# EXPERIMENTAL STUDIES ON STRUCTURAL CONCRETE MANUFACTURE WITH RECYCLED CONCRETE AGGREGATE AGED IN NORH CYPRUS

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**Hiba Muhammed MUHAMMEDEMIN: EXPERIMENTAL STUDIES ON STRUCTURAL CONCRETE MANUFACTURE WITH RECYCLED CONCRETE AGGREGATE AGED IN NORTH CYPRUS**

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**To my late father…**

# ABSTRACT

In today's world, the environment is threatened with increase in generation of waste materials arising from human activities. Waste are generated from construction activities and demolition of concrete elements as result of new development or failure in meeting serviceability and functional criteria. Management of construction and demolishing waste is important and this study evaluated the reuse of demolished concrete waste aged under North Cyprus climatic condition.

The used recycled aggregates were obtained from a 20 years old school building in Nicosia and the natural aggregates were obtained from Besparmak Mountain in Nicosia.

The structural concrete assessment was evaluated for eight different mixes with five different coarse recycled concrete aggregate replacement of 0%, 25%, 50%, 75% and 100% by weight with fine recycled concrete aggregate and silica fume use in only 50% replacement by weight.  Water demand was regulated between 18- 20 cm slump value for all mixes and cured under water at different ages.

The result shows that the mechanical properties of natural aggregate is not different from corresponding recycled concrete aggregate except for absorption due to extreme dry state and fineness of attached mortars.

The compressive strength of coarse recycled concrete aggregate meets the criteria of structural concrete at 28 days even with the use of fine recycled concrete aggregate. The addition of silica fume increases the strength property. The findings show that coarse recycled concrete aggregate can be applied in construction even with 100% recycled concrete aggregate.

***Keywords*****:** Structural concrete; recycled concrete aggregate; compressive strength; flexural strength; construction and demolition waste

# ÖZET

Günümüzde çeşitli insan faaliyetlerinden kaynaklanan atıklar çevreye tehdit oluşturmaktadırlar. Betonarme yapıların inşaat faaliyetlerinden ve bu yapıların servis ömürlerini tamamlamaları sonrasında yıkımlarından kaynaklanan ciddi miktarlarda atıklar oluşmaktadır; bu bağlamda, inşaat ve yıkım atıklarının yönetimi kritik önem taşımaktadır. Bu tez çalışması kapsamında, Kuzey Kıbrıs koşullarına maruz kalarak yaşlanmış beton binaların yıkımıyla elde edilen beton atıkların, yapısal beton üretimi içinde kullanılmasının fizibilitesini değerlendirmiştir.Yeni betonda agrega olarak kullanılan geri dönüştürülmüş beton atıklar, 20 yıl servis verdikten sonra yıkılmış bir okul binasından elde edildi ve doğal agregalar Lefkoşa'daki Beşparmak Dağı'ndan elde edildi.

Sekiz farklı karışım ve beş farkl kaba agrega 0%, 25%, 50%, 75% ve 100% oranın ağırlığa göre, ince geri dönüşümlü beton agrega ve silis dumanı kullanımı %50 oranında sınırlanarak, yapısal beton değerlendirilmesi yapılmıştır. Tüm karışımlar için su ihtiyacı 18-20 cm çökme değeri arasında düzenlenmiş ve farklı yaşlarda su altında sertleştirilmiştir.

Bu tez çalışmasında elde edilen sonuçlarla, su emme kapasitelerinde gözlemlenen fark hariç aşırı kuru durum ve ekli harçların inceliği nedeniyle., doğal agregalar ve geri dönüştürülmüş beton agregaların özelliklerinin birbirinden farklı olmadığı gözlemlenmiştir.

Kalın geri dönüştürülmüş agregalarla üretilen betonun 28 günlük basınç dayanımı, ince geri dönüştürülmüş beton agregalarla birlikte kullanıldıkları karışım dahil; yapısal beton kriterini karşılamaktadır. Silis dumanının ilave edilmesiyle mukavemetin arttığı gözlenmiştir. Bu tez çalışması kapsamında elde edilen bulgulara göre, geri dönüştürülmüş beton agregalarının, beton karışımındaki agregaların %100'ü olacak şekilde kullanıldığı durumda bile yapısal beton elde edilmesi mümkündür.

***Anahtar Kelimeler:*** Yapısal beton; geri dönüştürülmüş beton agregaları; basınç dayanımı; eğilme dayanımı; inşaat ve yıkım atıkları

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| | |
|---|---|
| **CNA:** | Coarse Natural Aggregate |
| **CRCA:** | Coarse Recycled Concrete Aggregate |
| **C & D:** | Construction and Demolition |
| **FNA**: | Fine Natural Aggregate |
| **FRCA:** | Fine Recycled Concrete Aggregate |
| **NA:** | Natural Aggregate |
| **NAC:** | Natural Aggregate Concrete |
| **RA:** | Recycled Aggregate |
| **RAC:** | Recycled Aggregate Concrete |
| **RCA:** | Recycled Concrete Aggregate |
| **SF:** | Silica Fume |

# CHAPTER 1

# INTRODUCTION

## 1.1 General Aspects of Construction Waste Problem

Concrete is composed of cement, coarse and fine aggregate as well as water and admixtures. Water is added for hydration of cement, which then produces a paste with binding properties used for different purposes. The demand on the use of concrete in construction world is continuously increasing due to its desired strength, preferred economy and ease of molding into different shapes. However, reinforced concrete structures are designed for specified service life.

The high demand for concrete use results in high consumption of natural aggregates (NA), whereas the desire for replacement or demolition of previous concrete elements produces concrete construction and demolishing C&D waste. Urbanization and great interest in modern building construction have caused an increased rate of construction waste recently. The resulting construction waste; replaced or demolished concrete waste poses a great threat to the environment.

The large portion of the C&D waste is disposed, as landfills and this is not considered as an environmental-friendly solution. Undesired landfills could occupy agricultural land with a huge amount of non-biodegradable waste, which makes the land unsuitable for agriculture purpose and this waste is increasing with time. On the other hand, disposed construction and demolishing waste has been reported to have contribution to air pollution, these wastes are embodied with hazardous materials and fine particles easily discharged into the atmosphere. In addition, pollution could arise from the demolition site, transportation as well as dumping of the construction waste.

Moreover, increasing use of “virgin” natural aggregates in concrete as result of high demand for housing in urban areas and other concrete based infrastructure construction especially in developing countries, may lead to depletion natural aggregate in time. According to geological studies, the formation of natural aggregates used in the construction of concrete is estimated around 1000 years (U.S. Geological Survey, 1949).

The natural aggregates are mostly obtained from mountains' excavation, which is a threat to the ecosystem. In addition to this, the mountains with quarries where NA is extracted in large quantities are faced with numerous problems.

The main source of natural aggregates that are used in North Cyprus is obtained from Besparamak Mountains. Excavation in the quarries releases hazardous fine particles which could cause a health problems to its surrounding. Also, excavation of aggregates leads to depletion of natural resources, and landslide may occur if the stability of the slope is altered. These activities destroy the mountainous terrain, which affects animals and plant survival within the ecosystem. The excavated parts of the mountain have also a negative visual impact as a result of not correctly managed Besparmak aggregate quarries the natural mountainous undulations are heavily destroyed.

The amount of natural aggregate used in construction and the produced construction waste is not sustainable. The large construction wastes could be reused in a manner to protect the environment and contribute to the construction of the new building through recycling.

## 1.2 Definition of Problem

The depletion of the NA is one of the main problems since there is limited number of natural resources, so Figure 1.1 shows the extraction of the natural aggregates of Besparmak Mountain.  The increase in concrete production increases the use of NA in one hand and the accumulation of construction waste after the end of buildings service life on the other hand are both causing environmental problems. The accumulation of all those construction waste will affect the environment negatively in terms of air pollution and the occupation of land that could be used for different purposes.

**Figure 1.1:** Pollution resulting from excavation at Besparamak Mountains

There are many studies done on the performance of the recycled concrete aggregate (RCA) by researchers all around the world while its use in North Cyprus is still not common. Manufacturing concrete with partial RCA replacement has not been studied extensively in North Cyprus. The performance of such type of concrete made with RCA aged in North Cyprus climate and environmental conditions should be investigated systematically, in order to provide insight on the feseability of RCA containing concrete manufacture in North Cyprus.

## 1.3 Objectives and the Scope of the Study

This research work will investigate the possibility of manufacturing structural concrete with RCA obtained from demolished structures aged in North Cyprus condition. The objective of this study is to carry out systematic experimental studies in order to investigate the performance of concrete made with varying RCA replacements in the aspects of compressive and flexural strength development. The disposal of the construction waste in a landfill is not a preferred solution in terms of environmental pollution that causes different problems like the occupation of the land with those construction wastes and the increase of those wastes as the end of service life of building structures. Taking 100% NA as a control for five different NA percentage replacements with RCA that are 0%, 25%, 50%, 75% and 100% have been used to manufacture recycled concrete. Compressive and flexural strength evolution of all the mixes will be determined at 7 and 28 day's age of the concrete. Additional tests on compressive strength at 90 days have also been carried out.

## 1.4 Significance of the Study

Results that will be obtained in this study will provide insight on the quality of RCA that was aged in Cyprus climate and environmental conditions and the performance of structural concrete manufactured with these aggregate. The systematic data showing the flexural and compressive strength of eight different concrete mixes made with different RCA replacement percentage will demonstrate the level of the feasibility of RCA concrete in North Cyprus and will help the concrete manufacture in this area while preparing their own mixes of RCA concrete in the nearest future. Obtained result will also provide contribution to the related literature.

## 1.5 The Structure of the Study

This thesis study includes five chapters that will explain the study in detail. The introduction is presented in chapter one, giving an overview of recycling problems and general background information on the topic. It defines the problem in detail, provides information about its threat to the environment. Also the scope, significance and objectives of this research are included in chapter one.

Chapter two is the literature review that explaines detailed information about previous research studies on RCA. Studies associated with recycled concrete are presented by explaining their observation about RCA.

Chapter three, which is the methodology, explains in details the steps that were taken to perform the experiments.

The results of the flexural and compressive strength of different RCA replacements has been presented and discussed in chapter four, which confirms the idea of recycling concrete. The summary and conclusion of the study will be presented in chapter five.

### 1.6 Study Limitations

Obtaining demolished concrete with desired criteria to be used in this study was not easy. Time, limited resource, is a key factor that is envisaged to limit the quality and affect the schedule of this research work. Some part of the test methods were expected to be carried out in this research were time-dependent and the risk of running trial tests could be completely eliminated which affected the total time duration needed to complete this study. The availability of recent test machines, cost and lab equipment’s have been constraints in the progress of research carried out.

# CHAPTER 2

# LITERATURE REVIEW

This chapter reviews the literature on the use of construction and demolishing waste as Recycled Concrete Aggregate (RCA) in the production of new concrete. The physical and mechanical properties of RCA, their use in different aspects of constructions, their effect in production new concrete, and possibility in increasing its quality is discussed in the below sections. The use of RCA in the production of High-Performance Concrete, Self Compacting Concrete and structural concrete is overviewed. Researchers have studied and discussed construction in different aspects for the purpose of recycling. Different ideas are suggested in the usage of RCA in order to give desired strength. It is possible to get the desired strength from RCA by limiting its partial replacement percentage with the use of natural aggregate (NA). The suggested ideas in the use of RCA are discussed below.

## 2.1 General Overview

The idea of recycling has been applied in concrete with different approaches that were proposed by previous researchers, with acceptable strength result in specific percentage replacement. There are several buildings in Northern Cyprus that completed their service lives or that will be completing soon, so with the time of their demolishing the accumulated wastes will be disposed as landfill. The amount of all those accumulated wastes will increase as more buildings are demolished in parallel increasing the environmental problems. There have been several pieces of research around the world taking the reuse of all those demolished wastes as RCA. Emphasizing on the Northern Cyprus region recycling construction waste can be considered as a viable option in rescuing all those wastes and reducing the consumption of natural aggregates.

**Figure 2.1:** Construction and Demolition Waste in Centre of North Cyprus, Nicosia

This study seeks to evaluate efficient means of reusing accumulated construction waste as RCA for getting structural concrete. The construction waste will be cleaned out from wastes like wood, paper, glass, metal and other minor contaminants. The concrete is crushed as it is mentioned in chapter three and sieved into three different sizes. The coarse recycled aggregates with different partial replacement were used with NA. The flexural and compressive behaviour of the RCA will be studied with respect to partial replacement of NA concrete.

## 2.2 Constructions and Demolishing Waste and Recycling

Recycled concrete aggregates are obtained from demolished sites and construction industry and those building which finished their service life and their construction demolishing waste originates by a large amount that impacts the environment negatively. The idea of using construction rubbles is generated from ancient times as a number of Roman aqueducts were made from recycled aggregates. After World War II the need for the recycling become very evident while reconstructing the ruined buildings. The “new era” of the beginning of the recycling started in the mid-seventies with an up-healing movement in environmental awareness. The use of the RCA become commercial and the first international symposium held in Rotterdam in 1985 for using RCA in construction (Evangelista & de Brito, 2014; Zieliński, 2017).

The high demand for concrete use in construction increases, so in parallel, the “Construction and Demolishing” (C&D) waste increases, when the constructed buildings finishing their service life no longer support its own structure. Each concrete constructed building has its designed service life, so at the end of their service life, the building should be demolished. The continuous circle of construction and demolishing is leading to the accumulation of construction wastes and their disposal to landfill. The global demolishing waste reported being around 2-3 million tons as cited in (Mohammed, Das, Mahmood, Rahman, & Awal, 2017). The disposal of all those wastes to landfill will cause a severe environmental problem. The utilization of all those C&D waste will not just save the environment, but also it will provide alternative to the use of NA.

## 2.3 Constructions and Demolishing Waste Management

The demand for the use of RCA is low because of the low price of NA; this makes the management of the C&D waste more difficult. The development of construction industries and their use of RCA are recommending some ways to ease the use of C&D waste in construction industries. The first way starts with transportation and disposal of all those C&D wastes in the landfill. The disposal of all those waste in different places makes it difficult in managing and organizing them. The transportation of all C&D wastes to the construction industry and crushing them by proper crushing machine like jaw crusher and using in the construction industry is one of the suggested ways for construction waste management. Another more preferred way is crushing those construction wastes in the demolished building area without transporting them for crushing process, so a crushing machine is transported to the demolished building area. There are also other problems besides transportation such as storage, treatment, recovery that can be managed by improving construction industry and giving special attention to its management. Kleijer, Lasvaux, Citherlet, & Viviani, (2017), suggested a scenario in the management of construction waste; producing recycled aggregate in construction company then transporting them to construction site. The amount of C&D waste generated in the UK reached to 70 million tons, 6.16 million tons in Australia, and 35 million tons accumulated each year in Japan (Estanqueiro, Dinis Silvestre, de Brito, & Duarte Pinheiro, 2018).

