

INVESTIGATION OF FATIGUE AND DURABILITY PROPERTIES OF
CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE

by

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ABSTRACT

INVESTIGATION OF FATIGUE AND DURABILITY PROPERTIES OF CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE

Population growth and construction industry have grown beyond limits in recent decades which lead to depletion of natural resources with increasing pace. Since this resembles a serious conflict with the desired sustainability and environmental perspective, serious efforts are being made to use recycled aggregates in structural concrete rather than dumping in landfills. In this study, four different replacement levels (0, 50, 75, 100%), two w/c ratios were used. Also mixes containing recycled aggregates were slurry treated with slag when mixing concrete. Also, a more sophisticated method called biodeposition was applied on recycled aggregate specimens and SEM analysis were conducted prior to compressive strength tests on mixes containing bacteria treated specimens. Fatigue strength tests under uniaxial compressive loading with two different S_{max} values (0.85 and 0.75) were applied on specimens to monitor the effects of recycled aggregates on fatigue behavior of concrete. Incorporation of recycled aggregates into concrete adversely affected the mechanical properties. Slurry treatment were found to be effective on both mechanical performance and durability. Biodeposition treatment was found to be effective in decreasing the water absorption of recycled aggregates. Fatigue performance of concrete containing recycled aggregates was found to be lower than natural concrete. Number of cycles to failure was more limited for recycled aggregate specimens and these specimens were not able to withstand higher strain development and failed after a less loss of stiffness with respect to natural concrete specimens and also slurry treated specimens.

ÖZET

GERİ DÖNÜŞÜMLÜ AGREGADAN ÜRETİLMİŞ BETONLARIN YORULMA VE DURABİLİTE ÖZELLİKLERİNİN İNCELENMESİ

Nüfus artışı ve inşaat sektöründe son yıllarda beklenenin çok üzerinde gerçekleşen büyüme doğal kaynakların hızlanarak tükenmesine neden olmaktadır. Bu durumun istenilen sürdürülebilirlik ve çevresel perspektif açısından çelişki oluşturmaları sebebiyle, geri dönüşümlü agregaların atılması yerine yapısal betonlarda kullanılması adına önemli çabalar gösterilmektedir. Bu çalışmada dört farklı ikame seviyesi (0, 50, 75, 100%) ve iki farklı su-çimento oranı kullanılmıştır. Ayrıca, geri dönüşümlü agregaların curuf ile bulamaç haline getirilerek beton karışımında kullanılması ile iyileştirme sağlanması hedeflenmiştir. Aynı zamanda, geri kazanılmış agregaların biodepozisyon adı verilen daha sofistike bir yöntemle iyileştirilmesi hedeflenmiş, SEM analizleri ve mekanik testlerle inceleme yapılmıştır. Dinamik yüklemeler altında geri dönüşümlü agregaların davranışını izlemek üzere eksenel basınç altında iki farklı maksimum yük seviyesinde (0.85 ve 0.75) yorulma testleri gerçekleştirilmiştir. Sonuç olarak geri dönüşümlü agregaların betonda kullanımı sonucu hem mekanik hem durabilite özelliklerinde düşüş gözlenmiştir. Bulamaç uygulaması sonucu verimli olduğu gözlenmiştir. Biodepozisyon uygulaması sonrası agregaların su emme değerlerinde iyileşme ve 28 günlük basınç değerlerinde de iyileşme olduğu görülmüştür. Yorulma performans karşılaştırıldığında geri dönüşümlü agrega içeren betonların normal betonlara göre daha zayıf olduğu gözlenmiştir. Kırılmaya kadar olan maksimum döngü sayılarının, geri dönüşümlü agrega içeren betonlarda daha sınırlı olduğu ve normal betonlarda gözlenen şekil değiştirme değerlerine kadar ulaşmadığı görülmüştür. Aynı zamanda normal betonlar daha yüksek rijitlik kayıplarına kadar kırılma yaşamadan dayanabilirken, geri dönüşümlü agregalarda daha düşük rijitlik kayıplarında kırılma gözlenmiştir.

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1. INTRODUCTION

The growth of the world population and widespread urbanization has remarkably increased the demand for both energy and raw materials for construction sector. Old buildings are being demolished to construct new ones to satisfy the demand in the cities all over the world. Aiming to reduce the demand for natural resources and minimizing the impact on environment, European Union has issued policies to promote the use of recycled aggregates in concrete for structural purposes [4].

A huge amount of concrete waste is generated all over the world causing environmental troubles including landfill problem. Using construction demolition waste as aggregate in concrete has high potential and has been the subject for a lot of researches for a long time. Operational costs of both economical and environmental is aimed to be eliminated by using these demolition waste as aggregate in concrete. Recycling construction waste also increases the life cycle of construction materials. With this intention, several governmental laws and specific regulations were issued by several countries and recycling of construction materials reached up to a level of 90% of the total amount [5].

Therefore, several studies have been carried out for understanding the behavior of concrete made with different types of recycled aggregates. Construction waste consists of various particles besides concrete elements but many studies focused on recycled aggregates obtained by demolition of concrete members and structures [6]. However, there are some problems that prevent the direct usage of construction waste in concrete production and these problems have to be dealt with prior to application for structural purposes and undoubtedly this can be possible by further research and development on the subject.

Recycled concrete aggregates can be modeled as a two-phase composite of natural concrete and the adhered mortar which is made of sand, hydration products and unhydrated cement. Several studies exhibit that recycled concrete aggregates are more

porous than natural aggregates which is mainly related to the presence of the attached mortar which involves micro cracks and capillary pores. The porosity of recycled concrete aggregate is believed to mainly depend on two parameters: the composition of original mixture and the crushing procedure performed for recycled aggregate production.

Main issues when using recycled aggregates in concrete is the porosity of these materials affecting the free water content of the mix [7] and also the weak and multiple interfacial transition zones that affect the overall integrity of the concrete mix [8, 9]. These issues have to be dealt with and considering the problems arising from the cracks on the outer surface possible modifications on specimen surfaces may be helpful. Biodeposition is a promising methodology when repairing existing or future damages in concrete and it is planned to have positive effect on properties of both recycled aggregates and concrete containing recycled aggregates. Reviews show that most mechanical and durability properties of concrete containing recycled aggregate are mainly inferior to natural concrete. Generally, most of the researches have been focused on the mechanical behavior of recycled aggregates concrete under monotonic static loadings [10, 11]. Research on structural behavior of concrete when exposed to cyclic loads, plays a significant role for the design of concrete structures and for the measurement of residual fatigue lifetime in existing structures. Also freeze-thaw durability is highly significant since recycled aggregates have porous structure and existing cracks on specimen surfaces and effect of treatment on durability also should be investigated thoroughly.

2. LITERATURE REVIEW

2.1. Production of recycled aggregate

Recycling plants have been established for recycled aggregate production in several regions. Aggregates are prepared by mechanical crushing for more than one stage to have desired aggregate dimensions. Crushing process is followed by screening of the aggregates in several dimension sizes and afterwards they are stocked due to their size. Demolished concrete contains mortar paste, gypsum and other materials such as plastics, ceramics, metals and glass. Removal of these substances are required since these impurities have various negative effects. Also in several studies concrete produced in laboratory are used and this will allow better control of the production and accordingly better characterization and evaluation of the concrete [12]. Controlling the characteristics of the source concrete will be advantageous when analyzing and interpreting results obtained from the concrete produced from recycled aggregates thus more clear judgments about the parameters that are to be analyzed in this study can be made. Production process of recycled aggregates influences its quality and composition highly. The source concrete that recycled aggregate was produced plays a very significant role in the properties of aggregates. In literature, there are two general types of recycled aggregate. Some recycled aggregates contain normal aggregates with attached mortar and in some recycled aggregates there are various types of contaminants such as ceramics, bricks, plastics and they also contain natural aggregates with attached mortar.

2.2. Evaluation of Attached Mortar Contents in Recycled Aggregates

Mortar content attached on recycled aggregates is highly significant for the properties of these aggregates. Mortar content attached on recycled aggregates is dependent on the stages of crushing process and can be reduced by more crushing processes. However, crushing process also increases production costs therefore, crushing processes have to optimized for both producing good quality recycled concrete and lower crushing

costs. Type of crusher is also highly important in the crushing process [13,14].

In order to determine the adhered mortar content, several methods were described by different researchers. Ravindrarajah and Tam used hydrochloric acid solution method which consists of the dissolution of cement paste when recycled aggregates are placed in [15]. Another popular method was the use of thermal treatment which is applied by soaking of aggregates and sudden cooling is applied after heating the specimens which results in cracks in the adhered mortar. Abbas *et al.* also applied a quick analysis in which recycled aggregates are exposed to freeze-thawing cycles in a sodium sulphate solution [16].

2.3. Physical Properties of recycled aggregate

2.3.1. Density of recycled aggregates

Density of aggregate is a very basic parameter and is important when designing concrete and controlling several parameters of concrete. Density of recycled aggregates are lower than natural aggregates. This is caused by the less dense and porous mortar in the recycled aggregates structure. Densities of recycled aggregates may differ depending on the attached mortar content. Aggregates with lower amount of attached mortar have higher density than the ones with higher content of attached mortar. Table 2.1 shows densities of recycled aggregates as reported in different studies from literature.

Density of recycled aggregate was found to be increased with increasing particle size [21]. The values ranging between 2165 to 2450 were reported as is seen in Table 2.1. In general, higher densities were reported when parent concretes with higher strength were used as expected.

2.3.2. Water Absorption of recycled aggregates

Water absorption capacity of recycled aggregates are higher than natural aggregates as they are composed of cement paste, which may absorb high amounts of water.

Table 2.1. Densities of different recycled aggregates from literature.

Literature	Aggregate Production	Density
		RA (kg/m ³)
Corinaldesi and Moriconi [13]	Recycle Aggregate Plant	2290
Poon <i>et al.</i> [7]	Demolished normal concrete	2409
Poon <i>et al.</i> [17]	Demolished high concrete	1390
Poon and Chan [18]	Recycled concrete	2310
Tangchirapat <i>et al.</i> [19]	In laboratory production	2450
Topçu [20]	In laboratory production	2450
Fonseca <i>et al.</i> [12]	In laboratory production	2310

Different water absorption capacities reported in different studies is due to the variation of attached mortar content on aggregates.

