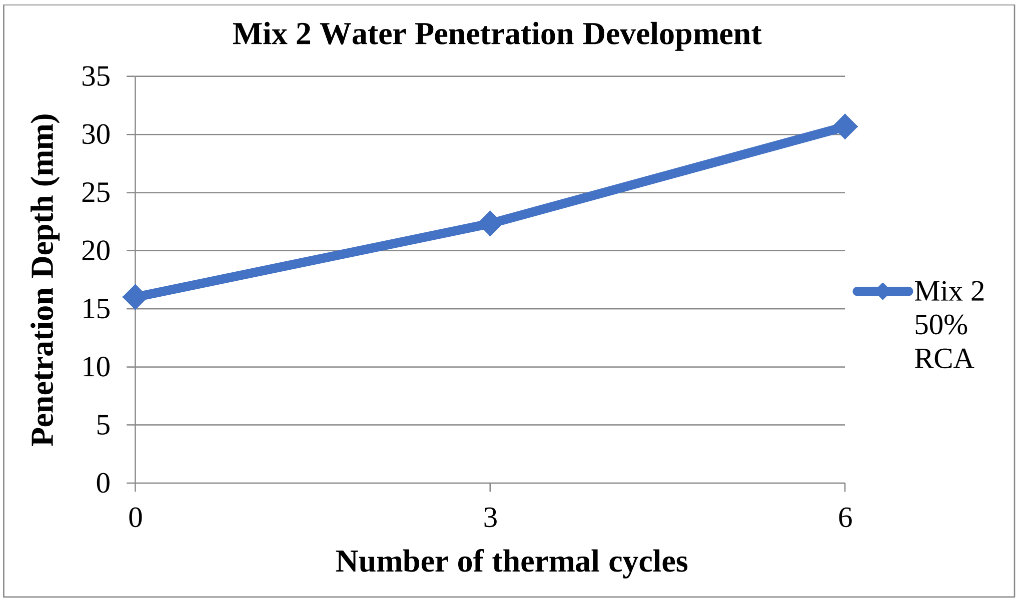

Figure 4.8: Mix 2 with 50% RCA water penetration depth development as exposed to thermal cycles

While in case of “Mix 2” containing 50% replacement ratio of RCA, samples also showed an increase in permeability by 3 and 6 was 39% and 91% respectively as shown in Figure 4.8.

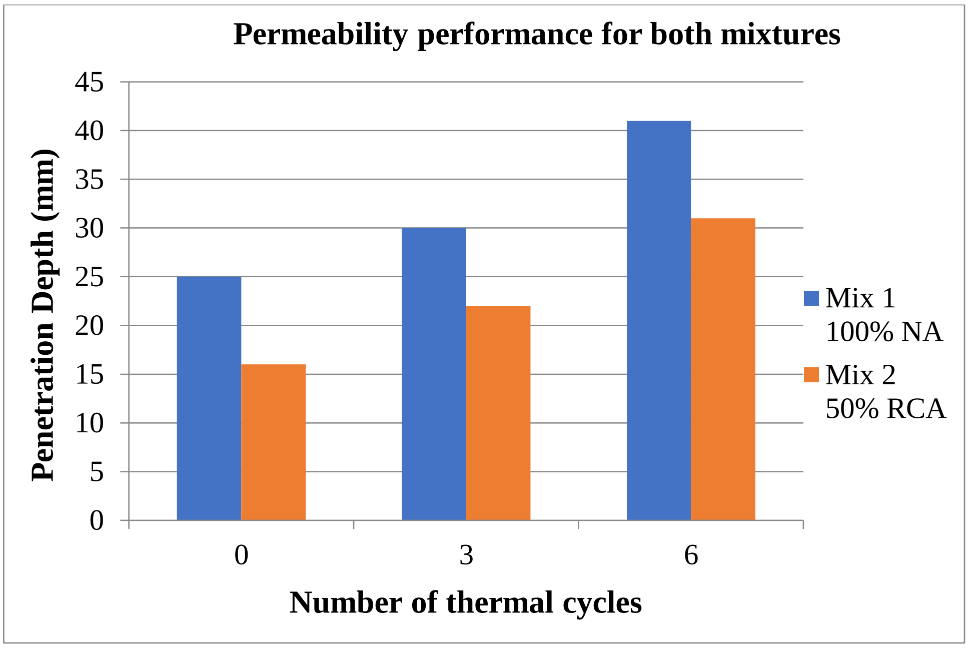

Figure 4.9: Permeability performance comparison of both mixtures with respect of number of thermal cycles