**Table 2.1:** Comparison between construction and demolishing waste and the percentage of recycling (Vivian W Y Tam & Tam, 2008)

| Country | Proportion of Construction Waste to Total Waste (%) | C&D Waste Recycled (%) |
|---|---|---|
| Australia | 44 | 51 |
| Brazil | 15 | 8 |
| Denmark | 25 - 50 | 80 |
| Finland | 14 | 40 |
| France | 25 | 20 - 30 |
| Germany | 19 | 40 to 60 |
| Hong Kong | 38 | No Information |
| Japan | 36 | 65 |
| Italy | 30 | 10 |
| Netherlands | 26 | 75 |
| Norway | 30 | 7 |
| Spain | 70 | 17 |
| United Kingdom | Over 50 | 40 |
| United States of America | 29 | 25 |

Japan is one of the well-known countries for the use of C&D waste and for the scientific studies on the use and the management of RCA, about 38% of the C&D waste is recycled (V W Y Tam & Le, 2008). In Europe, the C&D waste is believed to be 45 million tons and at the beginning of 1990’s 28% was used as recycled aggregate. Hong Kong and Taiwan annual C&D waste generated is about 14 million tons, so they started programmes for its utilization. Taiwan generated new plans for using construction waste especially after the earthquake, which happened in central Taiwan; resulted in severe damage of buildings and consequently accumulation of construction waste (Rao, Jha, & Misra, 2007).

## 2.4 Standards for RCA

The issue of using construction and demolishing waste as RCA is complicated since it is difficult to determine the amount and type of harmful impurities that may cause durability problems in the concrete. There are several organizations, which tried to define a scope for the use of RCA and classification for the ease of its use in construction. There are few certain guidelines, which classify the C&D waste into categories Zielinski, (2017). The effect of RCA on concrete is very controversial since there is not any standard to support the use of a specific percentage. However, there are standards which classify the RCA according to its types:

Zieliński, (2017) and (L. Butler, West, & Tighe, 2011), states that European standard RILEM (Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages), which classified recycled aggregated into three types,

RCAC Type I – rubbles derived from masonry,
RCAC Type II – rubbles originally coming from concrete,
RCAC Type III - a mixture of natural and recycled aggregates.

According to RILEM, the use of aggregates (>4) mm is preferred because it is hard to determine the contamination of fine aggregates that cause durability problems.

**Table 2.2:** RILEM Standard for using RCA (Liam Butler, Tighe, & West, 2013)

| Mandatory requirements | RCA Type I | RCA Type II | RCA Type III |
|---|---|---|---|
| Min. dry particle density (kg/m$^3$)[a] | 1500 | 2000 | 2400 |
| Max water absorption (% m/m) | 20 | 10 | 3 |
| Max. content of material with SSD < 2200 kg/m$^3$ (% m/m) [a] | - | 10 | 10 |
| Max. content of material with SSD < 1800 kg/m$^3$ (% m/m)[a, b] | 10 | 1 | 1 |
| Max. content of material with SSD < 1000 kg/m$^3$ (% m/m and % v/v) [a] | 1 | 0.5 | 0.5 |
| Max. content of foreign materials (metals, glass, soft material, bitumen) (% v/v) | 5 | 1 | 1 |
| Max. content of metals (% m/m) | 1 | 1 | 1 |
| Max. content of organic material (% m/m) | 1 | 0.5 | 0.5 |
| Max. content of filler (<0.063 mm) (% m/m) | 3 | 2 | 2 |
| Max. content of sulfate (% m/m)[c] | 1 | 1 | 1 |

[a] To convert from kg/m$^3$ to lb/yd$^3$ multiply values by 1.69.

[b] Water saturated surface dry condition (SSD).

[c] If the maximum allowable content of sand is exceeded, this part of the aggregates shall be considered together with the total sand fraction, refer to RILEM (1994).

[d] Water soluble sulfate content calculated as $SO_3$.

According to German standard DIN 4226-100 recycled aggregate is divided into four types. Concrete aggregate (type I), the aggregate from construction elements (type II), the aggregate from masonry (type III) and mixed aggregate (type IV). The use of calcium chloride ($CaCl_2$) as an additive is a threat to recycled concrete since it produces expansive alkali salt and led to decomposition of calcium silicate hydrate (C-S-H). The common use of calcium chloride as additive is due to its binding property of concrete during mixing stage but it causes deteriorates both hardened cement paste and reinforced steel. For this reason, German DIN 4226-100 standard put a limit on the use of soluble chloride in recycled aggregate (RA). Types I, II and III ≤ 0.4%, and for the type IV ≤ 0.15% by weight (Zieliński, 2017).

It is not easy to determine the strength class of the recycled aggregate while the chloride, sulphate, and organic material content is determined according to the standards like EN 1744-1 and for alkali-silica by EN 8520-22 that mentioned in the study done by (Seara-Paz, Corinaldesi, González-Fonteboa, & Martínez-Abella, 2016). The use of recycled aggregate can be determined according to the organic material content. Standards put a li it for the use of recycled aggregate, which contain chloride, sulphate or any other minerals.

## 2.5 Compositions of Recycled Concrete Aggregate

The composition of the RCA depends on the ruined buildings whether it contains brick, stone or another type of materials, which used for decoration beside the main component, which is concrete. Jindal, Ransinchung R. N., & Kumar, (2017), stated the source of RCA as roof slabs, road slabs, and structural elements of a building. Demolished concrete waste is obtained from buildings that finished its service life. The type of the building and its specific part determine the composition of the RCA. Generally, the RCA is composed of natural aggregates with mortars adhered to its surface with different layers of thickness and size in addition to size of NA (Salgues, Souche, Devillers, & Garcia-Diaz, 2016).

In addition to the concrete, brick is also the second construction waste material. The use of the waste brick powder, which obtained from construction debris as cement replacement increases the strength of the concrete. The replacement ratio of waste brick powder is 0%, 5%, 10% and 15% with the addition of RCA, so it was found that the waste brick powder should not exceed 5% in the case RCA use as combination since it decreases slightly the mechanical properties of concrete (Letelier, Tarela, & Moriconi, 2017).

Kumar, Ananthan, & Balaji, (2017), used cement stabilized masonry block made with brick powder, fine recycled concrete aggregate, and pozzolanic material asses the strength behaviour and water absorption characteristics of the cement stabilized masonry block, and it was found that the using FA is preferred in pozzolanic material in use of cement stabilized masonry block that give satisfying result of compressive strength and absorption characteristics.

## 2.6 Influence of Raw Materials on RCA

The material composition of recycled aggregate has a great effect on overall strength of the concrete made with Koper, Koper, & Koper, (2017), prepared five samples of RCA with different raw materials and water/cement ratio. The prepared samples with five different type of NA were crushed at the laboratory to obtain compressive strength result between

(30 to 60 MPa). The results have different compressive strength values according to the percentage of used recycled aggregate. So, the primary concrete properties affect the RCA. The effect of RCA changes with the change of the cement composition. It is important to highlight that the effect of the water-cement ratio and cement composition of primary concrete directly affect the compressive strength of the formed recycled concrete (Koper et al., 2017). It is clear that the primary property of concrete has an influence on recycled aggregate.

Zhou & Chen, (2017), used two different coarse aggregate as recycled crushed rock aggregate and recycled pebbles aggregate for stating the influence of the different recycled coarse aggregate on mechanical properties of new concrete. He concluded that the compressive failure of recycled crushed rock aggregate is faster than recycled pebbles aggregate. Also, recycled pebbles aggregate has higher compressive strength than recycled crushed rock aggregate since recycled pebbles aggregate has lower water absorption, which leads to improve in bonding. Hence the use of different raw materials has different effects on recycled concrete.

## 2.7 Properties of Recycled Concrete Aggregate

The properties of RCA are different from NA in both physical and mechanical aspects. Generally, RCA has high water absorption, a large number of pores and low-density in one hand and rough surface because of the attached old mortars on the other hand. So, RCA is a lower quality aggregate than NA only in the case of abrasion resistance it is found to have higher quality than NA by some researchers. The quality and properties of the recycled aggregate influence the concrete mix. Safiuddin, Alengaram, Rahman, Salam, & Jumaat, (2013), emphasizes some physical, mechanical and chemical properties of concrete. The physical properties such as specific gravity, texture, shape, pore volume, bulk density, and absorption of RCA influence the formed concrete and as compared to natural coarse aggregate they all show lower quality.

The RCA is divided into two parts one with coarse recycled concrete aggregate (CRCA) and fine recycled concrete aggregate (FRCA). The use of CRCA is preferred most in the construction industry while the use of FRCA is rare because of it is unknown durability problems. Letelier, Tarela, Munoz, and Moriconi (2016) suggest the use of CRCA in construction and point out some regulation that avoids using FRCA.

In order to know the strength class of the RCA, some tests are done on the aggregate and classified to its type for construction use. Some of the aggregate tests are particle size distribution, particle density, water absorption, dry strength, Los Angeles abrasion value, aggregate crushing value, aggregate impact value, flakiness index, particle shape, chloride and sulphate content in concrete aggregate. Those tests are important because according to those tests recycled aggregates were used in a specific area of construction.

Yiu, Tam, & Kotrayothar, (2009), carried out experimental structure on aggregate samples and put to test. Three samples from C&D site, four samples from centralized recycling plants and one form Demolition Company with one sample of NA from the quarry. They put all aggregates under tests like particle size distribution and found that all samples received a passing grade according to AS1014. This test is important in terms of workability. Density is one of the most important tests as well, since it has a direct effect on mix design and recycled aggregates have a lower density than natural aggregate. Different recycled aggregates have different properties, so they are important in determining the recycled aggregates strength class.

Researchers suggested different techniques for the use of FRCA in construction and save it from being the unwanted material of C&D waste. The crushing process affects the quality of FRCA, because while crushing some unknown materials is crushed and become fine material that decreases the quality of FRCA. For this reason some crushing machines is preferred for crushing RCA. Jaw crusher is recommended for getting particle sizes same as fine natural aggregate (FNA) (Evangelista & de Brito, 2014).

### 2.7.1 Water Absorption Capacity

The crushed concrete contains some attached mortars and cement from original concrete that influence the angularity and shape of the aggregates and the demand for more water during the mix, so the absorption rate increases as compared to NA. Kwan, Ramli, Kam, & Sulieman, (2012), investigates that the rate of absorption increases by increasing recycled aggregate.

The property of RCA is different from normal concrete in water absorption capacity. The water absorption of RCA is higher because of the porosity is higher. The mixing stage of RCA is important since it has a direct effect on strength of hardened concrete. Montero and Laserna (2016) propose that RCA need 10% to 15% excess water to support the workability of natural aggregate concrete (NAC). This excess of water decreases the strength of concrete since w/c is increased. The development in mixing methodology leads to the improvement of strength of concrete hence the decrease of w/c. Some mixing methodologies are conducted while mixing the NA with RCA; Montero & Laserna, (2017), recommended double-step mixing method, in which aggregates is mixed with the cement before water addition. The time in this method is not enough to get a homogenous recycled mixture. They suggest an increase in the time duration of mixing stage when water is added to improve the stability and consistency of RCA. Also, they mentioned the pre-mixing step of cement with aggregate is crucial before addition of water because it strengths the weak area of recycled aggregate concrete (RAC) and the interface zone of aggregate and new cement mortar at the same time.

### 2.7.2 Density

The density of RCA is lower that NA since the cement mortar contents in RCA lowers the density and increases the water absorption and porosity (Omary, Ghorbel, & Wardeh, 2016; Seara-Paz et al., 2016; V W Y Tam & Le, 2008).

### 2.7.3 Shape and Surface Texture

The surface texture of the RCA aggregate is different because of the attached mortars. The texture has a very rough surface and less angular than NA. Due to the adherence of mortars to the surface of RCA, which contain about 30-60% of old cement it results in more rough and angular surface (Safiuddin et al., 2013).

### 2.7.4 Specific Gravity

The specific gravity of RCA is lower than NA since the cement mortar content adhered to the aggregates decreases the specific gravity. The presence of old cement mortar decreases the specific gravity of RCA in compared with NA, which have lower density and greater porosity (Safiuddin et al., 2013). Some researchers found that the specific gravity of the RCA depends on the quality of the virgin aggregate as cited in (Omary et al., 2016). The specific gravity of NA is of better quality, the recycled aggregate tend to have lower specific gravity.

### 2.7.5 Adhered Mortar

The main difference between the RCA and NA is the percentage of adhered mortars. The adhered mortars tend to decrease the density and specific gravity with increasing the water absorption rate. There has been an intensive research by scientists to discover the effect of the attached mortars in RCA, since the increase in the percentage of attached mortar result in decrease of RCA quality. Andal, Shehata, & Zacarias, (2016), underlies the fact that the residual mortar surrounded the original stone in RCA directly affect the fresh, hardened state of concrete plus durability.

The quality of the porous concrete has an effect on the RCA in terms of alkali-aggregate reaction and sulphate content. The recycled aggregates contain some mortars attached to the aggregate, which represent the primary concrete strength. If the primary concrete is susceptible to alkali-aggregate reaction the same may happen in RCA. The same case is considered for the sulphate attack. The amount of the sulphate content in primary concrete affects the RCA by the same amount (Safiuddin et al., 2013). de Juan & Gutiérrez, (2009) claims that RCA with mortar content under 44% can be used for the structural purpose since at this percentage it is possible to get bulk specific density higher than 2160 kg/m$^3$ with water absorption lower than 8% and Los Angeles abrasion loss lower than 40%.

### 2.7.6 Aggregate Impact Value

The aggregate impact value is the measure of the resistance of aggregate against dynamic loading; the higher the aggregate impact value the weaker the aggregate is. In some pervious researches, RCA showed about (20-25 %) while NA (15-20 %) AIV; this showed that the resistance of the aggregates towards the dynamic load was not satisfactory (Safiuddin et al., 2013).While Limbachiya, Leelawat, & Dhir, (2000), found 23.7% for RCA and 19.7% for NA.

### 2.7.7 Aggregate Crushing Value

Aggregate crushing value, is the resistance of aggregate toward crushing under applied compressive load; the lower the value of aggregate crushing value, the stronger are the aggregates. The aggregate crushing value of RCA has greater value than NA. The aggregate crushing value obtained by Limbachiya et al., (2000) is 20% while for NA is 14%, and Safiuddin et al., (2013) claims that the range of aggregate crushing value of RCA is between (20-30%) and for NA (14-22%). The lower resistance of the RCA to crushing is because of the attached crushed mortars to the aggregate, which makes it weak.

### 2.7.8 Abrasion Resistance

Abrasion resistance is an important property, especially in RCA, used for road pavements. The use of RCA is preferred more in road construction because of its good abrasion resistance. Mechanical properties are also another aspect that affects the extent use of RCA in the concrete mix. Generally same with physical properties, the mechanical ones are observed to exhibit inferior quality in comparison with NA. The measure of the surface wear resistance of aggregate known as abrasion and the abrasion resistance of RCA is higher than NA; according to the typical Los Angeles the abrasion value of RCA is 20% to 45% while NA is 15 to 30% (Pasandín & Pérez, 2015; Safiuddin et al., 2013).