Vieira *et al.* reported the water absorption capacity of recycled aggregate as a function of time [1] (2.1). In the graph it is seen that most (80%) of water absorption of recycled aggregate happens in the initial period of immersion (5 minutes). After this period, increase of water absorption is very slow reaching 85% after 30 minutes. De Juan and Gutierrez noted that recycled aggregates reach 70-90 % of their absorption capacity after 10 minutes of immersion [2].

De Juan and Gutierrez reported that when source concrete is a lower w/c concrete then recycled aggregate has lower absorption and higher mechanical strength. Also particle size was found to have a significant influence on water absorption capacity of recycle aggregates: fine particle size specimens were found to have higher water absorption with respect to coarse aggregate particles [2].

Higher water absorption capacity of recycled aggregate causes lower workability when compared to using natural aggregates in concrete and also the relationship between water absorption and attached mortar content of recycled aggregate concrete is

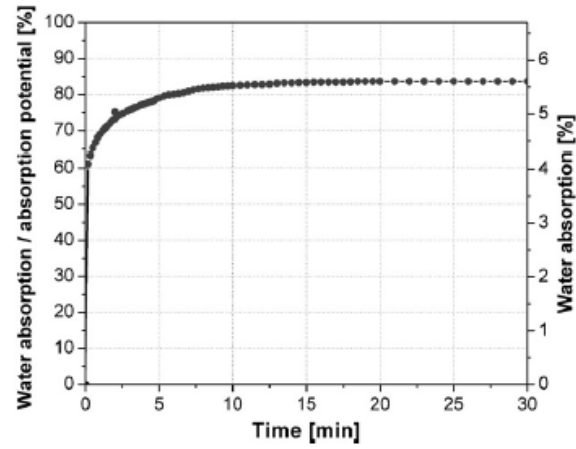


Figure 2.1. Water absorption versus time of recycled aggregates [1].

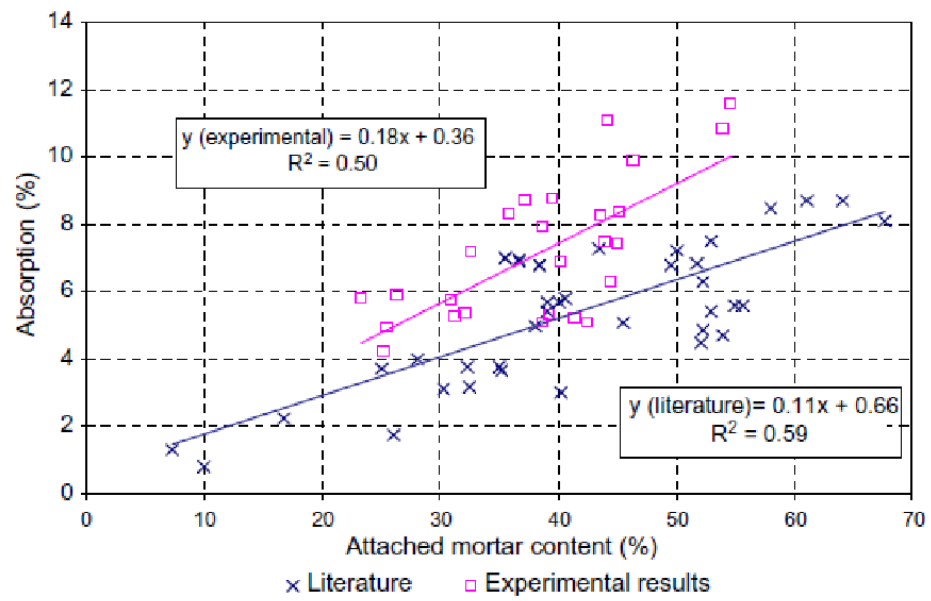


Figure 2.2. Water absorption – attached mortar content relationship [2].

given in Figure 2.2 [2].

Pre-soaking was found to be effective in preventing the fast suction of the mix water [22]. However, in another study it was reported that full saturation of the recycled aggregates might cause bleeding and lead to a weak interfacial transitional zone between the cement paste and saturated recycle coarse aggregates [7].

In a study it was recommended that 80 % of the total water absorption capacity of recycled aggregate for better performance in concrete [14]. Oliveira and Vasquez pre-soaked recycled aggregates and afterwards air dried for 30 minutes and reported better performance with respect to saturated or dry specimens [23].

In some studies, extra water was added to the mix to compensate the water absorbed by recycled aggregates [23]. Ferreira *et al.* applied a pre-saturation method and called it water compensation method. Amount of the extra water depends on the effective absorption and initial water content and these parameters should be known to have the effective water-to-cement ratio [24].

However, Oliveira and Vasquez reported that there may be differences between the free water absorption calculations and absorption of the water in the mix stage, thus this can lead to an excess water amount in the mixes and consequently an increase in the effective water-to-cement ratio [23].

Tam *et al.* proposed a two-stage mixing approach (TSMA) to compensate the higher water absorption capacity of recycled aggregates. They reported that using half of the mixing water leads to the formation of a thin cement slurry layer on the surface of recycled aggregates, which penetrates into old cement mortar filling the cracks and voids. Thus, stronger interfacial transition zone (ITZ) is generated by effectively creating structural chemicals such as portlandite, ettringite and calcium silicate hydrate [25].

2.3.3. Porosity

Commenting on the porosity of the recycled aggregates is easy since recycled aggregate has higher water absorption than that of natural aggregate which means that it has more pores than natural aggregate. Poon *et al.* [7] evaluated the mercury intrusion porosimetry of 3 different aggregate types which are natural aggregate, recycled aggregate produced from normal concrete and from high performance concrete and they reported porosities as 1.60, 16.81, 7.86 % , respectively. The authors attributed the higher porosity of recycled aggregates to the attached mortar content.

2.4. Mechanical Properties of Recycled Aggregate

2.4.1. Strength and Toughness

Strength of aggregate influences the mechanical properties of the resulting concrete and it depends on the texture, composition and structure of aggregate [26]. Crushing value of recycled aggregate is generally higher than natural aggregate. Limbachiya *et al.* [27] reported a crushing value with 10-14 % compared to a crushing value of 14 % for natural aggregate size . Li *et al.* [28] determined the crushing value of recycled aggregates as 27% and 20 % produced by using only jaw crusher and both jaw and impact crusher respectively. The toughness of the aggregate is determined using the aggregate impact value. Lower impact value implies higher toughness of the material with an acceptable limit between 25 and 45 % [26]. According to Rao *et al.* [29] impact value of recycled aggregate is higher than natural aggregate and they related this results to the adhered mortar content.

2.4.2. Particle Shape and Texture

Surface of recycled aggregates has a rough texture and porous structure due to the attached mortar [29]. Topçu concluded that the shape of recycled aggregates is angular because of the demolishing process [20]. Poon *et al.* [7] reported recycled aggregates as porous, weaker and less dense than normal aggregates. According to Zaharieva *et*

al. [22] recycled aggregates contain surface cracks that permit the ingress of water and air into the aggregates. Recycled aggregates used in a study of Gonzalez-Fonteboa and Martinez-Abella [8] were pictured as angular shapes including multiple cracking faces.

Chen *et al.* [30] evaluated the shape of recycled and normal aggregates and concluded they have many similarities. Moreover, conducting the analysis of shape indices of normal and recycled aggregates, Vieira *et al.* [1] reported that recycled aggregates have sharper edges than normal aggregates since shape indices of recycled aggregates are 35 % higher than normal aggregates. Etxeberria *et al.* [14] compared shapes of recycled and normal aggregates and reported that recycled aggregates had better shapes and had attributed well to concrete production.

2.4.3. Grading Size

The size distributions of recycled aggregates are generally different due to different production conditions. However, when manufactured in a production plant, crushing and screening processes are applied and therefore recycled aggregate is thought to have similar size fractions with natural aggregates. If similar crushing techniques are used with the same maximum size, both natural and recycled aggregates tend to have similar grading sizes [30].

2.5. Properties of Concretes Produced by Using Recycled Aggregate

2.5.1. Fresh Concrete Properties

Properties of recycled aggregates are different from normal aggregates, use of recycled aggregates in concrete extensively changes fresh concrete properties of the concrete mix such as density, workability and air content.

2.5.1.1. Density of recycled aggregate concrete. Density of fresh concrete is the mass of fresh normally compacted concrete, including entrapped air voids. Types of aggre-

gates and cement as well as water and void content are the important factors that change fresh concrete density.

Density of fresh concrete incorporating recycled aggregate is lower than natural aggregate concrete mix. Main reason for lower density of recycled aggregate concrete is the attached mortar left on the aggregates.

Lopez-Gayarre *et al.* (2009) [31] reported that recycled aggregates have minor effect on the density of concrete. They reported a decrease of about %5 in the density of concrete mix when all natural coarse aggregates were replaced by recycled coarse aggregates.

2.5.1.2. Workability. Workability of a concrete mix is a significant aspect for proper placing of the concrete besides it governs other fresh concrete properties such as density, air content. There are several studies concentrated on workability of recycled aggregate concrete. Most of the studies showed that fresh concrete properties of concretes containing recycled aggregates were not as good as natural concrete.

Topçu [20] found 25% less slump for concrete incorporating recycled aggregates with respect to natural concrete. Similar results were also reported from several studies and for this behavior extra water was added to mix to compensate the water absorption of recycled aggregates. Angularity and surface texture of recycled aggregates have consequential effect on workability [22].

In several studies, various mixing methods were implemented to control the workability related problems of concrete containing recycled aggregate [5]. They can be summarized as:

- (i) Pre-soaking recycled aggregates for 24h before use.
- (ii) Increasing the superplasticizer amount

- (iii) Extra amount of water added according to water demand of concrete mixes containing recycled aggregate
- (iv) Increasing the moisture content of recycled aggregates up to 80% of its capacity

Gonzalez-Fonteboa *et al.* [8] pre-saturated the recycled aggregates for 10 minutes before mixing to reach around 70% of the water absorption capacities of the recycled aggregates. Padmini *et al.* [32] also noted that 10 minute water absorption process supplied the desired workability whereas Etxeberria *et al.* [14] recommended 80% level of humidity and also Etxeberria *et al.* [14] used higher amount of superplasticizer to reduce water requirement without changing water to cement ratio.