“Mix 2” containing 50% RCA showed lower permeability in 0, 3, and 6 cycles by 36%, 26%, and 26% respectively than “Mix 1” that has 100% natural aggregates. In both mixtures, an increase in permeability was observed as number of heating and cooling cycles increased. In no thermal cycles case “Mix 2” with 50% RCA showed lower permeability by 36% than “Mix 1” with 100% NA (Thomas et al., 2013; Thomas et al., 2018) prepared concrete samples with 0%, 20%, 50%, and 100% RCA reporting that water penetration depth also tends to be related to the w/c ratio that is also related to the density of microstructure, also sealed porosity of RCA caused by carbonation or the higher water absorption of RCA that absorb excessive water providing denser microstructure of the mixture in hardened state. After exposure to thermal cycles “Mix 2” with 50% RCA showed lower permeability by 26% than control mix “Mix 1” after exposure to 3 and 6 thermal cycles. (Khaliq & Taimur, 2018) Prepared samples with 100% NA and 100% RCA exposing them to single thermal cycles in multiple temperatures reaching 100-200^{o} C reporting that the denser microstructure leads to higher formation of internal cracks due to higher internal pressures accompanied with exposure to elevated temperature. Permeability also provided better observation to the behavior of both types of concrete produced in this study than compressive strength performance when concrete is exposed to heating cycles. However, more experiments are needed to present solid conclusions and to verify the exact reason behind the observed behavior.

CHAPTER 5
CONCLUSSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study consists of systematical experimental investigations in order to study the behavior of RCA-containing concrete exposed to heating and cooling cycles. Fifty four samples were produced for both 100% NA and 50% RCA replacement. Samples were exposed to 0, 3, and 6 heating and cooling cycles ranging from ambient to 160^{o} C. Each cycle included 2 hours of heating and 1 hour of cooling in room temperature. Both mixtures were tested for compressive tensile splitting strength and permeability. Conclusions were made as follows:

- RCA showed higher absorption capacity than natural aggregates,
- Absorption capacity of RCA was not significantly higher than NA,
- RCA showed lower abrasion resistance than NA,
- Produced RCA are not recommended for use in case of abrasion exposure because they did not satisfy the allowed maximum mass loss limit,
- RCA-containing mixture showed noticeable higher compressive strength in case of no heating and cooling cycles,
- NA mixture showed compressive strength increase as thermal cycles increased, while RCA mixture showed noticeable drop of compressive strength performance,
- NA mixture showed better splitting tensile strength performance than RCA mixture when no thermal cycles were applied,
- Both mixtures showed a drop in splitting tensile strength performance after exposure to thermal cycles,
- RCA-containing mixture showed noticeable lower permeability than control mixture in all exposure and no-exposure cases,
- Permeability increase in RCA- containing mixture was relatively higher than control mixture after exposure to thermal cycles,

- It is observed that split tensile strength testing is more capable of reflecting the performance decrease due to RCA inclusion than compressive strength testing; which might have a closing effect on the cracks during testing.

5.2 Recommendations for future works

Results and observation of this study need to be repeated for confirmation of the results. Heating and cooling cycles should be repeated with higher temperature range or more cycles to verify the exact reason for the observed results. Different RCA production method may be needed to verify the effect of RCA production method on the properties of produced RCA. RCA samples from real demolished structure are needed to verify their behavior under exposure to heating and cooling cycles. More tests on concrete like rheology tests for fresh state and flexural strength and concrete durability tests for hardened state could be performed. More aggregate tests like bulk density, specific weight, and attached mortar content could be performed to determine further properties of produced RCA.

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