Abrasion resistance is also important in the construction of dams, which designed in such as a way to be protected from erosion and cavitation as the riverbed passes through and led to the disintegration of the surface (de Brito, 2010).

## 2.8 Replacement Ratio of Recycled Concrete Aggregate

The replacement ratio of the RCA changes the behaviour of the concrete completely especially the strength. Various studies are done on the recycled concrete aggregates for different aspects of concrete and each study recommended certain percentage of RCA replacement with NA. In a study done by Shaikh, (2016) it's suggested to use 100%, 15%, 30%, 50% of NA replacement with geopolymer concrete. On the other hand, Puthussery, Kumar, & Garg, (2017) recommended using 25%, 50% and 100% of RCA replacement of both coarse and fine with 100% NC as a control. Lau et al., (2014), recommended using 25%, 50% to 75% replacement ratio of the CRCA. The study done by the (Seara-Paz et al., 2016) suggested using 0%, 20%, 50%, and 100% of CRCA. Zaetang, Sata, Wongsa, & Chindaprasirt, (2016) used 0%, 20%, 40%, 60%, 80%, and 100% of RCA with NA replacement ratio by weight in performing permeable concrete. The properties of recycled concrete like its high permeability effect positively in producing permeable concrete, unlike normal concrete since in normal concrete high permeability, mean a decrease in strength. Geng, Wang, & Chen, (2016), recommended using 0%, 100% of RCA replacement for studying the creep behaviour.

The replacement ratio RCA affects the strength of the concrete, so the researchers suggest limiting the percentage use of RCA. The best result that recommended by the researchers is ranging from 20% to 50% of RCA replacement. (Puthussery et al., (2017), found that 25% replacement of recycled by natural aggregate give the desired strength. On the contrary to other researches mentioned above who recommend limiting RCA Safiuddin et al. (2013) find that even using 100% of recycled aggregate can possibly yield the desired strength. However, use of the fine recycled aggregate is not preferred since it decreases the compressive strength by a large amount; the use of the recycled fine aggregate should be limited to 20% (Safiuddin et al., 2013).

## 2.9 Crushing Process and Distribution of RCA

The C&D waste is crushed into a specific size of aggregates after removing the debris from it and reused for construction purpose. Jaw crushing machine breaks the demolished waste stream of concrete into 16"x24" of aggregate (Mbmmllc, 2014). This machine is able to crush 100 to 150 tons at a time or in other words 10 to 15 tons/hr. The crushing size used by Lau et al., (2014) is maximum 20 mm and the crushed concrete amount is about 70% in addition to 20% blocks, 5% asphalt, ceramic 4% and brick 1% in total.

**Figure 2.2:** Crushing Process of RCA (Kwan et al. 2011).

Moreno Juez, Cazacliu, Cothenet, Artoni, & Roquet, (2016), suggests using a particle size of 10-14 mm for both Natural and recycled aggregate. Crushing is critical in the preparation of the RCA since granulation is important. On the other hand, Koper et al., (2017) suggest the use of PN-EN 12620 standard for the particle size of 0-16 mm and they used sometimes double crushing to obtain the optimum granulation. The particle size distribution of RCA depends on its crushing process, which is very important in getting a well-graded aggregate distribution. The use of aggregate ≥4 mm is generally approved by the standards, which discards use of the FRCA, which may result in some unknown durability problems (Pasandín & Pérez, 2015).

The use of recycled concrete is also recommended in SCC as in a study done by González-Taboada, González-Fonteboa, Pérez-Ordóñez, & Eiras-López, (2017) used particle size between 4-11 mm, so the grading for both recycled and natural aggregate would be present in the same curve.

## 2.10 Effect of Cement and cementitious materials in Production of RCA

Andal et al., (2016) proposes using general use type Portland cement with Ground Granulated Blast Furnace Slag (GGBFS), which replaces the Portland cement. In order to improve mechanical properties of Recycled RCA some chopped basalt fibers is added of 0.1, 0.3, 0.5, 1 and 1.5% of total volume of the mix with ordinary Portland cement Type I (Katkhuda & Shatarat, 2017; Kwan et al., 2012). The basalt fibers was added to normal concrete mixes, which increases the strength especially in flexural and split tensile, while Manzi, Mazzotti, & Bignozzi, (2013) used cement type CEM II-A/LL.

The durability performance of the SCC made with RCA is increased by the addition of the fly ash 20% and Metakaolin or silica fume of 10% by weight of Portland cement that gave different result for different percentage which balances loss of durability but at 100% replacement of RCA Metakaolin is more effective than SF (Kapoor, Singh, & Singh, 2016).

The wide use of fly ash in construction increases even in the recycled concrete mix due to its small particle size about 0.075 mm (Sagara, Tjondro, & Putri, 2017). The percentage use of fly ash in concrete is limited to the 15% - 25% according to both ACI (American Concrete Institute) and SNI (Indonesian National Standard). Fly Ash (FA) can be used as a fine aggregate as a cement replacement, which increases the compressive strength. There is not a standard, which limits the use of FA in recycled concrete except some researches, which recommend the use of certain percentage.  According to Sagara, Tjondro, & Putri, (2017), the optimum amount of fly ash that can be added to RCA concrete mix is 35% that gives the highest compressive strength.

## 2.11 Mix Design And Mixing Procedure

The mix design of structural concrete is same as normal concrete but in case of use of recycled concrete aggregate superplasticizer is added to decrease the water cement ratio. The mixing procedure of RCA is very important since the aggregate is more fragile and have different physical and mechanical properties than NA, which affect the workability of the concrete paste. Some mixing techniques like double or two stage mixing or using specific mixers for mixing RCA. Moreno Juez, Cazacliu, Cothenet, Artoni, & Roquet, (2016) illustrated some mixing procedure of concrete since the mixing process affects the fragility of the RCA, in which two types of laboratory concert mixer; a planetary 301 mixer from shako and intensive 51 Enrich mixer was used. The gradation occurs while the RCA is in the dry mixing process, before addition of water, because of that the dry mixing of the materials is highly suggested and it is less aggressive than wet mixing about two times. For the Eirich mixer the gradation starts at 500 RPM, the higher the speed, higher gradation and mass loss is observed by Moreno Juez et al., (2016a) Pan- type mixer is used for mixing the cement paste for 5 min the coarse aggregates are added to the mixer and mixed for 3 min, so in total 8 min of mixing was applied (Zaetang et al., 2016).

Some researchers support the idea that it increases the strength and workability of concrete recommend the two-stage mixing approach. In normal mixing procedure coarse, fine aggregates, cement is mixed then water is added while in two-stage mixing procedure fine and coarse aggregates are mixed with half amount of water then cement is added and in the second stage, the remained water is added. In two-stage mixing, the mixing procedure is divided into two-stages as shown in Figure 2.3 (Vivian W.Y. Tam, Gao, & Tam, 2005).

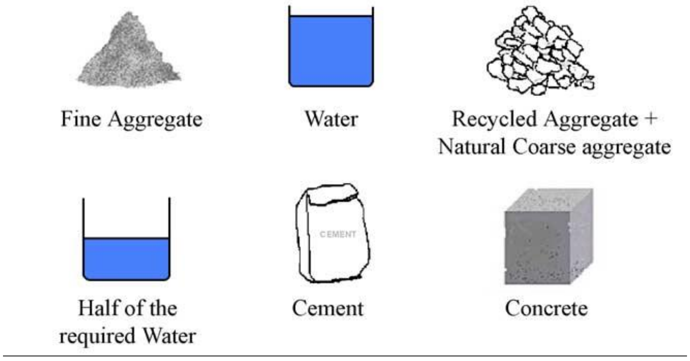
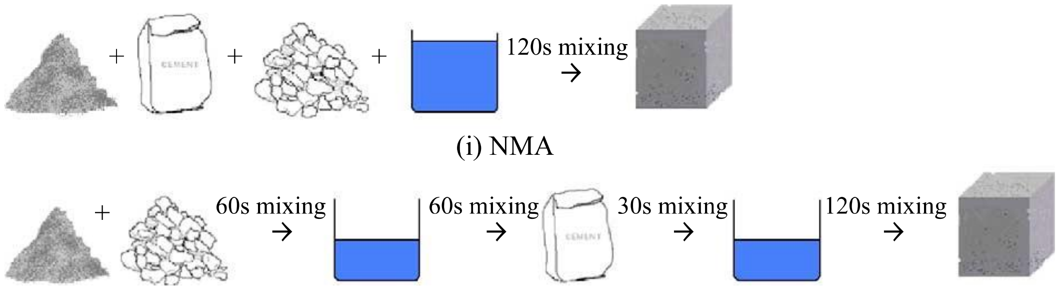


**Figure 2.3** Symbols display different materials (Vivian W.Y. Tam et al., 2005).



(ii) TSMA

**Figure 2.4:** Mixing stages of (i) normal mixing method and (ii) two-stage mixing method (Vivian W.Y. Tamet al., 2005)

Another mixing method which suggested by researchers is triple mixing method, so in this mixing approach RCA and NA of both coarse and fine were mixed, then water is added and mixed for 15 s, after that FA is added to ease its coating on the surface of aggregate, cement is added and mixed for 60 s, lastly the remaining water is added and mixed to get a homogeneous mixture (Surya, VVL, & Lakshmy, 2013).

## 2.12 Properties of RCA at Fresh and Hardened States

Researchers tend to classify the RCA into different strength classes according to some tests made on the aggregate, but it still does not give a satisfactory result since most of the times RCA contains unknown materials which makes it hard to determine its effect on the concrete at fresh or hardened states. There are some tests done at the fresh state of the concrete as slump test, compressive, flexural and split tensile tests are carried out for the hardened state.

### 2.12.1 Slump Test

Slump test is measured at the fresh state according to EN 12350-2 testing concrete at fresh state to measure the steadiness of the concrete (Andal et al., 2016; Koper et al., 2017; Seara-Paz et al., 2016; Vivian W Y Tam & Tam, 2008).

Salgues et al., (2016), points out that two aspects that are angularity and roughness on the RCA affect the workability of the fresh recycled concrete.

### 2.12.2 Compressive Strength Test

Compressive strength is one of the most used tests in determining the strength of concrete at hardened state since it determines the capacity of concrete cube toward compressive load. The compressive strength increases in the use of recycled aggregate as the curing increases, so according to Puthussery et al., (2017) measured compressive strength for 7 and 28 days of concrete with natural aggregate was 31.3 MPa and 38.8 MPa, which all mixes of recycled concrete aggregate achieved the target strength of 30 MPa in 7 days, so the compressive strength values close to concrete with natural aggregate. The study by Lau et al., (2014) examined the compressive strength of recycled aggregates on concrete and they observed that the compressive strength decreased up to 21% as the amount of recycled aggregate reached to 75%.

Kwan et al., (2012)The compressive strength is performed from cube dimensions 100mm, 100mm, 100mm, with 7,14, 28, and 56 days of curing time and it was observed that the strength is increasing over the age. According to the level of replacement of NA with RCA, the strength increased, so normal concrete showed highest compressive strength value.

Poon, Shui, Lam, Fok, & Kou, (2004), prepared cubic samples from aggregates at three different moisture states of air-dried, oven-dried, saturated surface-dried. The prepared samples were tested at 3,7, and 28 days with the natural aggregate replacement of 100%, 80%, 50% and 0%. All the samples reached its desired strength value at age of 28. The air-dried aggregate gave the optimum value of compressive strength at 50%.

### 2.12.3 Flexural Strength Test

Flexural behaviour of a concrete is very important, especially in road construction and in slabs. The flexural performance of reinforced beams of RCA made with recycled brick aggregate was studied under four points loading test machine by (Mohammed et al., 2017). They studied the deflection of the beams in the middle and middle third of the beam with crack width and depth. The result of both beams made with virgin and recycle brick was compared. In the load-displacement aspect, both of the beam types do not show very significant differences. Also, no significant difference is observed is failure pattern of both virgin and recycled brick aggregate and the cracking occurred in inclined lines for both beam types.

The flexural performance of recycled concrete depends on the used recycled aggregate. The use of good quality and strength class of recycled concrete gives a good flexural strength (Malešev, Radonjanin, & Marinković, 2010). Lau et al., (2014), examined the flexural strength of RCA decreases up to 39% at 75% replacement.

## 2.13 Curing Conditions

Kumar et al., (2017) points out curing condition of concrete cubes and beams achieve its specified strength. The concrete beams and cubes left outside for 24 hours to achieve the complete dryness without loose in strength then put into curing tanks according to their curing days. Kumar et al., (2017) suggested putting the specimens into curing tank until the complete day of curing. Abdel-Hay, (2017) proposed the use of three different types of curing techniques in his study for RC of open air curing, water curing and painted curing. He observes that in water curing of 100% RC replacement the compressive and tensile strength yields the highest value but for the all replacement ratios the permeability increased. Curing using water decreases in permeability while increases the tensile and compressive strength.

Abdel-Hay, (2017), standard Curing (water curing) is preferred for the increase in strength of concrete, but in case of recycled aggregate standard curing does not increase the strength of concrete equally and its effect changes according to the replacement ratios of the RCA. The increase in compressive strength for 100% replacement gave the highest value as Abel-Hay 2015 mentions. This case is different for split tensile strength since painted curing gave highest strength amount air and water curing.

Haghighatnejad, Mousavi, Khaleghi, Tabarsa, & Yousefi, (2016), put the specimens for 4, 7, 14 days as initial water curing and after that the samples were exposed to room temperature curing, water curing, and open air temperature curing until testing age. It is found that those samples that continued their curing condition in the water show high result of compressive strength by 23% as compared to those samples exposed to room temperature curing (Haghighatnejad et al., 2016).

## 2.14 RCA in Special Concretes and in Structural Concrete

Numerous experimental studies had been carried out for investigating the performance of RCA with normal concrete. The use of RCA in HPC is a new interest of researchers and there is still limited researches have been done on this topic. Currently, the use of HPC in construction is highly recommended due to its satisfactory strength. Researches is done for use of RCA in HPC confirm satisfactory of strength value that approves its use in construction. In a study the replacement ratio of (CRCA/FRCA%) is 0/100, 50/50, 100/100 without using NA in performing HPC and it was concluded that it is possible to produce HPC from RCA without using NA with satisfactory compressive strength, split tensile strength, modulus of elasticity, ultrasonic pulse velocity and bond strength (Pedro, de Brito, & Evangelista, 2017b).

The compressive and flexural strength behaviour of High-performance concrete made with recycled aggregate is important, at the same bond behaviour between reinforced bars and recycled concrete should be taken under consideration since it may cause strength problems in the future. The bond strength is not affected by the replacement rate of recycled aggregate only with a very small percentage, which can be neglected. In the case of bond stress-slip behaviour in direction of arranged bars both the vertical and horizontal arrangement showed similar bond stress regardless replacement rate, while in the horizontal arrangement of the bars, there is a drop in bond stress of top horizontal bars than lower (Kim, Lee, Lee, & Hong, 2014).