Yang *et al.* [33] reported 27 % decrease in slump value after the addition of pre-wetted recycled aggregates at 100% replacement level and that was attributed to weak and porous texture of adhered mortar content.

Li *et al.* [28] reported higher slump value in concrete containing recycled aggregate coated with pozzolanic powder than concrete containing coarse recycled aggregates prepared by conventional methods. Workability of the concrete incorporating recycled aggregate due to the adhered cement paste was highly improved due to the surface coating of recycled aggregate by pozzolanic powder resulting in a decrease in the water absorbed by the recycled aggregates.

Katz [34] reported similar workability and amount of free water in concrete containing normal and recycled aggregate. Kou *et al.* [35] noted that ground granulated blast furnace slag and fly ash addition to mix was also effective in improving the workability of recycled aggregate concrete.

2.5.1.3. Air-content of concrete cast by using recycled aggregate. Air content of fresh concrete is a significant parameter for the integrity of the fresh mix. In fresh concrete, 3% air content can reduce the water demand of concrete that reduces segregation and bleeding risk. However, air content higher than this may deteriorate the mechanical

properties of concrete.

Katz [34] reported that use of recycled aggregate in concrete increases the air content. Lopez-Gayarre *et al.* reported increasing air content for mixes incorporating higher than 50% RA replacement. In another study, contrary to these two studies, Sagoe-Crenstsil [36] reported no change in air-content between normal and recycled aggregate concrete.

2.5.2. Hardened Concrete Properties

2.5.2.1. Compressive Strength. Generally compressive strength of concrete was found to decline with the incorporation of recycled aggregates instead of normal aggregate. Reduction in strength had various results due to production of recycled aggregates and in some studies reached to 40%. Major reasons for this decline of strength were indicated as the increase in porosity and the formation of a weak aggregate-matrix interface.

Decreasing of compressive strength can be controlled by changing various properties of concrete mix such as changing the mixing procedure, treating RA, using a mineral addition or adjusting the water-to-cement ratio.

Ettxeberria *et al.* [14] noted that compressive strength of concrete containing recycled coarse aggregate with a replacement level of 100% was 20-25% lower than concrete containing normal aggregate. Sani *et al.* [37] observed 40% reduction in compressive strength with 100% replacement of recycled aggregates. Researchers used the same water-to-cement ratio without using any superplasticizers and they observed an inverse relation between the porosity of recycled aggregates and compressive strength of recycled aggregates. With the addition of fly ash as filler they reported 30% reduction of compressive strength for concrete containing 100% recycled aggregate.

Exteberria *et al.* [14] compared conventional concrete and 100% recycled aggregate concrete with same effective water-to-cement ratio and cement content and reported 20-25 % less compression strength. They also concluded normal strength concrete made with 25% of recycled coarse aggregates has the same mechanical properties with conventional concrete. Normal strength concrete with 50% or 100% replacement of recycled coarse aggregates requires 4-10% less effective water-to-cement ratio and 5-10% more cement than natural concrete to target the same compression strength. Gonzalez-Fonteboa and Martinez-Abella [8] experimented on specimens with same effective same water-to-cement ratio but increased the cement content and they reported similar compressive strength and workability to conventional concrete.

In their study, Exteberria *et al.* [14] concluded that the detrimental factors that affect the compressive strength of recycled aggregate concrete are the attached mortar content and crushing strength of recycled aggregate. Gonzalez-Fonteboa and Martinez-Abella [8] concluded that higher water absorption of recycled aggregates will decline the free water in the mix and that will lead to increase in compressive strength, however, after a certain level in the decrease of free water in the mix, workability will decrease and eventually this will attribute to deterioration in mechanical properties. Lopez-Gayarre *et al.* [31] reported that compressive strength will not be influenced if the total water to cement ratio is kept constant and chemical admixtures will be use to compensate the loss of workability [31]. Topçu and Şengel [20] reported a reduction of 33% and 23.5% in compressive strength compared to control concrete by using two different mixes at 100% replacement ratio.

Rao *et al.* [29] reported higher early strength gain in the first 7 days in recycled aggregate concrete than in natural aggregate concrete due to higher absorption capacity of old mortar present in recycled aggregate concrete and the rough texture of recycled aggregate provides better bonding and interlocking between the new mortar and recycled aggregate and they also concluded that there is not much significant difference observed in compressive strength up to a replacement ratio of 50%.

Contradictory to the most of the studies, some researchers asserted that the addition of coarse recycled aggregate does not adversely affect the compressive strength of concrete if some alterations are applied by improving concrete mixing methodology. Sagoe-Crentsil *et al.* [36] declared that there were no difference in 28-day and 365-day compressive strengths of mixes containing pre-soaked recycled aggregate and natural aggregate. However, a 5 % increase in binder content especially when slag cement was added in the mix recycled aggregate considerably increased the compressive strength [36]. Domingo *et al.* [38] found an increase in compressive strength as the replacement level increased that can be linked to the decrease in effective water-to-cement ratio due to the higher water absorption capacity of recycled aggregate concrete.

In 2 different studies, researchers asserted that reducing the aggregate to cement ratio is beneficial for the compressive strength of recycled aggregate concrete [18, 39]. In these studies, low crushing strength of the aggregates and weak interfacial transition zone were declared as the reason behind.

Chen *et al.* [30] reported lower difference between the compressive strength of natural concrete and recycled aggregate concrete, when the w/c ratio increased to a critical value and they became lowest for water-to-cement ratios between 0.58 and 0.90. Katz [34]) observed that there was minimal difference between the compressive strength of recycled aggregate concrete and natural concrete up to a replacement ratio of 75 % at a water-to-cement ratio between 0.65 and 0.75.

In another study, Oliveira and Vasquez [23] emphasized the significance of the moisture content of the recycled aggregates for compressive strength of resulting concrete. 90% saturated concrete was found to perform marginally better than dry coarse recycled aggregate. However, in another study, Poon *et al.* [17] rated three moisture levels with respect to compressive strength of the resulting concrete and concluded as: air-dried $\downarrow$ oven dried $\downarrow$ saturated surface dry.

In several studies, relation between the compressive strength and the properties of the source concrete that recycled aggregate concrete were produced from was re-

searched. Poon *et al.* [7] asserted that the compressive strength of concrete containing recycled aggregate from a source concrete of high compressive strength concrete is higher than that of from a source of normal strength concrete. However Santos *et al.* (2002) could not observe any significant relation between the strength of the source and the resulting concrete. In another study, Tavakoli and Soroushian [40] noted that source concrete was significant.

2.5.2.2. Splitting Tensile Strength. Splitting tensile strength of concrete containing recycled aggregate is found to be lower than that of natural concrete and it further declines with the increasing replacement level. De Brito and Alves [41] noted decrease in splitting tensile strength of the recycled aggregates concrete when compared to natural concrete and they also reported that the replacement ratio of recycled aggregates was more influential on compressive strength rather than splitting tensile strength.

Etcheberria *et al.* [14] observed higher splitting tensile strength of recycled aggregate concrete with 25 and 50 % replacement. Also in this study, the compressive strength of recycled aggregate concrete with 100% coarse recycled aggregate was close to that of natural concrete.

Kou *et al.* [35] observed lower splitting tensile strength for concrete containing recycled aggregate concrete but authors reported higher splitting tensile strength when curing period was prolonged.

Gonzalez-Fonteboa *et al.* [8] reported higher splitting tensile strength for recycled aggregate concrete than in natural concrete at the water-to-cement ratios of 0.50; conversely, the splitting tensile strength of natural concrete was higher than that of the recycled aggregate concrete at the w/c ratio of 0.65. However, Kou and Poon [35] observed higher splitting tensile strength for concrete containing recycled aggregates with high w/c ratio than that prepared with low w/c ratio and they related this variety in results to surface texture of recycled aggregates.

Yang *et al.* [42] related splitting tensile strength with the water absorption capacity of recycled aggregates and asserted an inverse correlation between them and also Kou *et al.* [35] reported similar findings of an inverse relationship between splitting tensile strength and porosity.

2.5.2.3. Flexural Strength. Flexural strength decreases with the addition of recycled aggregates in concrete. However, most of the studies approve flexural strength is less affected with the incorporation of recycled aggregates with respect to compressive strength.

Sadiuddin *et al.* (2011) reported no significant differences in flexural strength of recycled aggregate concrete with respect to that of natural concrete. The researchers advocated their results with mechanical interlocking due to the angularity and surface roughness of recycled aggregates.

Yang *et al.* [33] observed a 10-15 % reduction in flexural strength for %100 replacement level, whereas Mas *et al.* [43] studied the effect of the water-to-cement ratio and found 13, 20 and 30% decrease in flexural strength with water-to-cement ratios of 0.72, 0.65 and 0.45, respectively. Akbarnezhad *et al.* [44] also observed 15% reduction in flexural strength whereas it was 30% reduction in compressive strength. Yang *et al.* [42] related flexural strength performance to water absorption capacity of recycled aggregates.

Tam *et al.* [45] observed advantages of the use of a two-stage mixing approach instead of the normal mixing approach to increase several mechanical properties including the flexural strength of RAC. The replacement of coarse NA by RA in the 25-40% range yielded the optimal flexural strength, along with other mechanical properties of concrete using the two-stage mixing approach.

2.5.2.4. Modulus of Elasticity. Modulus of elasticity of concrete containing recycled aggregate is generally lower than natural concrete and it decreases as the amount

of recycled aggregate in concrete increases. Weaker aggregate cement paste bonding, lower modulus of elasticity of recycled aggregates and porosity of the resulting concrete were recognized as the reasons behind lower modulus of elasticity of concrete containing recycled aggregates.

Safiuddin *et al.* [46] reported a 18 % decrease in 28-day modulus of elasticity whereas decrease in compressive strength was 12 %. Chen *et al.* [30] noted a 22 % decrease in modulus of elasticity in comparison to a 15% reduction in compressive strength at a water-to-cement ratio of 0.5.