Pedro et al., (2017) evaluated the influence of SF and RCA on the behaviour of HPC. The mechanical performance and durability problems are studied and it was found that limited amount of FRCA and CRCA does not have a negative impact on the formed concrete. The addition of SF is as 5%, 10%, 15% as a cement replacement, while the percentage of RCA replacement by volume is FRCA with FNA and CRCA with CNA by 50/50, 0/100, 100/100 respectively. The concrete mixes achieved the compressive strength between 70 MPa and 85 MPa and the carbonation depth reached to 6.0 mm in 91 days.

It is found that the use of 30% replacement ratio of CRCA in high strength concrete does not effect on strength value. The use of CRCA in high strength concrete HSC gives the satisfactory result of compressive strength, flexural strength, and modulus of elasticity while a decrease in shrinkage and creeps strain is observed. The CRCA was obtained firm rejected precast concrete industry and used in HPC which have good durability performance as resistance to chloride, chloride-induced corrosion, freeze/thaw and abrasion alike of NA (Limbachiya et al., 2000).

Gonzalez-Corominas, Etxeberria, & Fernandez, (2017), took recycled aggregate from rejected pre-stressed concrete sleepers of 50% and 100% recycled concrete replacement for producing recycled HPC and the result compared with normal HPC. The cracking load of recycled HPC is lower than normal HPC.

Self Compacting Concrete (SCC) is very highly recommended in construction work because of its high strength and self-consolidation. Due to the high demand of SCC researchers tried to from it with RCA. The compressive strength is higher than conventional concrete with the low water-cement ratio. The use of CRCA is recommended more than the use of FRCA because of unknown effect of FRCA that jeopardizes the concrete, which is also applies to SCC. V. B. M. Kumar, Ananthan, & Balaji, (2017) concludes the increase in use FRCA in SCC can result in significant decrease in fresh and hardened properties of concrete, so the use of FRCA can be limited to 20% of FNA by FRCA.

González-Taboada et al., (2017), used 20%, 50%, 100% by volume of natural with coarse recycled aggregate. In this study, the vibrated recycled concrete is used for studying the strength behaviour of SCC. It has been observed that as the level of CRCA is increasing the compressive strength, split tensile strength and modulus of elasticity decreases. The study conducted by Güneyisi, Gesoglu, Algın, & Yazıcı, (2016), suggested using 0%, 50%, & 100% of NA replacement by CRCA.

SCC is known from its good workability because of its ease of distribution without using a vibrator. For testing the workability of the SCC with RCA and NC replacement of (0, 50, 100%) is evaluated by using slump flow test, L-box test, V funnel test and J-ring test by (Kapoor et al., 2016; V. B. M. Kumar et al., 2017).

Bensalem, Amouri, Houari, & Belachia, (2017) focused on flexural creep of SCC under four points loading which is studied by very few researchers. The samples were prepared with same w/c ratio of (10 x 10 x120 $cm^3$) dimensions with the addition of glass power limestone powder, marble powder, and granulated blast furnace slag, so in total four sets of beams were prepared. The addition of limestone powder showed the best creep behaviour, so the replacement of limestone powder by glass powder and GBFS will decrease the creep behaviour while marble powder increases.

Another aspect besides the strength of the concrete is its durability performance, so the addition 10% of silica fume (SF) or metakaolin by weight of cement was observed to be capable of compensating durability problems of SCC especially in 50% replacement of NA by RCA. It was also observed that in 50% NA replacement by RCA the addition of metakaolin shows fewer durability problems than SF. The compressive strength at 28 days decreased by 13% in addition of NA replaced by RCA, while in addition of metakaolin or SF the compressive strength reduced to 3% and 8%. The results showed that the addition of metakaolin gives best result of compressive strength than SF (Kapoor et al., 2016).

Porosity is one of the main factors that affect the physical and mechanical properties of concrete. The increase in the number of pores of recycled aggregate decreases its strength and increases the water absorption (Gómez-Soberón, 2002). The way of converting this disadvantage of an increase in a number of pores to advantage is by using it in porous concrete.

Due to increase in porosity of the RCA Zaetang et al., (2016), suggested the use of its use for pervious concrete. The rate of porosity of RCA is higher than normal concrete which leads to the decrease in its strength in compared with NA. The rate of porosity has a clear effect on water absorption that led to decrease in strength. It is possible to change the disadvantage of those pores by its use in previous concrete since it has high void content and permeability. Zaetang et al., (2016), used two type of RA one with Recycled Block Aggregate and the other is RCA with different percentage of natural aggregate replacement from 0%, to 100%. The effective level of compressive strength in recycled block aggregate was 13.4 MPa with 40% NA, while the ideal compressive strength of RCA is 15.0 MPa with 60% of NA. This showed that recycled block aggregate has the better compressive strength that RCA for the use in pervious concrete. Also, the previous concrete with recycled block aggregate and NA did not show any drop or change in flexural and splitting tensile strength, in contrast with RCA showed a significant drop. Zaetang et al., (2016), mentioned that recycled block aggregate and RCA have good surface abrasion resistance and strength, which is very acceptable in permeable concrete.

The definition of structural concrete deals with the use of concrete for structural purposes, which needs sufficiently high strength value to resist the load. According to ACI 318 structural concrete is used for any structural purposes including plain and reinforced concrete.

Similarly, BS-8110-1—1997,”structural use of concrete”, specified the lowest grade that could be used for structural purposes with the minimum concrete cover of 20 mm at mild exposure condition is C35 (BS-8110-1997: Table 4.8). Although for reinforced concrete requirements for normal-weight aggregate such as used in this study, the lowest grade requirement is C25. Hence, in this study the term, “structural concrete” is adopted as the value (35MPa) for minimum concrete grade at mild exposure condition and for 20mm concrete.

## 2.15 New Approaches to Increase the Quality of Recycled Concrete Aggregate

Katkhuda & Shatarat, (2017), used a different approach by using acid treatment of recycled aggregate by soaking them into HCl solution for 24 hours; this acidic treatment detaches the mortars and strengths the bond between recycled aggregates and improves the mechanical properties of concrete. The optimum blast fibers is added to acid treated recycled aggregate is limited by 0.3% and to untreated recycled concrete by 5%. Wang et al., (2017), suggested soaking RCA to the acetic acid solution, which reacts with the cement hydration products and lessens the attached mortars to the surface of RCA, which can be removed easily later by mechanical rubber.

## 2.16 Recommendations Provided in the Related Literature

Puthussery et al., (2017), reported that there should be a further study on the quality and quantity of the used RA and a database should be generated. Safiuddin et al., (2013) suggested that detailed investigation should be carried out on splitting tensile strength, drying shrinkage, and creep behaviour of concrete. Also, how shear impact the RCA with water absorption, porosity, chloride penetration resistance, and thermal expansion of concrete should be over-investigated. A comprehensive study should be done on the effect of RCA on durability performance like sulphate attack, corrosion, carbonation, alkali-silica reactions and acid attack in concrete. A detailed research is required about the types of the RCA, which affect the concrete mix. New mixing techniques should be investigated. The use of the recycled concrete is generally used widely in road works, sub-grades and especially in the road construction due to its high abrasion resistance (V W Y Tam & Le, 2008). Further investigation should be done on w/c ratio of RCA; for example, different w/c in RCA combination proportions should be studied for their influence on the creep behaviour of the formed concrete. Also, a different type of RCA suggested being used with different cement type, natural aggregate or chemical admixture for the best creep model (Geng et al., 2016).

## 2.17 Conclusions presented in the Related Literature

The disposal of the construction waste causes sincere problems in North Cyprus, so its use as recycled aggregate is recommended in production of concrete. The general properties of recycled aggregate are lower than natural aggregate as density, specific gravity, and water absorption, abrasion resistance and also recycled aggregate has lower mechanical strength than natural aggregate. The permeability of the RCA is lager due the angularity and roughness of the aggregate, which results in the higher permeability hence high w/c ratio, is also high.

The main difference between recycled aggregate and natural aggregate is the presence of attached mortars, which causes durability and strength problems in the formed concrete.

Despite all the disadvantages of the recycled aggregate its is possible to get strength value close to natural aggregate by limiting its replacement or suggesting new approached as discussed in above sections for increasing its quality.

## CHAPTER 3

## MATERIALS AND METHODOLOGY

### 3.1 Overview of Materials and Methodology

This research is focused on the use of recycled concrete in the North Cyprus by different replacement of natural aggregate with RCA, as well as the evaluation of its structural concrete characteristics. The RCA was obtained from 20 years old school building in Bayraktar, Nicosia with unknown initial characteristic strength. The obtained aggregates were crushed in two stages and categorized into three different aggregate sizes. Portland cement type II/B-S 42.5 N with slag content was used, which is the most conventional type of cement in Cyprus due to prevailing climate changes. The natural aggregates were obtained from Tufekci Company quarry at Besparmak Mountain Nicosia, Cyprus.

Eight different mix designs were prepared with five different replacement ratios of natural aggregate with RCA: NA/RCA of 0%, 25%, 50%, 75%, and 100% is used. Silica Fume (SF) was used at 50% RCA replacement (Table 3.1). In general the coarse recycled concrete aggregate was used in all replacements and the fine recycled concrete aggregates at only 50% replacement. Three cubes and three beams samples were prepared for compressive strength and flexural strength respectively for each structural concrete mix. The samples were tested for three different testing ages of 7, 28 and 90 days of curing, while the samples stayed in curing tanks until the testing date for only compressive test. In flexural test, samples were tested at 7 and 28 days of curing.

**Table 3.1:** Organization and distribution of test samples

| Replacement Ratios | 7 Days | | 28 Days | | 90 Days | |
|---|---|---|---|---|---|---|
| | No of cubes compressive | No of cubes Flexural | No of cubes Compressive | No of cubes Flexural | No of cubes compressive | No of cubes Flexural |
| NA 100% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA 25% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA+FRCA 50% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA+FRCA+SF 50% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA 50% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA+SF 50% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA 75% | 3 | 3 | 3 | 3 | 3 | 3* |
| CRCA100% | 3 | 3 | 3 | 3 | 3 | 3* |

**results was discarded due to equipment error.*

## 3.2 Materials

The aggregate materials like the natural aggregate of both fine and coarse, cement, silica fume, and superplasticizer except recycled concrete aggregate were acquired from one of the leading ready-mix company in North Cyprus Tufekci Company. RCA was obtained from a demolished old school building in Bayraktar from Nicosia. The detailed information about the materials is discussed below.

### 3.2.1 Natural aggregate

Besparmak Mountains are the main source of NA for all North Cyprus regions. There are more than eight quarries working daily for aggregate extractions. The boulders that were extracted from the mountain were crushed into different sizes of aggregate. The aggregates are sent to the ready-mix concrete companies for manufacturing concrete. Coarse natural aggregate (CNA) and fine natural aggregate (FNA) was used in all replacements.

### 3.2.2 Recycled concrete aggregate

The recycled aggregates were obtained from an old school in Bayraktar, Nicosia as shown in Figure 3.3 below. The building was demolished; the large sections of the concrete elements were taken to the Tufekci Company facilities for crushing. The recycled concrete aggregates contained reinforced bars, brick, wood, papers, glass and some other minor contaminants, was removed during sieve analysis process. The removal of the contaminants is important as they may lead to a decrease in the performance of manufactured concrete. Within the CRCA, the removal of contaminants was easy since they are large enough to be identified. Whereas in the case of FRCA, beyond aggregates of particle size less than 2 mm was much difficult in removal of contaminants.

The use of CRCA is most preferred as discussed in Chapter two. According to its physical properties, CRCA can be classified into type I, II and III (see section 2.15). The FRCA was adjusted to 50 % replacement with and without silica fume. The replacement content adopted was in agreement with reviewed literature.

**Figure 3.1:** Bayraktar school before demolition, Nicosia, North Cyprus.

**Figure 3.2:** Demolished school building waste in Bayraktar School, Nicosia.

### 3.2.3 Cement

Portland cement CEM II/B-S 42.5 N containing slag was supplied by Tufekci Company, Nicosia, North Cyprus, was used. Cement with slag content is traditional cement in North Cyprus due to average high temperature experienced throughout the year. The slag additive contributed to lower heat of hydration during construction at high temperatures.

**Table 3.2.a:** Chemical composition of cement that is used in this study

| | 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 | 0.000 |

**Table 3.2.b:** Physical Properties of Cement that is used in this study

| 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 day | 22.45 |
| | 7 day | 37.12 |
| | 28 day | 52.89 |

### 3.2.4 Silica Fume

Silica fume is a sought-after construction material due to its advantageous chemical and physical properties. Addition of SF in concrete is known to increase the strength and durability of the concrete and the same case is applicable to recycled concrete (Pedro et al., 2017b; Pedro, de Brito, & Evangelista, 2017a). Therefore, the use of SF is also beneficial for the production of recycled concrete. This study restricted SF addition to 50% RCA replacement in two cases one with CRCA and FNA and the other with CRCA and FRCA. The quantity used was set to 10 % of the cement by weight. The chemical composition of the SF is as shown in Table 3.3 below.

**Table 3.3:** Chemical Composition of Silica Fume Used in this Study

| Chemical Composition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Compound | $SO_3$ | $SiO_2$ | CaO | $Na_2O$ | MgO | $Al_2O_3$ | $Fe_2O_3$ | $K_2O$ |
| Content (%) | - | 94.3 | 0.30 | 0.27 | 0.43 | 0.09 | 0.01 | 0.830 |

### 3.2.5 Superplasticizer

Superplasticizer or water reducers are used to enhance the workability and increase the compressive and flexural strength of the concrete by decreasing water-binder ratio. The use of superplasticizer allows the reduction of the water content by a large quantity, which yields increase in the performance of concrete in terms of strength and durability. With less water used, good workability can be achieved for high quality concrete. In this study, superplasticizer was first mixed in water and manually stirred to obtained homogenous mix. Note that the water used in the mix above (superplasticizer and water) was the actual water content of the concrete mix.

### 3.2.6 Water

Water is added to start the hydration process of concrete. After mixing all aggregate mixture with cement, water is added and mixed until good workability is achieved. Potable water was used in this study.

## 3.3 Methodology

The use of RCA in producing structural concrete can be considered as a new subject in construction area since there is only limited number of research carried out. In this study, the recycled concrete aggregate is used in manufacturing structural concrete, with different replacement ratios of RCA (*see* Table 3.1).

The optimum replacement ratio of RCA was investigated. RCA was categorized into coarse and fine recycled aggregate as reviewed section 2.4 of chapter two. All the mixes contain certain percentage of CRCA except for mix NA with 0% RCA content. As a result of the behaviour of the FRCA, silica fume was added in the mixture CRCA+FRCA+SF 50to improve the workability of the concrete. Also the mixture CRCA+SF 50% was introduced to evaluate the performance of FRCA in the study.

The samples used in evaluation of compressive and flexural test were unreinforced concrete cubes and beams. In total 72 beams and 72 cubes were prepared. However, the results of 90 days flexural test was discarded due to error in test result.

### 3.4 Crushing Recycled Concrete Aggregate

The first step for processing the demolished concrete was Lt drill machine. The boulders were crushed into smaller sizable aggregates convenient enough to be further crushed with hand held hammer with LT drill machine. Similarly, the Lt drill also performed second functions of stripping off reinforcement from the rubbles. The secondary aggregate processing was carried out using *hand held hammer* where medium sizes aggregates were crushed into required sized particle.

The recycled concrete was observed to be brittle, so special care was taken while crushing it in order to obtain required particle size range. It was observed that with Lt machine the ratio of fine size aggregate was higher than the coarse size aggregate when recycled concrete was crushed. The Lt drill is just good for separating the samples into boulders of 20 to 40 cm due high-applied force. The *hand held hammer* is the most difficult aspect encountered in the processing of the aggregates, the intensity of the applied force must be consistent and moderate to obtain the required smaller sized aggregate.

**Figure 3.3:** First stage of crushing process by LT Drill

**Figure 3.4:** Second stage of crushing process by hammer

### 3.5 Splitting of Aggregate for Percent Composition of CRCA

Recycled concrete aggregate contains virgin plus mortar attached to the virgin aggregate. The coarse recycled aggregate samples were taken from 4-12 mm and 12-19 mm particle size into riffle box of sample splitter. The samples were divided into two equal parts of similar dimensions. The aggregates were taken into a tray and separate into two parts; virgin aggregate with mortar and aggregate see details in Table 3.4.

Procedure:

Two samples of 4-12 mm and 12-19 mm recycled aggregates were taken. The samples put into riffle box for the equal division and subsequently, divided into two equal samples on the tray. The aggregate samples were weighted and separated as virgin aggregate with attached mortar and aggregate without attached mortar. The virgin and mortar attached recycled aggregated were weighted, then the percentage of each type of aggregate was calculated as shown in Table 3.4.

**Table 3.4:** The Percent Composition of CRCA

| Composition of Recycled Aggregate | | |
|---|---|---|
| Size range | 4-12.5 | 12.5-19 |
| Aggregate | 24.39% | 26.70% |
| Aggregate with Mortar | 75.60% | 72.30% |

### 3.6 Gradation by Sieve Analysis

The particle sieve analysis was done for natural and recycled aggregates. The aggregates were graded into three different sizes of 0-4 mm, 4-12 and 12-19 for convenience in achieving maximum dry density for the aggregates. The samples were prepared with oven dried at 110 $^{o}$C ±5. The NA was from North Cyprus Mountain and the RCA were collected from 20 years old demolished building site at Bayraktar, Nicosia.

**Figure 3.5:** CRCA of particle size 4-12 and 12-19

The two samples of natural and recycled aggregated of 500 g were placed in the oven to dry at 110 $^{o}$C ±5 for at least two hours. The samples of 0-4, 4-12.5 and 12.5- 19 from each sample were sieved carefully. Particle sieve analysis was conducted according to BS EN 933-1:1997.

## 3.7 Tests on Aggregate

Tests were carried out on aggregate to determine the quality of the recycled aggregate and its classification according to the RILEM standard. The following tests were done on both natural and recycled aggregates.

### 3.7.1 Density

Density test is done for both natural and recycled aggregate of the coarse and fine aggregate. The required amount from both natural and recycled aggregate was placed in the oven for 24 h at 110 $^{o}$C ±5. A cylinder of 3 L capacity was used for fine aggregate and 15 L capacity for coarse aggregate. Balance used for weighting the aggregate and a tamping rod of 16 cm diameter and 60 cm long. The test was carried out according to ASTM C127-04.

An empty cylinder is weighted with the balance. One-third of the cylinder was filled with aggregates and tamped using the tamping rod for 25 strokes. The aggregates were poured into the cylinder for another one-third level and tamped for 25 times The cylinder was filled with aggregate until overflowed. Extra aggregate above the cylinder was removed with a straight edge and the sample was weighed.

Calculation of density:
Compacted unit weight or bulk density = W/V
W = Weight of compacted aggregate in the cylinder in kg
V = Volume of the cylinder in Liters

### 3.7.2 Specific gravity of coarse aggregates

Coarse aggregates were placed in the oven for 24 at 110 °C ±5. Subsequently, the aggregates were placed in water for 24 h and thereafter the water was drained. The residue aggregates were allowed to dry and achieve saturated surface dry condition. A basket was used with a rope attached from a balance as shown in Figure 3.6 and immersed in water until a consistent reading was obtained. The test was done according to ASTM C127-04 for coarse aggregate.

The specific gravity of the aggregate was measure as follow:
Specific Gravity: A (B-C)
A: mass of oven dry sample
B: mass of saturated surface dry sample
C: mass of saturated surface dry sample in water

**Figure 3.6:** Specific Gravity Test

### 3.7.3 Absorption capacity test of coarse aggregates

Absorption is an important property of aggregate especially recycled since it determines the w/c ratio of the mix design for getting good workability. The following procedures were done according to ASTM C127-04 for coarse aggregate.

Coarse aggregates were weighted then put into the oven for 24 h at 110 $^{o}$C ±5. The coarse aggregates were put into a tray and filled with water left for 24 h. The aggregates were sieved form water and left for dry. The SSD aggregates were weighted again. The calculation of the absorption is done as following:

A: Weigh of the dry aggregate
B: Weight of saturated surface dry aggregate
Formula used is Water absorption = $[(A – B)/B] \times 100\%$.

### 3.7.4 Specific gravity and absorption test of fine aggregate

The specific gravity and absorption tests of fine aggregate were done at the same time. Equipment: Pycnometer, mold, filter paper, cylinder, funnel, glass rode, wash bottle, weighing balance, the cone with tamper and oven was used.

In determination of the specific gravity of the fine aggregate, the sample was balanced in SSD and placed in water for 24 h. Rod and cone were used for testing the SSD condition. The SSD aggregates were put into Pycnometer and filled with water. Glass rod was for stirring the fine aggregate in water to eliminate any entrapped air. The pycnometer was closed with a cone head and filled from the apex with water by wash bottle then balanced, weighed and recorded. The content of the pycnometer was emptied into a tray. Pycnometer was refilled with water to the same (containing water and aggregate sample). Trapped air was removed and the sample was weighed and recorded. The water in the tray was poured into a cylinder by decantation. The decanted water was filtered as shown in the Figure 3.8. The residue fine material in the filter paper was collated alongside the samples in the tray and placed in the oven at 110 $^{o}$C ±5 for 24 h. The sample was taken out of oven, weighed and recorded. The test was carried out according to ASTM C128-15. The calculation for both specific gravity and absorption was done as follows:

D: Weight of oven dry sample
C: Weight of SSD aggregate
A: Weight of pycnometer + Sample + Water
B: Weight of pycnometer + Water
Absorption: C-D /D x 100
Specific Gravity: D / C - (A-B)

**Figure 3.7:** Testing SSD condition and Pycnometer

**Figure 3.8:** Extraction of water from fine aggregate by the help of filter paper.

### 3.7.5 Los Angeles abrasion test

Abrasions test was carried out to determine the abrasion resistance of the sample aggregates. The coarse aggregates of same size distribution were added to horizontally rotating drum and sieved in 1.7 mm sieving for calculating the abrasion value.

In this study, two type of coarse aggregates were tested; (4-12) mm and (12-19) mm according to ASTM C 131.

Procedure for Los Angeles:

- 5000 g form (4-12) mm and (12-19) mm of natural and recycled aggregate were weighted

- The weighted aggregates were washed carefully
- The washed aggregates were put into the oven for 24 h at 110 $^{o}$C ± 5
- The oven-dry aggregates were taken out from oven left until cooled down
- The aggregates were put into Los Angeles abrasion machine
- According to the standard 11 balls were added to the machine
- The machine rotated for 500 revolution
- The 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 calculated
- The result was calculated as follow

Original weight of both type aggregate sample NA and RCA = W1 g
The weight of both NA and RC aggregate sample retained = W2 g
Weight passing 1.7mm IS sieve = W1 – W2 g
Abrasion Value = (W1 – W2) / W1 X 100

The obtained result will be Los Angeles abrasion value. The test is done for two times and the mean is calculated as abrasion value.

### 3.8 Mix Design of Concrete

As the result of the sieve analysis for RCA and NA, the percentage of both coarse and fine aggregates was determined for each type. The mix design calculations were done according to the one-meter cube of concrete and a target compressive strength of 40 MPa. Percentage of each type of aggregate was calculated as shown in Table 3.5.

**Table 3.5:** Mixing proportions of recycled concrete aggregate and natural aggregate mixes

| **Constituents** | **Proportions (Kg/m3)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Mix1** | **Mix 2** | **Mix 3** | **Mix 4** | **Mix 5** | **Mix 6** | **Mix 7** | **Mix 8** |
| Cement | 310 | 310 | 310 | 310 | 310 | 310 | 279 | 279 |
| Natural Fine Aggregate | 933 | 933 | 933 | 933 | 933 | 497 | 933 | 497 |
| Fine Recycled Concrete Aggregate | 0 | 0 | 0 | 0 | 0 | 462 | 0 | 462 |
| Natural Coarse Aggregate | 855 | 637.6 | 427.5 | 213 | 0 | 427.5 | 427.5 | 427.5 |
| Coarse Recycled Concrete Aggregate | 0 | 231 | 462 | 693 | 924 | 462 | 462 | 462 |
| Admixture | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Silica Fume | 0 | 0 | 0 | 0 | 0 | 0 | 31 | 31 |
| Water | 165 | 165 + 9 | 165+12 | 165+20 | 165+28 | 165+56 | 165+32 | 165+72 |
| Water Cement Ratio | 0.53 | 0.56 | 0.57 | 0.6 | 0.62 | 0.71 | 0.64 | 0.76 |

Mix design recipe that is commonly used by a leading ready-mix Tufekci Company in North Cyprus is taken as the basis for this study.

## 3.9 Determination of Water to Cement Ratio

The process of concrete hydration starts when water is added, w/c ratio is normally calculated with mix design but for practical work, the trial mix should be done to obtain good workability and low permeability. The water-cement ratio is determined according to the slump test or the workability of concrete. In total, eight mix designs were prepared and with corresponding slump test determined. Trial mixes were used to adjust w/c ratio for all eight mixes.

The 0 % replacement of NA needs less water and the water demand increases with increase in replacement ratio. The water absorption test carried out revealed the rate of water demand in RCA due to presence of dry mortar attached to the aggregates. Excessive absorption of water results in reduction in strength properties of the concrete. It was also observed that the addition of the silica fume as cement replacement increased the amount of w/c ratio as well as the addition of RCA.

Slump test was done by checking the workability of concrete at fresh state for each batch of concrete and 18-21 cm as the target slump value. Trial mixes where carried out to until target slump value was obtained. Tamping rod, slump cone, metal base slump plate, scoop, metal funnel and a steel ruler was used for the slump test, see Figure 3.9.

**Figure 3.9:** Stages of performing slump test

## 3.10 Mixing and Casting

The aggregates of different replacement ratios were added to the mixing drum for the production of the desired concrete mix. The aggregate from each replacement type was added to the mixing drum and mixed for 30 seconds, then cement was added and mixed for another 30 seconds thereafter the water (water mixed with superplasticizer where applicable) was added mixed for four to five minutes until observing a homogeneous consistent was obtained.

The molds were cleaned and painted with thin layer of oil before concrete was placed in it. The concrete mixture was placed in three layers and compacted with the tamping rod for at least 25 times to extract the voids and achieve maximum bulk-density and tapped 20 times by the sides. The same process repeated for each layer of concrete. Hammer and trowel are used for smoothening the surface of the specimens. The molds were left to set for 24 hours after preparation and demolded. The process of mixing and casting was done according to

ASTM C862. The prepared beams and cubes were identified with numbers and placed in a standard curing tank (water curing) until their testing dates.

## 3.11 Curing

Curing is an important stage, which promotes hydration of cement. In this research, water curing was used. The cubes and beams were demoulded after 24 h of air curing. The water tanks were filled with potable water and the samples placed into it as shown in the Figure 3.10. The water was filled until all the samples were completely submerged and replaced at two weeks intervals.

Figure 3.10: Beam samples in curing tank

## 3.12 Compressive strength

The compressive strength test is the most used in construction area to determine quality and strength of the concrete class. The amount of the load applied to the concrete surface area in contact with load defines the strength of the concrete at hardened state. Cube samples were used generally for testing as it is recommended by EN standards, while cylinder specimens are suggested by ASTM standards.

Cube with dimensions of 15x15x15 cm was used in this study for both the NA and RCA replacements. The cubes were tested for compressive strength at different curing ages. The cubes were taken out form curing tank and allowed to dry. The dried cube was weighed and thereafter placed on the compressive machine as shown in figure 3.11. The compressive test was carried out according to EN-12390-3.  The cubes were tested at 7, 28, and 90 days corresponding to curing duration.

**Figure 3.11:** Compressive Strength Machine (Tukekci Company)

### 3.13 Flexural Strength Testing

Flexural strength is studied to analyse the bending behaviour of unreinforced beams. It is also called as modulus of rapture and it is used in pavements or slabs or other structure, which may encounter bending stress. It would be meaningful to consider flexural strength properties in this study. There are cases where flexural strength test are neglected due to difficulties associated with its large size of preparation and testing.

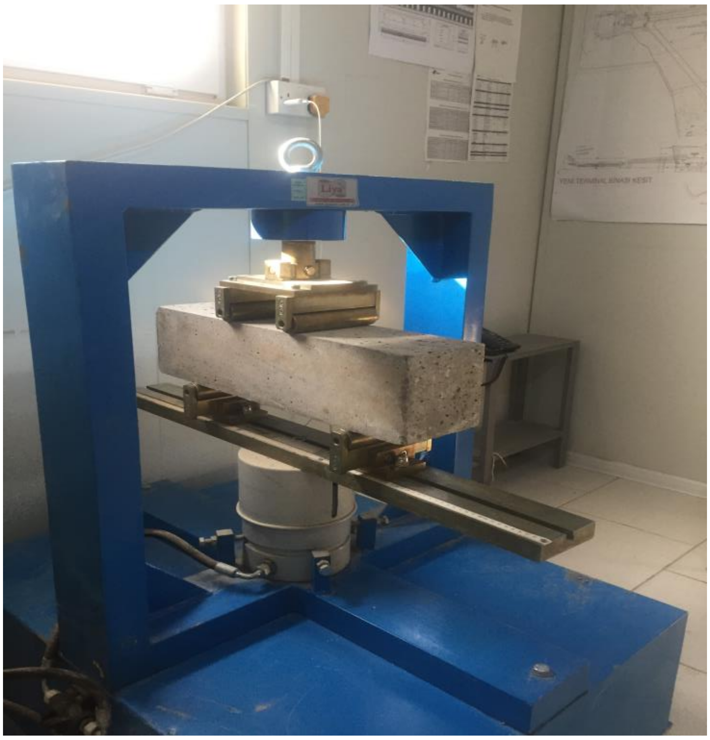


**Figure 3.12**: Flexural Strength Test

Centre point loading and two points loading are the two most known standard methods for evaluation of flexural strength. In this study two points loading is used for testing the flexural strength behaviour. The cured specimens were weighed and tested at different curing ages of 7 and 28. The test was carried out according to TS EN- 12390-5 on dimension of 15x15x60 cm beam samples.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 General Overview

The results of the experimental investigations of the mechanical properties of concrete mixes made with recycled concrete aggregate aged under Cyprus condition are presented in this chapter. For the evaluation of the compressive strength, the cube samples were prepared and tested according to EN -12390-3 standards, while the flexural properties was evaluated using 15x15x60 mm beam in accordance with TS EN- 12390-5 standards. The mechanical properties of the concrete are discussed with respect to recycle aggregate replacement of the natural aggregate and the different ages of curing.