Etcheberria *et al.* [14] also observed a decrease in the modulus of elasticity due to replacement at three different levels of 25, 50, 100% of natural coarse aggregates by recycled aggregates. Decreases found were 5, 15, 20 % respectively. Rao *et al.* [29] also reported decreases of about %15 for elasticity of modulus in their studies. Poon *et al.* [39] observed 17-23% reduction in modulus of elasticity when natural aggregates were replaced with recycled aggregates. They also followed a curing process that were continued for 5 years and observed that decrease in modulus of elasticity was about 10 % and emphasized on higher gain over time for concrete containing recycled aggregates.

Tam *et al.* [45] investigated modulus of elasticity for concrete mixed by a two-stage mixing method. In this method, water was used in two parts; the first part added to the dry mixed aggregates and the remaining part to the cement and mixed aggregate and reported the best improvement at a replacement level of 31%. Tam and Tam (2008) noted an enhancement of 16 % in modulus of elasticity of concrete containing coarse recycled aggregates at 30 % replacement level.

Thangciharapat *et al.* [19] (2008) noted that there is no significant effect of mineral additions and reported that modulus of elasticity of concrete principally depends mostly on aggregate properties rather than the cement paste. Gonzalez-Fonteboa and Martinez-Abella [8] observed no improvement in modulus of elasticity of concrete containing recycled coarse aggregate after replacing 8% of cement of silica fume. Kou and Poon (2006) observed some improvement in the modulus of elasticity of concrete con-

taining recycled aggregate as a 20, 50, 100 % replacement of coarse natural aggregate due to the addition of fly ash for a 25% replacement of ordinary portland cement.

2.5.2.5. Fatigue. Generally, most of the researches have been focused on the mechanical behavior of recycled aggregates concrete under monotonic static loadings. Research on structural behavior of concrete when exposed to cyclic loads, plays a significant role for the design of concrete structures and for the measurement of residual fatigue lifetime in existing structures [47]. The fatigue behavior of concrete materials is of utmost significance for structures under cyclic loadings, such as floors under vibration of crowds, road pavements and girders supporting highway bridges under traffic, and offshore structures [10].

For recycled aggregate concrete, there is a general consensus that there is a loss in the physical and mechanical properties but the fatigue behavior has not been extensively analyzed [11]. Thomas *et al.* [11] reported that the negative effect of the recycled aggregate on the dynamic properties of concrete is greater than caused on the static and also observed that new concrete quality is also as important as the effect of the recycled concrete aggregates.

In the same study, Thomas *et al.* [11] conducted their own method to obtain fatigue limit and observed that the reduction in fatigue limit by incorporating the recycled concrete aggregates is greater when new concrete quality is higher. Reduction is minimal when new concrete quality is close to the old concrete quality from which the recycled concrete aggregates are obtained.

In another study by Thomas *et al.* [11], authors reported that for the same water-to-cement ratio, recycled aggregate concrete presents a higher loss of stiffness at the same strength conditions. According to the results, concrete shows a critical strain increment at a stress level of 65% of the compressive strength for control concrete, 60% for the 20% recycled concrete, 55% for the 50% recycled concrete, 45% for the 100 % recycled concrete.

Xiao *et al.* [11] reported that fatigue behavior of recycled aggregate concrete under uniaxial compression does not differ from conventional concrete significantly. Conversely, fatigue life of recycled aggregate concrete under bending is found to be lower than that of conventional concrete.

2.5.3. Freeze-thaw durability

A durable concrete structure has to withstand effects of environment and physical actions. Good durability performance is expected from concrete to withstand long service years. Durability of concrete depends on various factors such as the concrete's ingredients and their proportioning and quality. Curing conditions and external environment conditions are of extreme significance for long-term considerations.

For cold regions, freeze-thaw durability of concrete structures are highly important. Freeze-thaw action takes place when stress in pores in cement paste arises because of the expansion of freezing water. Cracks may occur if the stress formed is higher than the cement paste strength and further cycles will contribute to higher damage.

Gokce *et al.* [48] reported a minimal development in the freeze-thaw resistance of concrete due to the use of coarse recycled aggregate with small adhered mortar content. They also reported that freeze-thaw resistance was significantly enhanced with the reduction of water-to-cement ratio from 0.55 to 0.33 when recycled aggregate concrete was used as coarse aggregate.

3. EXPERIMENTAL STUDY

3.1. Materials

3.1.1. Cement

In this study, portland cement CEM I 42.5R was used as binding material. Although they were the same type, two different cements were used in the project (one of them is parent concrete). For production of the source concrete ready mixed concrete was used. Detailed report for this cement is given Table 3.1. Other cement that was used for all in-laboratory work was supplied from Büyükçekmece Akçansa factory in 50 kg packed form. Physical, chemical properties and strength characteristics of the cement are given in detailed data sheet (Table 3.2).

Table 3.1. Data sheet for cement properties. (ready-mixed concrete)

SiO ₂ (%)	19.8	LSF	0.96
Al ₂ O ₃ (%)	5.58	Insoluble Residue (%)	0.29
Fe ₂ O ₃ (%)	3.42	S.CaO-Free Lime (%)	2.2
CaO (%)	63.7	Loss on Ignition (%)	1.85
MgO (%)	1.22	Specific Gravity (gr/cm ³)	3.14
SO ₃ (%)	3.34	Setting Time (Vicat) Initial / Final	103 / 173
Cl ⁻ (%)	0.04	Soundness (Le Chatelier) (mm)	1
Na ₂ O	0.24	Blaine Specific Surface (cm ² /gr)	3490
K ₂ O (%)	0.66	Residue on 45 μ m sieve (%)	4.5
C ₃ S	47.92	Residue on 90 μ m sieve (%)	0.3
C ₂ S	20.7	fcc (2 days) MPa	27
C ₃ A	9.01	fcc (7 days) MPa	42
C ₄ AF	10.41	fcc (28 days) MPa	55

Table 3.2. Data sheet for laboratory work cement.

SiO ₂ (%)	20.02	LSF	0.95
Al ₂ O ₃ (%)	5.4	Insoluble Residue (%)	0.31
Fe ₂ O ₃ (%)	3.51	S.CaO-Free Lime (%)	2.2
CaO (%)	63.54	Loss on Ignition (%)	1.75
MgO (%)	1.32	Specific Gravity (gr/cm ³)	3.14
SO ₃ (%)	3.3	Setting Time (Vicat) Initial / Final	106 / 169
Cl ⁻ (%)	0.04	Soundness (Le Chatelier) (mm)	1
Na ₃ O	0.23	Blaine Specific Surface (cm ² /gr)	3450
K ₂ O (%)	0.66	Residue on 45 μ m sieve (%)	4.4
C ₃ S	46.79	Residue on 90 μ m sieve (%)	0.3
C ₂ S	22.18	fcc (2 days) MPa	28
C ₃ A	8.38	fcc (7 days) MPa	41
C ₄ AF	10.68	fcc (28 days) MPa	56

3.1.2. Ground Granulated Blast-Furnace Slag

In this study, ground granulated blast furnace slag (GGBS) was used. Slag was supplied from Akçansa factory in packed form. Detailed analysis report is given in Table 3.3.

Table 3.3. Slag analysis report

SiO ₂ (%)	37,92	Mn ₂ O ₃ (%)	2,4
Al ₂ O ₃ (%)	9,35	Loss on Ignition (%)	0,18
Fe ₂ O ₃ (%)	0,84	(CaO+MgO)/SiO ₂	1,19
CaO (%)	36,85	CaO+MgO+SiO ₂	83,15
MgO (%)	8,38	Specific Gravity (gr/cm ³)	2,88
SO ₃ (%)	1,83	Blaine Specific Surface (cm ² /gr)	4199
Cl- (%)	0,1	Residue on 45 μ m sieve (%)	2,3
Na ₂ O	0,23	Residue on 90 μ m sieve (%)	0
K ₂ O (%)	0,88	fcc (7 days) MPa	47
TiO ₂ (%)	2,09	fcc (28 days) MPa	71

3.1.3. Admixtures

In this study, admixture was used as water reducing agent. Rheobuild 1000 is an ASTM C494 Type F high range superplasticizer produced by BASF –YKS. It is a poly naphthaline sulphonate condensate type of superplasticizer. Properties of superplasticizer may be viewed in Table 3.4.

3.1.4. Aggregates

In this study, crushed sandstone aggregates extracted from a stone mine in Ayazaga was used. These natural aggregates were crushed in the same site and transported to Bogazici University for this study. Besides these natural aggregates, recycled aggregates were also used in this study. For the production of source concrete of re-

Table 3.4. Properties of superplasticizer.

Color	Dark Brown
State	Liquid
Specific Gravity	1.2 ± 0.03
pH	6.5-8.0
Chloride Content	$\leq 0.1\%$
Alkali Content	$\leq 5\%$

cycled aggregates, ready mixed concrete was ordered and also aggregates from same source were used in the ready-mixed concrete. Details about recycled aggregates are given in later sections.

3.1.5. Production and Curing of Source Concrete

In order to obtain recycled concrete aggregates, use of ready mix concrete was decided since high amounts of concrete were required. 1250 x 2500 mm plywood plates were acquired and with the help of a carpenter 10 units of big molds with dimensions of 1250 mm x 2500 mm x 300 mm were constructed. Molds were strengthened from sides to endure the weight of such a big concrete block. 10 m^3 of ready mixed concrete was ordered from nearby ready mixed concrete plant and casted into these blocks with the help of sufficient personnel and proper compaction was ensured by using several poker vibrators. Ready mix concrete casting may be viewed in Figure 3.1.

Slump of the mix was measured as 110 mm. Concrete samples were taken from fresh concrete and cured in water bath for 28 days. Concrete was ordered to be C16 and average compressive strength of samples taken were found to be 20 MPa. Concrete blocks were casted in the backyard of civil engineering laboratories. In order to protect the concrete from direct sunlight they were coated with textiles. Blocks were cured by sprinkling water every 4-hour period. After waiting for 48h, molds were disassembled gently by screwing off.



Figure 3.1. Ready mix concrete casting into molds.

3.1.6. Recycling of Source Concrete

After 90 days, big concrete blocks were crushed into smaller dimensions by the help of a wheeled crusher and loaded to trucks to transport to crushing site in Ayazaga (Figure 3.2).