The first set is prepared with 0% of NA replacement and used a as control set. Then 25%, 50%, 75% and 100% NA replacement were prepared; so in total eight mix designs were studied as shown in Table 4.1 for compression strength and Table 4.2 for flexural strength. Mixes 1,2,3,4 and 5 were prepared with only coarse recycled aggregate. Mix 6 is consist of 50% wt. fine and coarse recycled aggregate. Mix 7 is replacement of coarse recycled aggregate by 50% with addition of silica fume. Mix 8 is consist of 50% wt. coarse and fine recycled concrete aggregate with addition of silica fume.

Physical and mechanical properties of the natural and recycled aggregates were evaluated in accordance with relevant standards; the results are presented and discussed. Comparison was made between the natural and recycled aggregate to evaluate the behaviour and the departure from acceptable values.

## 4.2 Properties of Aggregates

### 4.2.1 The Density

The density of both the coarse and fine of the natural and recycled aggregates were measured according to ASTM C127-04. The results (Table 4.1) show that the density of the recycled (fine and coarse) aggregate was lower when compared with corresponding natural aggregates. The presence of mortar attached on the surface recycled aggregates contributes to the reduction in density of the overall aggregates.

**Table 4.1:** Properties of the natural and recycled aggregates

| | **Recycled Aggregates** | | | **Natural Aggregates** | | |
|---|---|---|---|---|---|---|
| | **Coarse** | | **Fine** | **Coarse** | | **Fine** |
| **Particle size range (mm)** | **19-12.5** | **12.5-4** | **4.0-0** | **19-12.5** | **12.5-4** | **4.0-0** |
| Absorption (%) | 4.6 | 6.1 | 12.8 | 0.5 | 0.75 | 1.4 |
| Density (Oven Dry) (kg/m$^3$) | 1.19 | 1.2 | 1.16 | 1.39 | 1.4 | 1.66 |
| Roded Density (Oven Dry) (kg/m$^3$) | 1.3 | 1.3 | 1.26 | 1.4 | 1.53 | 1.85 |
| Specific Gravity | 2.64 | 2.74 | 2.3 | 2.70 | 2.78 | 2.64 |
| Humidity % | 0.9 | 1.3 | 2.5 | 1 | 0.8 | 0.5 |

The packing density of aggregates of the same source increases as the particles sizes decreases because of the reduction in void ratio. All natural (fine and coarse) aggregates used in this study are of the same origin. The results (Table 4.1) shows that for size range 12.5 – 19 mm, the density increased by 1% when the size range was reduced to 4 -12.5 mm, and further increased to 19% for size range less than 4.00 mm from the natural aggregates. For the case of recycled aggregates, the density increased with increase in the size of the aggregates. The results suggest that the fine aggregates contained in the recycled aggregates quantity are of different origin, possibly mortar and other non-structural material, which have lower density when compared with coarse aggregates.

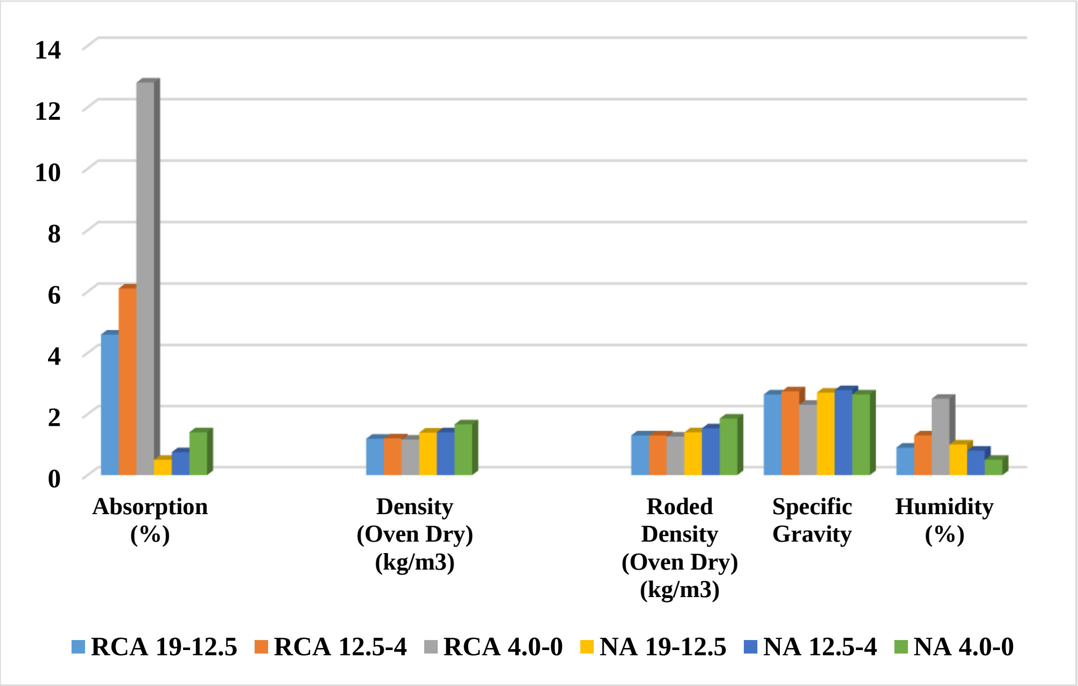


**Figure 4.1:** Comparison between on the behavior natural and recycle aggregates properties

However, the results of roded density did not show appreciable difference between corresponding size in recycled and natural aggregates. It was observed that within each size range the increase in the density as a result of compaction was between 7 to 11 %. All recycled aggregates range shows 8 % increase in the density except 12.5 – 19 mm with 9 % increase. There was 2 % increase within the size range used for natural aggregates, which suggest that natural aggregates requires less compactive effort to achieve a desired wet density for constructed fresh concrete.

### 4.2.2 Absorption

The absorption is an important criteria that affects the workability of the concrete. The absorption degree of aggregates determines the desired water demand for a concrete mix. The water absorption of the reused aggregates was more than natural aggregates due to presence of attached old mortar to the surface of the aggregates. The mortars increase the absorption degree of water due to their porosity.

The results in Table 4.1 show aggregate absorption value for both natural and recycled aggregates of the study. It can be deduced from the results that the recycled aggregate water absorption was nine times more than natural aggregate same result was found by (V. B. M. Kumar et al., 2017). The demand of water in mixing process tends to decrease the strength of concrete as found also by (Güneyisi et al., 2016). Also it was found by (Limbachiya et al., 2000), that the water absorption of aggregates recycled for concrete production was twice higher than the natural aggregate.

The humidity percentage of NA is lower than RCA as shown in table 4.1 above. CRCA did not show a significant difference as compared with natural coarse aggregates while in the fine aggregates the difference is more significant.

### 4.2.3 Specific gravity

The specific gravity is the measure of weight of aggregate in air compared to equal weight of aggregate in water. Generally recycled aggregate has lower specific gravity than natural ones due to presence of old mortars, which contain voids. The same case was observed by (Limbachiya et al., 2000; Safiuddin et al., 2013). The decrease in specific gravity of recycled aggregate is observed as shown in table 4.2 above.

### 4.2.4 Los Angeles abrasion test

The Los Angels test was done to calculate abrasive resistance of the aggregates. The recycled aggregate was observed satisfactory abrasion resistance value. Table 4.2 show the abrasion resistance value of natural and recycled aggregate and it can be observed that recycled aggregates abrasion value is only 1% lower than natural aggregate. This finally indicates that RCA can be safely used for concrete elements that are exposed to abrasion. The Los Angeles abrasion value was fond to be 33.0 % for RCA in the study (Pedro et al., 2017b).

**Table 4.2:** Los Angeles Abrasion Resistance Value

| | Recycled Aggregate | Natural Aggregate |
|---|---|---|
| Los Angeles Abrasion LA % | 26.8 | 28 |

### 4.3 Concrete Workability

Workability of fresh concrete is primarily controlled by the water/cement ratio used in the production of the concrete. Slump value has been used as a conventional workability measurement for fresh concrete. The slump values (Table 4.4) were 8 – 20 cm. The effect of water/cement within 2 cm slump value was assumed to be negligible in order to evaluate the behaviour of replacement on the water demand for a workable concrete at 18 – 20 cm slump.

**Table 4.3:** Water cement ratio

| Replacements | Water/Cement Ratio |
|---|---|
| Mix 1- NA | 0.53 |
| Mix 2- 25% CRCA | 0.56 |
| Mix 3- 50% CRCA | 0.57 |
| Mix 4- 75% CRCA | 0.6 |
| Mix 5- 100% CRCA | 0.62 |
| Mix 6- 50 CRCA+ 50 FRCA | 0.71 |
| Mix 7- 50 CRCA+SF | 0.64 |
| Mix 8- 50 CRCA+50 FRCA+SF | 0.76 |

The results (in Table 4.3 and Figure 4.2) observed in this study shows that the addition of recycled aggregate increased the water demand for a "predetermined" workability. The average increase for water demand was observed to be 2% for every 25% increase in the recycled aggregate replacement of the natural aggregate. The addition of silica fume in the mix design was carried out to enhance the strength performance of the recycled concrete. However, the addition of silica fume has further increased the water/cement ratıo.

At 50 % coarse recycled aggregate replacement, there was 7% increase in water demand. When the fine and coarse natural aggregates were to be replaced with 50 % fine and coarse recycled aggregate respectively, 14 % increase in water demand was observed.

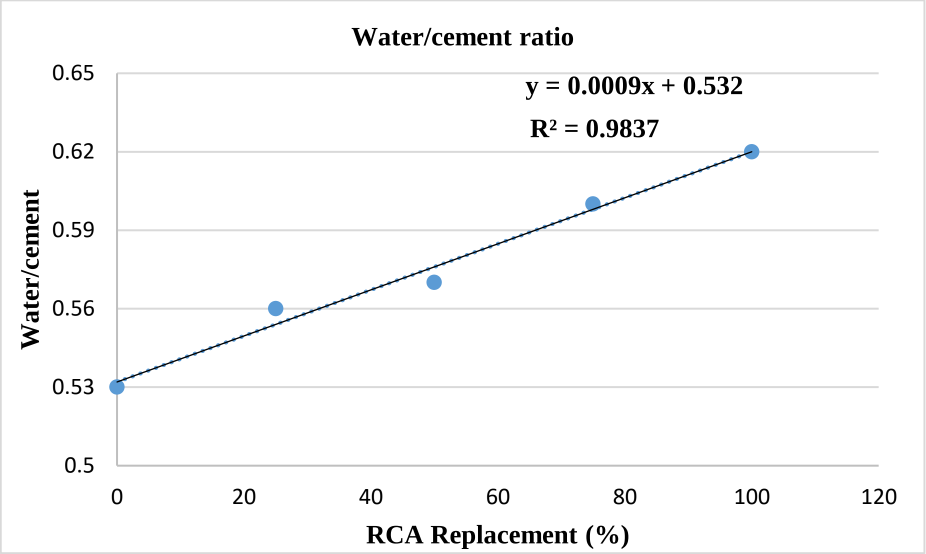


**Figure 4.2:** Evolution of water/cement with RCA replacement of the NA.

It was further observed that the addition of silica fume to 50% fine recycled aggregate replacement of fine coarse recycled concrete aggregate in Mix 3 (50 CRCA) has 19 % increase in the demand of water and 5 % in Mix 6. In general, it was observed water demand due to silica fume addition is intendant of RCA replacement and dependent on cement content. This was evident with 5 % increase in water demand between Mix 3 (50 CRCA) and Mix 7(50 CRCA+SF) and Mix 6 (50 CRCA+ 50 FRCA) and 8 (50 CRCA+50 FRCA+SF).

**Table 4.4:** Slump test

| | Replacements | Slump Test (cm) |
|---|---|---|
| Mıx 1 | NA | 18 |
| Mıx 2 | 25 CRCA | 19.5 |
| Mix 3 | 50 CRCA | 18 |
| Mıx 4 | 75 CRCA | 20 |
| Mıx 5 | 100 CRCA | 21 |
| Mıx 6 | 50 CRCA+ 50 FRCA | 18 |
| Mıx 7 | 50 CRCA+SF | 18 |
| Mıx 8 | 50 CRCA+50 FRCA+SF | 18 |

## 4.4 The Concrete Compressive Test Results

The compressive strength is traditionally used in order to classify the grade and therefore the quantity of concrete at hardened stage. The compressive strength of concrete has been widely studied and correlations are made to determine its relationship with other properties. The results on the evolution of the structural concrete are presented in this section. Correlation between the percentages of replacement of natural aggregate with recycled aggregate was made with the compressive strength. The results (Table 4.5) of each sample were evaluated by calculating the standard deviation of the mean compressive strength. The deviation of the mean is within justifiable range.

**Table 4.5:** Compressıve strength of concrete mıxes used in this study

| | | 7 days | | 28 days | | 90 days | |
|---|---|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mıx 1 | NA | 52.20 | 1.68 | 64.77 | 1.50 | 73.10 | 4.53 |
| Mıx 2 | 25 CRCA | 46.10 | 1.39 | 61.33 | 2.12 | 67.50 | 2.86 |
| Mıx 3 | 50 CRCA | 45.47 | 1.72 | 49.40 | 4.73 | 60.53 | 2.15 |
| Mıx 4 | 75 CRCA | 42.37 | 3.39 | 50.83 | 3.51 | 57.47 | 1.35 |
| Mıx 5 | 100 CRCA | 38.63 | 3.06 | 44.90 | 0.44 | 49.03 | 1.30 |
| Mıx 6 | 50 CRCA+ 50 FRCA | 34.27 | 2.06 | 39.33 | 0.60 | 46.40 | 3.87 |
| Mıx 7 | 50 CRCA+SF | 48.97 | 0.64 | 50.13 | 0.31 | 65.43 | 0.85 |
| Mıx 8 | 50 CRCA+50 FRCA+SF | 24.60 | 3.10 | 33.58 | 1.15 | 38.93 | 5.16 |

### 4.4.1 Effect of CRCA replacement on the compressive strength.

The results of the replacement of natural aggregate with CRCA are presented in Table 4.6 and Figure 4.3 Three different ages (7, 28 and 90) of the concrete were considered for evaluation. It was observed that increase in CRCA content of the concrete resulted in decrease in compressive value of the concrete. At 7 days of curing the compressive strength of the natural aggregate depreciated by 11.68 % when replaced with 25 % of the CRCA. With further increase of the CRCA from 50% up to 100 % replacement, the depreciation of the strength value was 12.84 %, 18.77 % and 29.89 % for 50%, 75% and 100 % RCA content respectively.