3.1.7. Crushing Process

In the crushing site, originally natural rocks were being crushed. For this study, all the process in the crushing site was stopped in order not to mix recycled aggregates with the natural aggregates that were being manufactured at the time in the site. Concrete blocks were crushed in the new crusher unit installed apart from all the production in the crushing site.

3.1.8. Labelling and Storing Recycled Aggregates

After crushing of the concrete blocks, they were filtered and sieved with maximum diameter size of 25 mm and later transported back to Bogazici University by trucks. Recycled aggregates were sieved as 0-4 mm, 4-12 mm and 12-25 mm by the crushing



Figure 3.2. Concrete blocks prepared for transport to aggregate crushing site

site. In laboratory, both for being sure and also to maintain better control on mixture proportions, coarse aggregates were sieved again in 3 different sizes (4-8, 8-16, 16-25 mm). Afterwards, they were bagged and moved to storage in the same humidity controlled depot with the natural aggregates subsequent to proper labelling of the sacks.

3.2. Aggregate Tests

3.2.1. Sieve Analysis of Aggregates

Sieve analysis of both natural and recycled aggregates were done according to TS 802. This standard defines limits inside which the grading curves for mixtures must coincide. In this study, maximum aggregate size (D_{max}) was 25 mm for both aggregate types. So appropriate grading curve chart was selected as the chart with maximum aggregate size of 32 mm and may be viewed in Figure 3.3 . There are 5 regions that grading may fall inside. When designing the aggregate proportions, it is particularly advised that Region 4 and 3 has to be used.

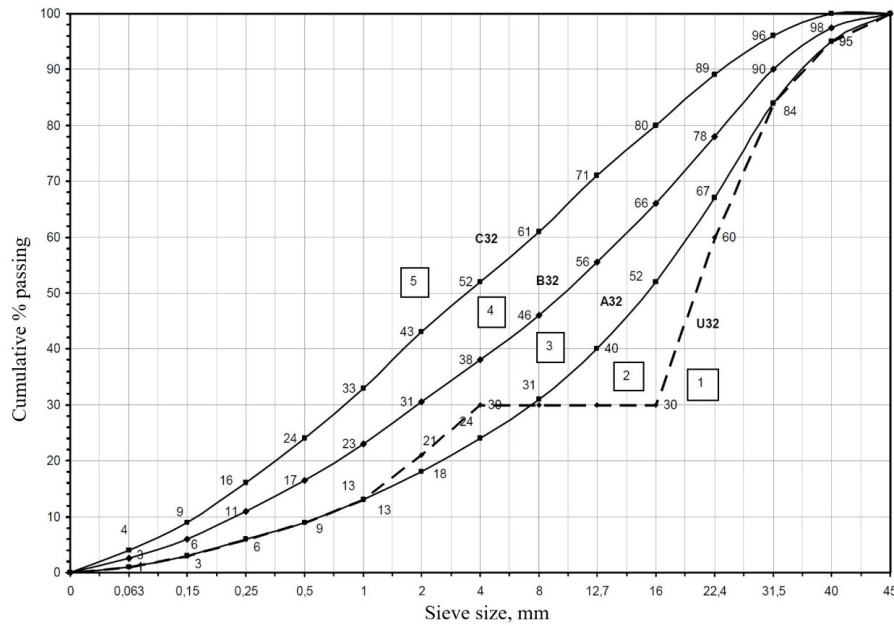


Figure 3.3. Grading limitations of concrete with maximum aggregate size of 32 mm [3].

Also to be noted, in TS 802 [3] standard limitations for different maximum aggregates sizes are given for 8 mm, 16 mm, 32 mm and 63 mm. So grading curves chart for 32 mm were selected although maximum aggregate size in this study is 25 mm.

3.2.2. Aggregates Unit Weight and Water Absorption

Water absorption capacities of aggregates are extremely important for concrete production. Proper determination of water absorption capacity helps starting from the fresh state to the hardened state. Proper placing and compacting of the concrete is highly affected from the water absorption of the aggregates in concrete mix. Unexpected suction of the mix water into aggregates is going to change mix water volume thus affecting many properties starting from fresh state.

Unit weights of the aggregates are also evaluated. Unit weight of the aggregate is a highly significant parameter assessing the concrete mix recipe alike the water absorption capacity. Determining the unit weight of aggregates is going to reveal

many details prior to forming the recipe and producing the concrete mix respectively. Especially for recycled aggregate concrete, water absorption is of extreme importance since they differ much with respect to natural aggregates. Recycled aggregates contain attached old mortar that has substantial cracks in it. These cracks surely lead water deep into these type of aggregates and surface area that may absorb water increases.

In this study, calculation of unit weight and water absorption capacity is done according to standard given in TS EN 1097-6 [49]. In the same standard within the same tests, both assessments are done concurrently.

Unit weight is calculated as the ratio of mass to volume. Mass is measured by weighing the specimen in saturated and surface dry (SSD) and later oven-dry conditions. Volume is measured by using the basket or picnometer method. In this study, picnometer method is used to have more accurate results which is also highly applicable to all aggregate diameter ranges.

Picnometer has to be calibrated with respect to instructions given in the standard. Volume of picnometer is to be calculated by filling picnometer with water at 22 ± 3 °C and leaving for 1h. Test specimen is dried in oven at 110 ± 5 °C till reaching stable mass and left at ambient temperature for cooling.

Picnometer and cone is weighed (M^1). Test specimen is placed into the picnometer and entrapped air is removed by rolling and shaking the picnometer gently. Picnometer is placed into the water bath and test specimen is left for 24h at 22 ± 3 °C. At the end of soaking period, picnometer is taken out of the water bath and entrapped air is removed if there is any by rolling and shaking the picnometer softly.

Water is added to picnometer till overflowing occurs and lid is placed on top without entrapping any air. Exterior of picnometer is dried and weighed (M_2). Water temperature is also recorded. Aggregate pieces is taken out of the water and left for drying for a few minutes. Then picnometer is again filled with water and lid is also closed and picnometer is weighed (M_3) after drying the exterior of the picnometer.

Test specimens are taken onto fabrics in order to create surface-dry condition. All water films are removed and after ensuring saturated surface dry condition test specimens are weighed (M_1). Aggregate particles are dried in an oven at a temperature 110 ± 5 °C (M_4).

$$\text{Unitweight} : \rho_a = \frac{M_4}{M_4 - (M_2 - M_3)} \quad (3.1)$$

$$\text{Ovendriedunitweight} : \rho_{rd} = \frac{M_4}{M_1 - (M_2 - M_3)} \quad (3.2)$$

$$\text{Saturatedsurfacedryunitweight} : \rho_{ssd} = \frac{M_1}{M_1 - (M_2 - M_3)} \quad (3.3)$$

Water absorption ratio is calculated as the ratio of 24h soaked specimen weight to dried weight and calculated as given in Equations 3.1, 3.2, 3.3.

M_1 = mass of picnometer and cone, g. M_2 = mass of picnometer, cone and specimen, g. M_3 = mass of picnometer, cone, specimen and water, g. V = volume of picnometer, ml. ρ_w = density of water at test temperature,

3.2.3. Flakiness Test

Flakiness test has been done according to specifications given in EN 933-3 [50]. Flakiness index test is applied to all aggregates whether natural or not including lightweight aggregates. This standard is to be used for specimens with a minimum

diameter of 4 mm and a maximum diameter of 80 mm.

This part of the standard is expected to be used in accordance with part 2 and 5. Part 2 gives detailed information about selecting the proper amount of specimen for testing. Part 5 gives information about standard devices and their calibrations.

In general, test consist of two sieving processes. In first sieving, specimen batch is sieved according to particle diameter fractions given in Table 3.5. Every particle size fraction d_i/D_i is sieved through the parallel bar sieves which have $D_i/2$ spacing between bars.

Table 3.5. Experimental Masses for Aggregates

Aggregate Specimen Max Diameter (mm)	Min. mass of experi- mental batch (kg)
63	40
32	10
16	2.6
8	0.6
≤ 4	0.2

Total flakiness index is the ratio of dry mass of specimens passing through the sieves shown in Figure 3.4 to the total specimen dry mass and given in percentage.

Experiment batch size is decided with respect to specifications in TS EN 933-1 [51]. For our experiment maximum aggregate size is 25 mm so as can be viewed from Table 3.5, 10kg of specimen was taken randomly from the stock.

Aggregates are dried to constant mass subjecting to a temperature of 110 ± 5 °C in an oven. After they cooled down on their own, specimens are weighed and recorded as M1 As the max specimen size is 25 mm, 25/31.5 mm standard sieve and with respect to that from Table 3.5, 16 mm is selected as maximum bar sieve. Bar sieves may be

viewed from Figure 3.4.



Figure 3.4. Cylindrical Bar Sieves

Sieving process is conducted by hand and sieving process was continued at least for 1 minute till there is not any change in mass more than 1%. For every bar sieve specimen passing was weighed and recorded.

All measurements of particle size fractions are summed and recorded as M_1 whereas specimens passing from the bar sieves are recorded as M_2 . Flakiness index was calculated with the following equation.

$$FI = M_2/M_1 \times 100 \quad (3.4)$$

Table 3.6. Bar sieve selection table

Diameter Fraction d_i/D_i (mm)	Bar sieves opening size d_i/D_i (mm)
63/80	40
50/63	31.5
40/50	25
31.5/40	20
25/31.5	16
20/25	12.5
16/20	10
12.5 / 16	8
10 / 12.5	6.3
8.10	5
6.3 / 8	4
5 / 6.3	3.15
4.5	2.5

3.2.4. Aggregates Crushing Value Test

Aggregates crushing value test is used to obtain a relative value of strength for aggregates' resistance to crushing under regularly increasing load. All measurements were done in accordance with BS 812-110 [52]. This method can be applied to specimens that can pass through 14 mm but not 10 mm standard sieves. Standard procedure is to fill a suitable steel cup and apply compressive loading with standard increments given and afterwards sieving the specimen batch through 2.36 mm sieve to see the amount of the specimen that has been really crushed and can no more be accepted as a coarse aggregate. Specimen batch is selected randomly and sieved through 14 mm and 10 mm sieves. To be selected, specimen has to have a maximum aggregate size of 14 mm and a minimum of 10 mm. Then specimen taken is filled in to a steel mould as three layers, when filling they have to be rodded 25 times for proper placing of each layer. Afterwards with the precise equipment given in the standard, aggregates are placed into compression testing device. Loading is done in 10 minutes increasing regular with a loading rate of 0.67kN/s to a maximum load value of 400 kN (Figure 3.5).