The results in Table 4.6 and Figure 4.3 are read discussed simultaneously. In this section, the mix having 0% CRCA has the highest compressive strength and it decreases with increase in CRCA content. Since characteristic strength of concrete is measured at 28 days, hence the result of 100% CRCA can be promising in structural use of concrete. The result shows that beyond 25 % CRCA content, the strength gain of the CRCA-concrete increases slight as shown in Figure 4.3. The strength value between 50% and 75% of CRCA show a close result, the use of 75% CRCA can be suggested too.

The main difference happened at the 100% CRCA which showed the highest strength result at 90 days of curing age, so even the use of 100% of CRCA is safe and gives better result than other replacements of CRCA. This may occur because of the correlation between the aggregates of same type.

**Table 4.6:** Compressive strength result for CRCA replacements

| | | **7 days** | | **28 days** | | **90 days** | |
|---|---|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 52.20 | 1.68 | 64.77 | 1.50 | 73.10 | 4.53 |
| Mix 2 | 25 CRCA | 46.10 | 1.39 | 61.33 | 2.12 | 67.50 | 2.86 |
| Mix 3 | 50 CRCA | 45.47 | 1.72 | 49.40 | 4.73 | 60.53 | 2.15 |
| Mix 4 | 75 CRCA | 42.37 | 3.39 | 50.83 | 3.51 | 57.47 | 1.35 |
| Mix 5 | 100 CRCA | 38.63 | 3.06 | 44.90 | 0.44 | 49.03 | 1.30 |

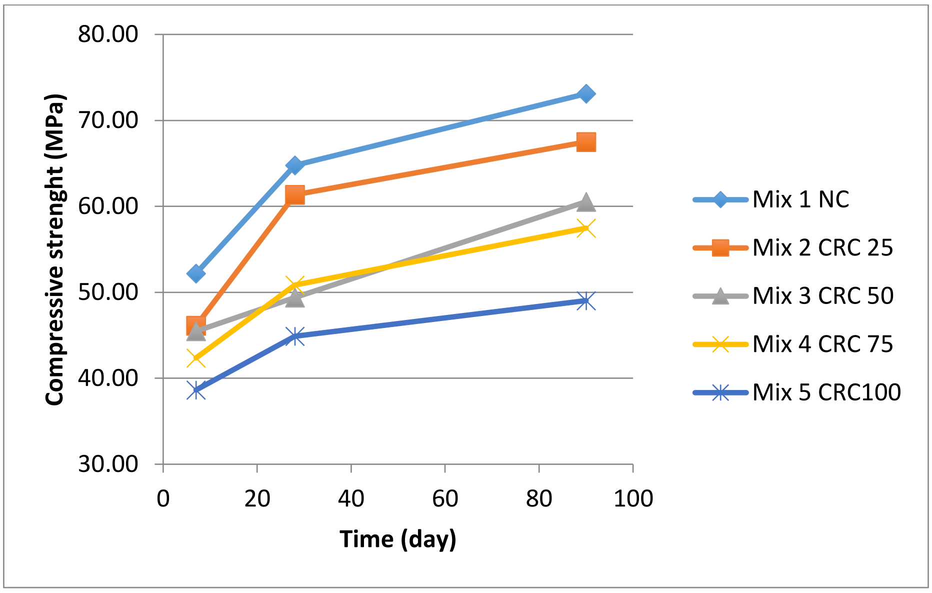


**Figure 4.3:** Effects of CRCA on compressive strength development

### 4.4.2 The effect of FRCA on the compressive strength of CRCA-concrete

The resulting fine aggregate (< 4.00 mm) from the processing of CRCA was incorporated in Mix 6 and 8 with addition of silica fume to mix 8. The essence is to evaluate the behaviour of incorporating FRCA in CRCA-base concrete. The results (Table 4.7 and Figure 4.4) show that incorporating FRCA decreases the strength of the concrete below a strength value that could not be applicable for structural concrete. The compressive strength of Mix #6 (50 CRCA+ 50 FRCA) at 28 days was above 35 MPa, which supports its use in structural concrete.

**Table 4.7:** Compressive strength test result coarse and fine RCA at 50% replacement

| | | 7 days | | 28 days | | 90 days | |
|---|---|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 52.20 | 1.68 | 64.77 | 1.50 | 73.10 | 4.53 |
| Mix 3 | 50 CRCA | 45.47 | 1.72 | 49.40 | 4.73 | 60.53 | 2.15 |
| Mix 6 | 50 CRCA+ 50 FRCA | 34.27 | 2.06 | 39.33 | 0.60 | 46.40 | 3.87 |

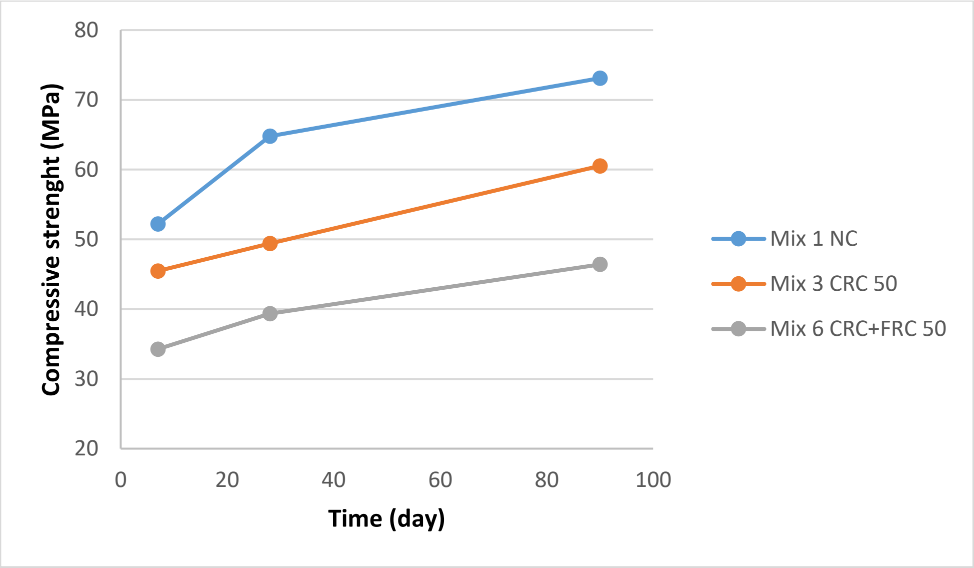


**Figure 4.4:** Effect of coarse and fine RCA on compressıve strength development at 50% Replacement

### 4.4.3 The effect of silica fume on coarse and fine RCA.

Silica fume is cementitious material that is used as cement replacement to increase the strength of concrete. It is an expensive material in construction industry and its use should be considered together with the cost. However, the cost analysis of RCA concrete mixes with silica fume is beyond the scope of this study.

**Table 4.8:** Compressıve strength test result for CRCA at 50% replacement with SF

| | | **7 days** | | **28 days** | | **90 days** | |
|---|---|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 52.20 | 1.68 | 64.77 | 1.50 | 73.10 | 4.53 |
| Mix 3 | 50 CRCA | 45.47 | 1.72 | 49.40 | 4.73 | 60.53 | 2.15 |
| Mix 7 | 50 CRCA+SF | 48.97 | 0.64 | 50.13 | 0.31 | 65.43 | 0.85 |

The results (Table 4.8 and Figure 4.5) shows with addition of silica fume to the CRCA, the performance did not exceed that of the NA. Since the performance of CRCA incorporated with silica fume meets the criteria of structural concrete, therefore the use RCA for structural concrete structures should be encourage.

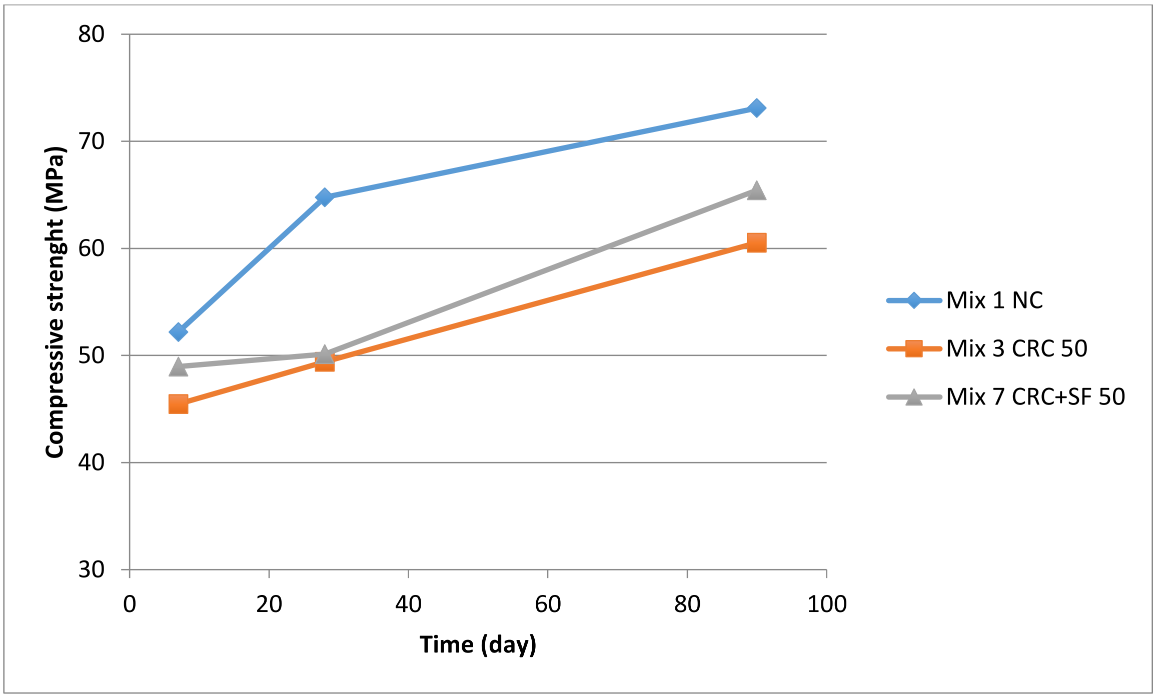


**Figure 4.5:** The effect of CRCA at 50% replacement with SF on compressive strength development.

**Table 4.9:** Compressive strength test for coarse and fine RCA with SF.

| | | **7 days** | | **28 days** | | **90 days** | |
|---|---|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 52.20 | 1.68 | 64.77 | 1.50 | 73.10 | 4.53 |
| Mix 6 | 50 CRCA+ 50 FRCA | 34.27 | 2.06 | 39.33 | 0.60 | 46.40 | 3.87 |
| Mix 8 | 50 CRCA+50 FRCA+SF | 24.60 | 3.10 | 33.58 | 1.15 | 38.93 | 5.16 |

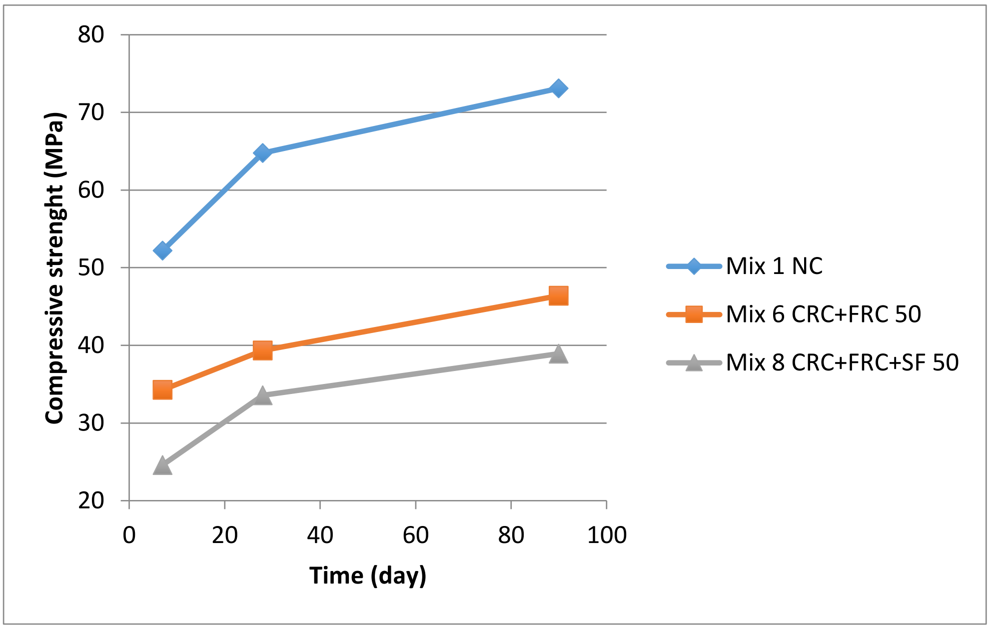


**Figure 4.6:** Effect of coarse and fine RCA at 50% with SF on compressive strength development.

### 4.5 The Flexural Strength Test

The flexural strength is carried for 7 and 28 days with the result were tested on average of three beam specimens of 15x15x60 cm. It was observed that with the increase in the ratio of RCA replacement with natural aggregate strength increases as shown in Table 4.6 below. The same result was found by the (Lau et al., 2014) that the reduction in the use of recycled aggregate tends decrease in flexural strength.

**Table 4.10:** Flexural strength of concrete mixes used in this study

| | | 7 days | | 28 days | |
|---|---|---|---|---|---|
| | | Strength (MPa) | Std. Dev. | Strength (MPa) | Std. Dev. |
| Mix 1 | NA | 7.82 | 0.47 | 9.12 | 0.59 |
| Mix 2 | 25 CRCA | 6.93 | 1.13 | 8.73 | 0.34 |
| Mix 3 | 50 CRCA | 4.91 | 0.16 | 6.34 | 0.19 |
| Mix 4 | 75 CRCA | 6.12 | 0.15 | 8.53 | 0.40 |
| Mix 5 | 100 CRCA | 5.07 | 0.36 | 9.13 | 0.32 |
| Mix 6 | 50 CRCA+ 50 FRCA | 3.01 | 0.38 | 5.12 | 0.43 |
| Mix 7 | 50 CRCA+SF | 5.10 | 0.38 | 6.61 | 0.44 |
| Mix 8 | 50 CRCA+50 FRCA+SF | 3.92 | 0.65 | 5.98 | 0.15 |

### 4.5.1 Effect of CRCA replacement on flexural strength of RCA

The flexural strength of the concrete samples was carried out to determine it’s susceptive toward bending. The results presented in Table 4.11 and Figure 4.7 are used to evaluate the effect of the flexural strength on different replacement of coarse natural aggregate with CRCA with respect to curing age. At 7 days the flexural strength shows decreased with increasing CRCA content except for 50 % CRCA content. However, as the age of the samples increases the flexural strength converge except for 50 % CRCA content.