Figure 3.5. Aggregate crushing value test under compression loading

Crushed specimens are taken from the steel mould and sieved through 2.36 mm diameter standard sieve. Crushing index may be calculated by dividing the mass passed to the overall mass of the specimen. M_1 = mass of all specimen, M_2 = mass of specimen fraction passing through 2.36 mm standard sieve, M_3 = mass of specimen fraction remained on 2.36 mm standard sieve. Then aggregate crushing value may be calculated as given in the equation below in percentage;

$$ACV = M_2/M_1 \times 100 \quad (3.5)$$

3.2.5. Aggregate Impact Value Test

Toughness is the property of a material to resist impacts. Aggregate impact value is a relative measurement of aggregates resistance to sudden compressive loading also called impact loading.

Aggregates passing from 14 mm and retaining on 10 mm standard test sieves are selected for testing.

The dried test portion shall be sieved firmly on the 12.5 mm and 10 mm test sieves to get rid of the oversize and undersize fractions. Sieved fractions are divided into three test specimens each of sufficient mass to fill the measure.

The measure should be filled to overflow with the test specimens. The aggregates should be tamped 25 blows by the free falling of the tamping rod from a height of 50 mm above the surface of the aggregates. Surplus aggregates were removed by rolling the tamping rod across and contacting with the top surface of the container walls. Net weight of the aggregates in the measure shall be weighed.



Figure 3.6. Aggregate Impact Value Test Device

With the minimum disturbance to the test specimen the test specimen should be fixed in position on the base of the testing machine 3.6. Height of the hammer shall be adjusted to a height of 380 ± 5 mm above the higher surface of the aggregates in the cup and then it is released to fall freely. The test specimen shall be subjected to 15 blows.

Aggregate impact value is calculated as given in Equation 3.4 where M_1 is the mass of the test specimen, M_2 is the mass of the material passing the 2.36 mm test sieve.

$$AIV = M_2/M_1 \times 100 \quad (3.6)$$

3.3. Fresh and Hardened Concrete Tests

3.3.1. Designation of mixes

Following notation was used for designation of the specimens. Based on this system, NA and RA stands for natural and recycled aggregate specimens. Last two digits resembles the water-to-cement ratio in percentage whereas first two digits are given for specimens containing both natural and recycled coarse aggregates at the same time representing the recycled coarse aggregate percentage in the mix (Figure 3.7).

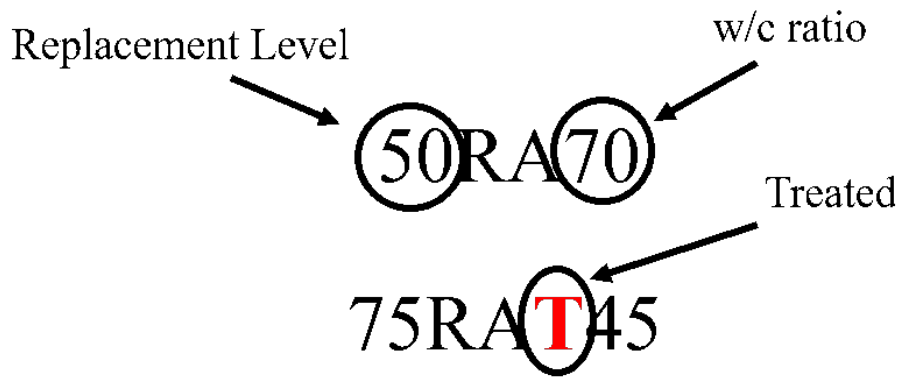


Figure 3.7. Designation of mixes used in the project

Mixes including “T” letter represents the specimens with slurry method treatment which is going to be discussed in the latter chapters.

3.3.2. Fresh Concrete Tests

Air content measurement was conducted for all series in fresh state. Measurement was done according to TS EN 12350-7 [53] by the pressure gauge method. Concrete is poured into the apparatus which is a container and sealed with less entrapped air as possible. Then concrete is compacted and the instructions given in the standard was prosecuted. Also fresh concrete weight was measured and recorded for all concrete cast stages.

In this study, two water-to-cement ratios and four replacement ratios were used. Concrete mixture designs were made for eight different mixtures. Two different binder dosages were selected as there are two different water-to-cement ratios. TS 802 [3] standard is used for design.

D_{max} is 25 mm for the aggregates to be used in this project. From the TS 802 [3] code, chart for 32 mm of D_{max} is selected for best resemblance as also suggested by the code. The results after sieve analysis of all the aggregate batches are used for creating a curve to be in 3rd or the 4th region as suggested by the standard.

As mentioned in previous sections, all aggregates are packed in sacks and labelled due to their origin (natural or recycled) and also their maximum size (4-8 mm, 8-16 mm, 16-25 mm). Sieve analysis data of all diameter sizes and origins are entered into basic tabular software Excel and by also adding the sieve analysis data of fine aggregates, curves were constructed. By altering the proportions of aggregate sizes, eight curves (for each mix) are designed to fall into the 3rd or the 4th region as prescribed in the standard (Figure 3.3).

With the help of the other specifications and recommendations in TS 802 [3] standard, water and cement content selection was done to achieve to a slump target of 150 ± 10 mm. Concrete mix composition for all series is given in Table 3.7.

Table 3.7. Concrete mix composition for all series

	NA45	RA45	NA70	RA70	50RA45	75RA45	50RA70	75RA70
NA 4-8mm	241	0	258	0	192	97	206	104
NA 8-16mm	407	0	436	0	163	82	174	88
NA 16-25mm	426	0	456	0	170	86	182	92
RA 4-8mm	0	230	0	246	192	292	206	312
RA 8-16mm	0	389	0	416	163	247	174	264
RA 16-25mm	0	407	0	435	170	258	182	276
Sand	333	318	357	341	326	330	349	344
Crushed Sand	444	425	475	454	434	439	465	459
Slag	174	174	112	112	174	174	112	112
Cement	261	261	168	168	261	261	168	168
Water	180	180	180	180	180	180	180	180
SP	4.79	9.40	3.08	4.96	7.73	8.69	3.88	4.61

3.3.3. Concrete Mixture Design

Concrete mixture for this study were all designed according to TS 802 [3]. In this phase, concrete mix design was conducted for eight different mixtures.

3.3.4. 1st Stage Production

In the first stage of this study, aggregate tests for both natural and recycled aggregates are conducted as described in previous sections. Production of natural and recycled aggregates concrete are done. Two water-to-cement ratios and four different replacement ratios (0, 50, 75, 100) are selected.

3.3.5. 2nd Stage Production

In the 2nd stage of this study, surface treatment methods are applied to enhance surface characteristics of recycled aggregates. In this stage, a method inspired from other studies in literature is conducted. When surface treatment is searched in literature, there are many different types of studies. Surface treatment in this study is based on changing concrete mixing procedure. Recycled aggregates are composite materials and more like concrete rather than natural aggregates. Since recycled aggregates are extracted from bigger concrete blocks, till they are downsized, they experience many destructive forces which influence all integrity of these materials. Recycled aggregates have attached old mortars that have many cracks and voids. In this stage, rehabilitating these cracks and voids is targeted.

Method used for coating in this stage of the study mainly originates from a study of Tam et. al [25] called two stage mixing approach. A modified version of this two-stage mixing method gels up the recycled aggregates with cement slurry with the half of the cement and half of the water that has to be originally used in concrete mixture recipe. In this study, ground granulated blast furnace slag is used for slurry.

Before mixing procedure, half of the ground granulated blast furnace slag is mixed with half of the mix water creating a slag slurry in another bucket with the help of stirrer motor that can be viewed in Figure 3.8.



Figure 3.8. Stirring of slag slurry.

In the second phase of the mixing procedure, coarse aggregates in the mixer tank are dry mixed and then slag slurry that has enough fluidity is poured on those aggregates in 60 seconds and mixing continues for 60 seconds more. Then recycled aggregates are accepted as slurry coated aggregates that can be viewed in Figure 3.9. Afterwards, fine aggregates and cement are added to mix and remaining water is added in 60 seconds period. Finally, all ingredients are mixed for 60 seconds more. Illustrated expression of this procedure may be viewed from Figure 3.10.

3.4. Bacteria Surface Treatment

Recycled aggregates have surface deficiencies that should be dealt with. Since biodeposition is used for rehabilitating concrete cracks and imperfections it may show promise when problems of recycled aggregates are considered.



Figure 3.9. Slurry coated aggregates

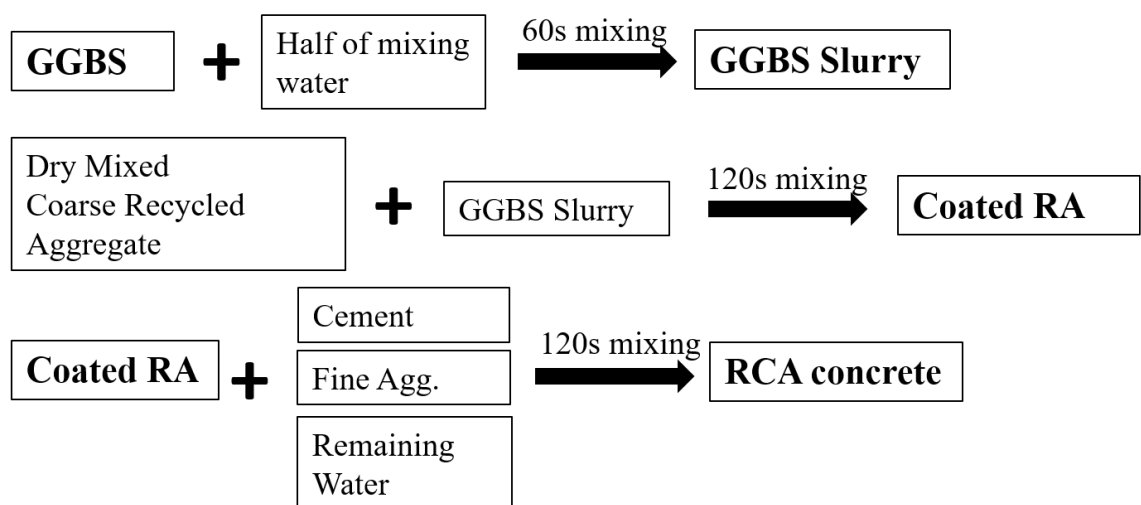


Figure 3.10. Application scheme of slurry method

In this stage of this study, biodeposition technique MICP, microbial induced calcium carbonate precipitation is adopted. *S. Pasteurii* cells were selected as they are resistant to both high pH and temperature. It is a common type of bacteria that can be found in soil showing high enzyme activity. It has endospore formation and also highly capable to precipitate CaCO_3 .

3.4.1. Microorganism Selection

Various microorganisms that can induce calcium carbonate precipitation are available. Microorganism to be selected should endure high pH conditions since concrete has highly alkaline environment. *S. pasteurii* is the most commonly used bacteria for biodeposition application in soil due to high intercellular urease enzyme activity and its alkaliphilic nature. *S. pasteurii* is a non-pathogenic microorganism that has endospore formation and highly capable to participate CaCO_3 . Furthermore, *S. pasteurii* cells have negative surface charge creating electrostatical attraction to dissolved calcium cations in the cement.

3.4.2. Growth of Microorganisms

Carbon, nitrogen and other nutrients are required to keep the microorganisms in active metabolic state. Urea and peptone are used nitrogen and carbon sources consecutively for *S. pasteurii* in MICCP applications.

Bacterial strain, *S. Pasteurii* was grown in urea peptone culture medium composed 20 g of urea, 20 g peptone, 5 g of NaCl per liter of distilled deionized water (DDI) with neutral pH of 7.0 ± 0.1 . 12 grams of agar was added to the medium when solid agar plates were needed. *S. Pasteurii* cells were injected in 400 mL urea-peptone culture media and were incubated with 190 rpm shaking conditions at 30 °C until the stationary growth period was reached. Stationary growth period initiates when rate of growth falls to zero.

Growth statistics were followed to better understand relation of the peak concentration of bacteria medium versus time. Growth data of bacteria medium was estimated from the solutions taken from these media and were placed on agar plates at each time interval and bacterial colonies were counted. One mL of sample was obtained every two hour and samples for plate counts were serially diluted ($10^0 - 10^{-7}$). Afterwards, they were vortexed to provide homogeneity. Growth curve batch experiments were conducted in triplicate. After several trials, peak concentration was observed as 24 hours after implantation. The cell concentrations were obtained by counts and represented as colony forming units per mL (CFU/mL).

3.4.3. Treatment of Recycled Aggregates

Treatment of recycled aggregates are applied by immersing aggregates into bacterial solutions formed. A liquid culture media of 1200 mL that consists of 24 g urea, 24 g peptone and 6 g NaCl is prepared. Following the injection of bacteria, solution is placed and kept in incubator with 190 rpm shaking conditions for 24 hours at 30 °C. Afterwards, bacteria cells were harvested by centrifuging the culture medium to obtain high concentrated cells which were washed by DI water and were used to resuspension in a new 1000 mL liquid culture media which includes 20 g urea, 20 g peptone and 5 g NaCl. New culture media is poured to 200 g of recycled aggregates which were dried at a temperature of 78 °C for 4h and consecutively left in humid room for 24 hours.

50g calcium nitrate ($Ca(NO_3)_2$), 20 g urea and also 100 mL DI water are added to recycled aggregates and left for 5 days in the damped room. Calcium nitrate is preferred to other types like calcium chloride, since it does not bear any risks (e.g. corrosion) for reinforced concrete structures. At the end of 5 days duration, solution is removed and aggregates are dried at 60 °C for 24 hours. As a result, surface treated recycled aggregates are obtained.

3.4.4. Water absorption and unit weight tests

Water absorption tests mentioned in Section 3.2.2 were also conducted on bacterial surface treated recycled aggregates. Picnometer method described in TS EN 1097-6 [49] standard is applied and results obtained are used for comparison of these treated aggregates to untreated ones. Since water absorption is one of the biggest deficiencies of recycled aggregates, limiting or at least decreasing this vulnerability will be helpful.

3.4.5. Optical Microscopy

Surface treated recycled aggregates are investigated in optical microscopy to inspect on extra layers occurred after the treatment. Microscopic investigations are conducted in order to comment on the effects of the layer on surface characteristics.

3.4.6. Scanning Electron Microscopy (SEM)

Scanning electron microscope equipped with energy dispersive X-ray analysis (SEM-EDX) examining primary and secondary mineral phases in pastes, pores, cracks and other microscopic details. With the help of SEM device, formations occurred on treated recycled aggregates are investigated deeply. Both untreated and treated specimens were compared.

Energy dispersive X-ray (EDS) analysis is also conducted. EDS is a spectroscope that identifies and counts the impinging X-rays based on their characteristic energy levels. EDS is extremely helpful when an unknown sample is considered. The electron microanalyzer provides a complete analysis of microscopic masses of solids through X-ray emission spectrometry and provides elemental X-ray images.

All ESEM-EDX analysis are conducted by Philips XL30 ESEM-FEG/EDAX system located in Boğaziçi University research and development center electron microscopy and microanalysis unit. Since recycled aggregates used for bacterial study are small

coarse aggregates (4-8 mm) before ESEM analysis there is no need to minimize aggregates. Eight treated and eight untreated recycled aggregates are prepared for examination. Since concrete is not a conductor material, in order to prevent blur images after bombardment of weak electrons onto the specimen a thin layer of gold coating is applied. Recycled aggregates are gold coated and prepared for examination. And the accelerating voltage is kept at different values (7, 10, 15, 50 kV) and observation distance was 10-15 mm at various magnifications.

3.4.7. Compressive Strength Tests

Bacterial surface treatment was applied on recycled aggregates to eliminate deficiencies hence they are to be used in structural concrete. Therefore, concrete containing treated recycled aggregates should endure higher compressive stresses so that compression tests are conducted on these specimens.

Bacteria treatment is conducted on recycled aggregates in relatively smaller amounts with respect to other concrete casting operations since bacteria treatments are done on 4-8 mm sized aggregates. Higher amount of surface treated aggregates were highly time and supply consuming for an initiative study like this. Consequently, smaller size 50 x 50 x 50 mm steel molds are preferred for concrete casting. Concrete mixture was designed as water: cement: coarse aggregate: sand = 1:2:2:2 and water amounts are designed with data acquired from water absorption tests. All ingredients are dry mixed for 60 seconds and consequently water added in 60 seconds period and finally all ingredients are mixed for an extra 60 seconds. Once the mixing process is complete, concrete was cast into a half height into molds on the vibration table and after vibrating for convenient duration concrete was cast into full height and vibration was applied again to be sure that air voids are not entrapped. Specimens were tested under 0.4 MPa/s compression stress in 7 and 28 days following the usual curing process in water tank.

3.5. Durability Tests

3.5.1. Freeze-Thaw Tests - Part I

Resistance of concrete to rapid freezing and thawing tests are conducted on specimens with recycled aggregates in changing amounts as prescribed in ASTM C666 [54]. Procedure A (rapid freezing and thawing in water) is preferred in this study out of two procedures given in standard. Tests are planned to have information in determining the effects of variations in concrete properties when resisting the freeze-thaw cycles.

Freeze-thaw apparatus shall consist of a chamber in which the specimens may be subjected to freezing-thawing cycles, together with the automatic control system including refrigerating and heating systems creating freeze-thaw cycles by its own. Freezing-thawing cycle shall provide lowering the temperature of specimens from 4 °C to -18 °C and raising it from -18 °C to 4 °C in 4 hours. Changes in weight and dynamic modulus of the specimens shall be measured within prescribed time intervals. Dynamic modulus of concrete prisms shall be measured with an electro-acoustical transducer which produces longitudinal vibrations when held in contact with the concrete under test.

For this study, triplicates of all 16 types of concrete mixture are cast into 75 x 100 x 400 mm steel molds and demolded after 24 hours and finally placed into water tank containing lime saturated water at 20 °C.

After 28 days of curing period, concrete prisms are weighed in saturated surface dry condition and noted as initial weight. Ultrasonic pulse testing of concrete is also done and marked as initial dynamic modulus of concrete. For every new measurement of weight and dynamic modulus of specimens a week's time which is equal to 42 cycles was predetermined. Every week all the prism specimens were taken out of the freeze-thaw cabinet and washed. Measurements of weight and dynamic modulus were done and placed back to cabinet which was restarted from where it was stopped. Also for visual comparisons specimens are photographed every week. Two measurement data

were collected for each specimen till deteriorations of the specimens are high (at least %60 of initial dynamic modulus) and taking new measurements were hard and instable. Subsequent to termination of first series, second series and third series specimens were also subjected to same procedure.

3.5.2. Freeze-Thaw Tests - Part II

Freeze-thaw test results obtained in the first part is used as preliminary findings in the second part for residual flexural strength tests. 16 different series of concrete prisms were subjected to freeze-thaw cycles in the same manner, however this time duplicates from different series of concrete prisms were taken out of cabinet but for mechanical testing. Preliminary two prisms of each series were directly cracked after curing and afterwards two prisms of each series of concrete were taken every week and subjected to flexural loading until failure and average maximum flexural strengths were recorded and this process continued till termination of the test.

Maximum number of weeks results that were previously determined in the first part of the freeze-thaw tests were used here for number of specimens to be tested for residual flexural strength determination tests. Thus a total of 58 prisms were cast for these tests.

3.6. Fatigue Testing

Plain concrete when subjected to repetitive loads, may show excessive cracking and in time they will fail after a number of load cycles although maximum loading stress is lower than static compressive strength. In this part of the study, two different water-to-cement ratio specimens both treated or untreated with different replacement levels are subjected to repetitive compressive loads.

For the experimental investigations, prismatic beam specimens were prepared with dimensions of 100x100x300 mm. Height to width ratio was chosen to be 3 to ensure unobstructed lateral deformation. This ratio was chosen by some fatigue studies

[55], [10], [56].

For concrete production, a 90-liter laboratory mixer was used. All mixing methodology was as used in previous tests. For every concrete casting, the fresh concrete quality, the slump, the fresh concrete density and air volume were checked.