**Table 4.11:** Flexural strength result for CRCA replacements

| | | 7 days | | 28 days | |
|---|---|---|---|---|---|
| | | Strength (MPa) | Std. Dev. | Strength (MPa) | Std. Dev. |
| Mix 1 | NA | 7.82 | 0.47 | 9.12 | 0.59 |
| Mix 2 | 25 CRCA | 6.93 | 1.13 | 8.73 | 0.34 |
| Mix 3 | 50 CRCA | 4.91 | 0.16 | 6.34 | 0.19 |
| Mix 4 | 75 CRCA | 6.12 | 0.15 | 8.53 | 0.40 |
| Mix 5 | 100 CRCA | 5.07 | 0.36 | 9.13 | 0.32 |

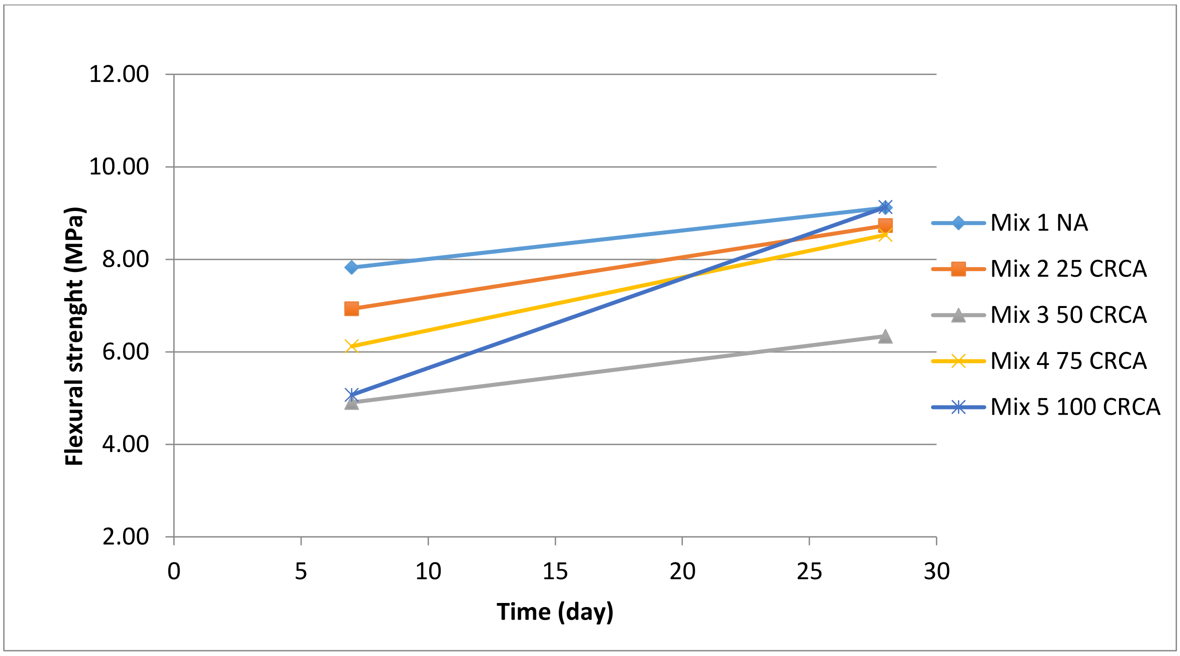


**Figure 4.7:** Effects of CRCA on flexural strength development

### 4.5.2 The effect of FRCA on the flexural strength of CRCA-concrete

The incorporation of FRCA in concrete with recycled coarse aggregate increases the sustainability of recycling in concrete industry. However, the mechanical performance characteristics of the practice should meet basic strength requirements.

**Table 4.12:** Flexural strength test results for coarse and fine RCA at 50% replacement

| | | **7 days** | | **28 days** | |
|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 7.82 | 0.47 | 9.12 | 0.59 |
| Mix 3 | 50 CRCA | 4.91 | 0.16 | 6.34 | 0.19 |
| Mix 6 | 50 CRCA+ 50 FRCA | 3.01 | 0.38 | 5.12 | 0.43 |

The results in Table 4.12 and Figure 4.8 shows with replacement of 50 % fine natural aggreagte with 50 % of FRCA, the flexural strength decreased apprecaible at 28 days.

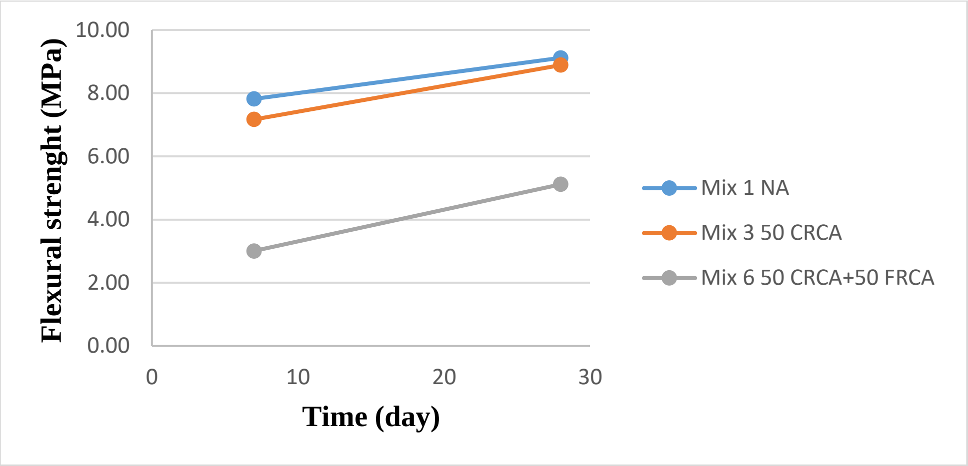


**Figure 4.8:** Effect of coarse and fine RCA on flexural strength development at 50% replacement

### 4.5.3 The effect of silica fume of the flexural strength

Silica fume was incorporated to improve the performance on the mechanical properties of the RCA. The results (Table 4.13 -14 and Figure 4.9 -10) presented shows partial replacement of the cement content with silica fume improved the flexural performance of the RCA concrete.

**Table 4.13:** Flexural strength test result for CRCA at 50% replacement with SF

| | | 7 days | | 28 days | |
|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 7.82 | 0.47 | 9.12 | 0.59 |
| Mix 3 | 50 CRCA | 4.91 | 0.16 | 6.34 | 0.19 |
| Mix 7 | 50 CRCA+SF | 5.10 | 0.38 | 6.61 | 0.44 |

Compression was made between the performances of silica fume addition on CRCA as shown in Figure 4.9. The 10 % cement content replacement with silica fume slightly improved concrete resistance to bending. When 50 % of the fine and coarse natural aggregate are replacement with corresponding fine and coarse recycled aggregate, there was a significant improvement in the strength properties of the samples. The results suggests that addition of silica fume improved the microstructure and bonding between RCA aggregate with fresh mortar.

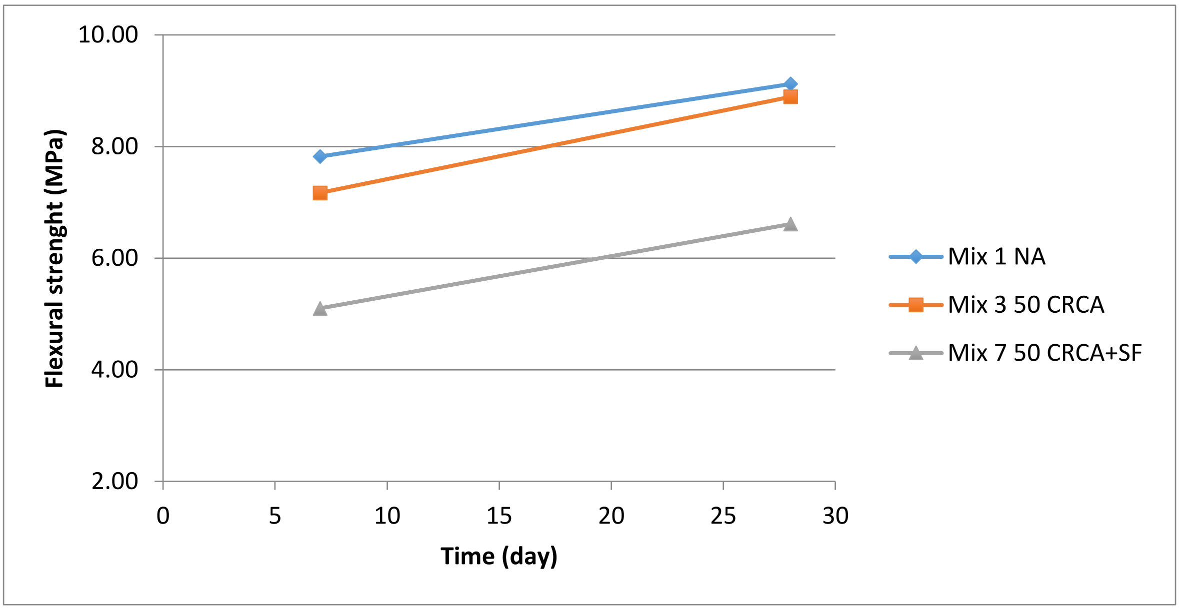


**Figure 4.9:** The effect of curing age on the flexural strength of CRCA with silica fume.

**Table 4.14:** Flexural is strength test for coarse and fine RCA with SF.

| | | 7 days | | 28 days | |
|---|---|---|---|---|---|
| | | **Strength (MPa)** | **Std. Dev.** | **Strength (MPa)** | **Std. Dev.** |
| Mix 1 | NA | 7.82 | 0.47 | 9.12 | 0.59 |
| Mix 6 | 50 CRCA+ 50 FRCA | 3.01 | 0.38 | 5.12 | 0.43 |
| Mix 8 | 50 CRCA+50 FRCA+SF | 3.92 | 0.65 | 5.98 | 0.15 |

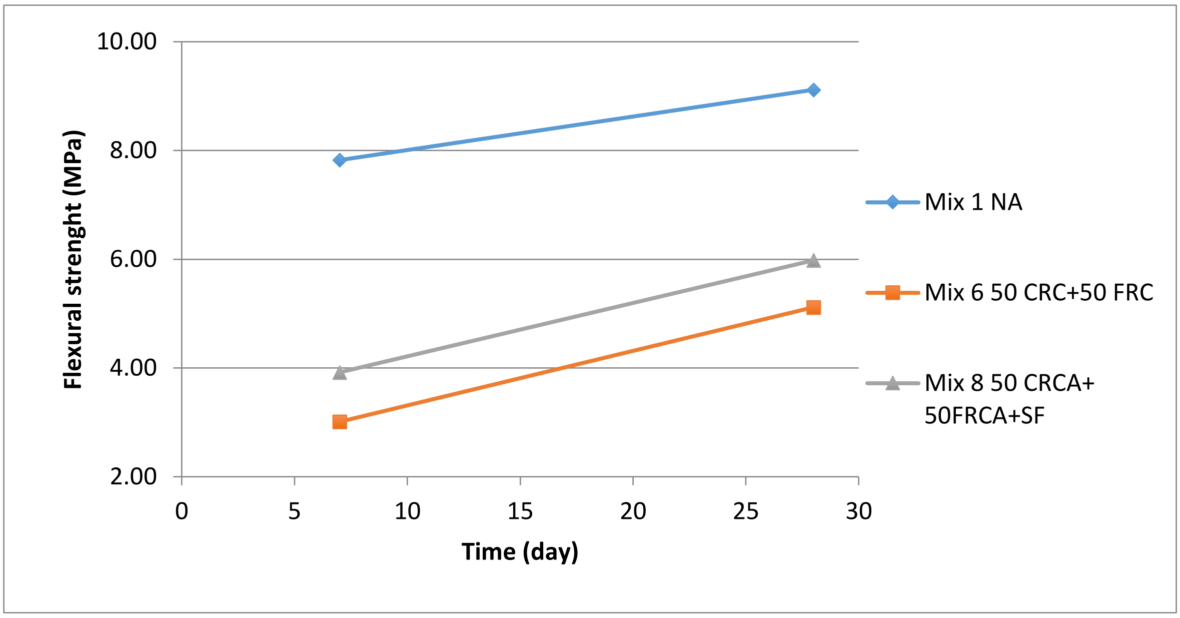


**Figure 4.10:** The effect of curing age on the flexural strength of FRCA/CRCA with silica fume

Due to extreme dry surface and increase water demand for FRCA base concrete, incorporation of silica fume is necessary to promote bonding between RCA-mortar interfaces.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 CONCLUSIONS

The increase of construction and demolition waste percentage raises a threat to the environment. The use of recycled aggregate in the construction industry is strongly recommended if satisfactory strength can be achieved. The incorporation of waste concrete in construction generates a new type of concrete called recycled concrete and this concrete generally has lower strength than normal concrete. Lower strength does generally imply prevention in its use in construction industry. The specific replacement percentage of recycled aggregates with natural aggregates can give satisfactory strength results that are close to concrete made with natural aggregate if certain precautions are taken.

The hypothesis that was stated in chapter one on the use of recycled aggregate in manufacturing of structural concrete has been proven. Different replacement ratio of 0%, 25%, 50%, 75% and 100% yields compressive strength values applicable for structural concrete. The results for 8 different mixes comprising of CRCA and FRCA were studied and the following conclusions were drawn from it:

- On the physical properties; the density and specific gravity of recycled aggregate are observed to be lower compared to NA due to presence of attached mortars.
- The absorption between natural and recycled aggregate was measured on the coarse and fine aggregates, the absorption of RCA was nine times larger than the absorption of natural aggregate. The main reason is attributed to presence of attached dry mortars with high porous character, which increases the absorption of water in RCA.
- Abrasion resistance of RCA observed to be satisfactory. The percentage decrease as compared to natural aggregate was 2%.

- The water cement ratio increased with the increase of NA replacement by RCA up to 14% when 50% of both coarse and fine aggregate replaced.
- The curing condition is observed to have direct affect on the strength value of the concrete, as the increase of the curing age therefore strength increases. In all replacement ratios, at 28 days of curing, the values exceed 35 MPa, even for incorporation of the mixture with the 50% fine aggregate replacement.
- The density of the RCA concrete was found to have decreased when the percentage of NA replacement increases 7 and 28 days of curing. However, at 90 days, the concrete gained additional weight if replacement exceeds 50 %. This attributed to high degree of water absorption of RCA.
- The flexural strength of RCA increased with addition of silica fume. At in general, it decreases with addition of FRCA.
- Generally, it was observed that use FRCA could cause a potential decrease in mechanical properties and its use should be limited to low to medium strength structural elements or even non-structural load bearing members.

## 5.2 RECOMMENDATION FOR FUTURE STUDIES

Observations made and results obtained in this study should be verified with repetition of similar mechanical experiments for concrete mixes prepared with RCA obtained form other demolished buildings as well. Additionally, split tensile tests that can be done in future studies have the potential to yield future insight on the performance of RCA concrete. Furthermore the long-term durability of RCA concrete should also be investigated along with the strength performance of RCA concrete mixes. The modulus of elasticity of the concrete should be studied for recycled concrete in North Cyprus. Investigations should be done on the performance of those demolished buildings in North Cyprus and the mechanical and physical properties should be studied.

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