All test specimens were casted into 100x100x500 mm prism molds by placing the concrete with shovels filled with two layers and each layer was compacted for 10 seconds on a vibrating table. After casting concrete specimens were stored and covered with PE foil to prevent moisture loss and specimens were demolded 24h subsequent to casting. Prismatic beam specimens were cured for 28 days and stored for 150 days before fatigue testing.

Before the experimental investigations, the specimens were cut to about 300 mm and the test surfaces were grounded till reaching plane-parallel position to provide the most uniform distribution of loading and stress possible. For each sample, the raw concrete density was determined prior to tests. Tests were carried out on specimens with a concrete age of 180 days whereby the experiments of the individual tests series were completed in two weeks' time in each case. Two different stress levels for fatigue loading is used for all testing. Fatigue stress level of 75 and 85 % were selected hence minimum stress level ratio was constant at 5 % of maximum static compressive strength.

3.6.1. Fatigue Tests

Uniaxial pressure tests were used without changing the load parameters during the test. The minimum stress ratio (S_{min}) was 5% for all specimens. The cyclic load applied was force-controlled for all tests. For every specimen middle load was calculated with the average of S_{max} and S_{min} values. Specimens were loaded to middle load. Specimens were loaded with a speed of 5 kN/s to middle load and then cyclic loading was initiated. Maximum and minimum test forces F_o and F_u were calculated from the average of the compressive strength which were determined from the quasi-

static tests. Average of the compressive strength were calculated from 3 specimens with the same geometry of the specimens subjected to fatigue tests.

Specimens were tested under MTS servo-hydraulic test machine with a capacity of 500 kN with a closed loop system.

Two strain gauges with a length of 80 mm are used to take longitudinal measurements were placed to record vertical strains on the specimen surfaces. Strain gauges were placed on opposite surfaces. Specimen surfaces were grinded prior to gluing application for better adherence with the specimen surface. Strain gauges were glued and left for at least 24h prior to testing. Strain gauges were connected by suitable wires to the data acquisition system that may record data in 1000 Hz.

Specimens were placed into the testing device with ensuring that specimen is placed properly. Specimens were loaded until midload and strains until this load were checked to see if stress is transferred uniformly to the specimen.

Specimens were loaded until midload and cyclic loadings were started with sine waveform and cycles were conducted with a loading speed of 10 Hz and with two different maximum stress ratio which are 75% and 85% whereas minimum stress ratio was 5% for all specimens and force command and actual force recorded were found to be as given in Figure 3.11. For each batch, three or more specimens were tested and given in Table 3.8.

Table 3.8. Number of specimens subjected to fatigue tests.

$S_{max} = 85\% - S_{min} = 5\%$				$S_{max} = 75\% - S_{min} = 5\%$			
NA45	5	NA70	5	NA45	5	NA70	5
50RA45	3	50RA70	3	50RA45	3	50RA70	3
75RA45	3	75RA70	3	75RA45	3	75RA70	3
RA45	5	RA70	5	RA45	5	RA70	5
RAT45	5	RAT70	5	RAT45	5	RAT70	5

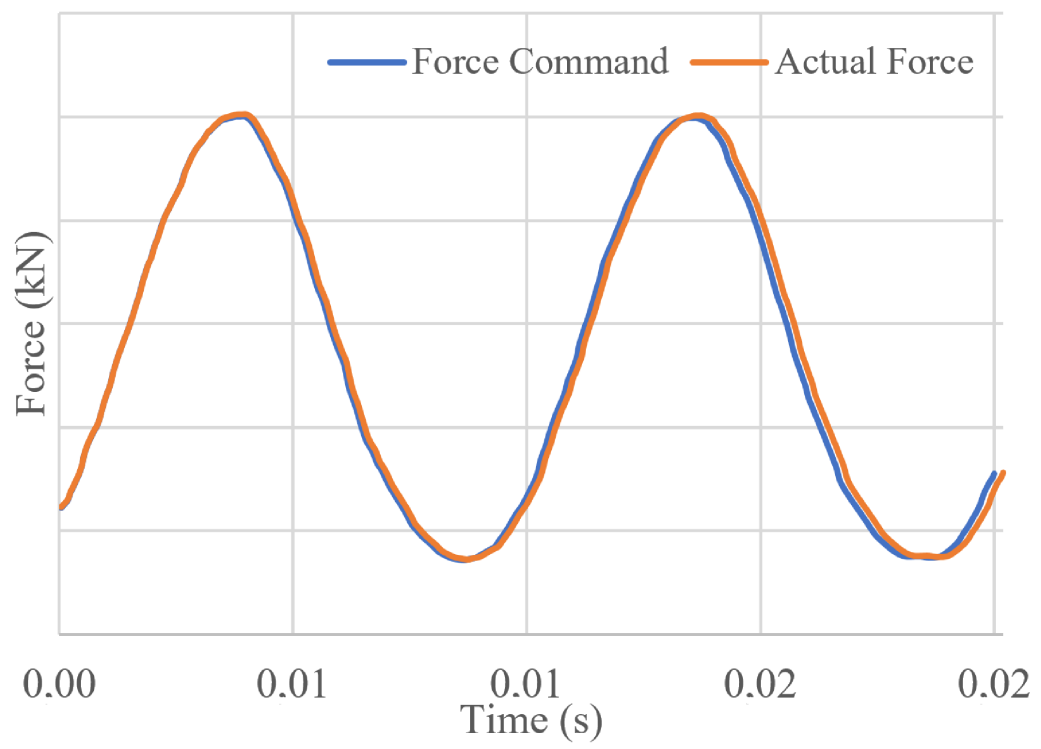


Figure 3.11. Sinus waveform applied in fatigue loading.

Same specimen types were used in previous sections. Two water-to-cement ratios and four different replacement levels were used for fatigue tests. Treated specimens with 100% replacement level were also used. Five prisms were crushed under cyclic loads for 0% and 100% replacement level specimens whereas 3 prisms were crushed for 50% and 75% specimens as given in Table 3.8. A total of 84 tests were conducted on 84 specimens and analysis were carried out.

Since number of cycles to failure may show scatter considerably. Specimens produced from same batches are used for all comparison within each specimen type to eliminate any influence of batches on the results.

4. RESULTS AND DISCUSSION

In this chapter, results of all tests explained in the previous section are given. Aggregate tests were conducted to compare recycled aggregates to natural aggregates prior to casting of concrete mixtures. Fresh concrete properties were assessed and slump values were compared for both concrete containing recycled aggregates and normal concrete in order to create mixes with similar slump values by adjusting the superplasticizer amount.

Compressive, flexural and splitting tensile strength tests were conducted on specimens including slurry treated specimens. Also specimens with biodeposition treatment were examined.

4.1. Aggregate Tests

Aggregate tests were conducted on coarse aggregates, for both recycled aggregates and natural aggregates which were also subjected to all tests to have better understanding of the deficiency that recycled aggregates involves. As mentioned before, source concrete of recycled aggregates was composed of aggregates that came from the same source as the natural aggregates that have been used throughout all the study. Since then there are two types of coarse aggregates used in the project.

Aggregates are subjected to tests to check if they are available for use in concrete that is planned to be used for structural purposes.

4.1.1. Aggregate Impact Value

Aggregates impact test results are given in Table 4.1. When test results are investigated individually, recycled aggregates are found to be available for use. Due to specifications given in BS 812 112 [57], aggregates impact results are found to be 11.25% for natural aggregates whereas 18.25 for recycled aggregates. Since recycled aggregates

have old mortar attached on them, impact strokes crushed more from the original piece compared to natural aggregates. Six different batches from both natural aggregates and recycled aggregates were subjected to impact loadings with the same apparatus under laboratory conditions. When results are statistically compared, it was seen that standard deviation of the natural aggregates samples were smaller with respect to recycled aggregates. This result was most probably linked to composite structure of the recycled aggregates that have both natural aggregate and old mortar attached on the specimens. If recycled aggregates are visually inspected individually, one can easily see that percentage of natural aggregate and old mortar attached are not the same for each aggregate particle. In several batches, it is highly logical to see such differences within batches when aggregates are randomly selected. Aggregate impact values may be viewed from Table 4.1. When all specimens are considered together, standard deviation was high with respect to natural aggregate batches standard deviation. The toughness of the aggregates is determined using the aggregate impact value. Lower impact value implies higher toughness of the material [58].

Table 4.1. Aggregate impact value test results

	Impact Value (%)	
	Natural	Recycled
Batch #1	10.23	17.34
Batch #2	9.92	13.99
Batch #3	12.81	20.64
Batch #4	12.76	21.95
Batch #5	11.61	14.52
Batch #6	9.98	21.06
Std. Dev.	1.24	3.28
Average	11.22	18.25

4.1.2. Aggregate Crushing Value

Crushing value of aggregates to be used in structural concrete is significant since strength of aggregates may influence the overall capacity of concrete incorporating those aggregates. Crushing value tests were conducted according to BS 812-110 [52] as prescribed in Section 3.2.4. Aggregate crushing values may be viewed from Table 4.2. Recycled aggregates mean crushing value were found to be %21.54 whereas Li *et al.* [28] had similar conditions and produced from laboratory made concrete by using both jaw crusher and consequently impact crusher. Researchers reported aggregate crushing value result was found to be 20 %. In the same study, when concrete blocks were crushed only by jaw crusher, ACV was found to be 27 %.

Results of the crushing value stated that both natural and recycled aggregates were available for use in concrete. When crushing value of both natural and recycled aggregates were compared, it is obvious that recycled aggregates had higher values than natural aggregates as expected. If ACV results are compared statistically, as in the impact value (AIV) results, standard deviation of recycled aggregate samples are higher. This increase in standard deviation may easily be connected to differences of mortar proportions that every individual recycled aggregate involves.

If sample values are inspected individually, one can say that first batch of recycled aggregates might consist of samples that have less old mortar content provided that its crushing value is very close to natural aggregate results.

4.1.3. Aggregate Flakiness Index

Flakiness of aggregates are of extreme significance when used in concrete since provided that recycled aggregates are composite materials, they display different behavior under crushing process with respect to natural aggregates. Shape of aggregates in concrete may conform to standard EN 933-3 [50], with this intention tests are conducted on coarse recycled and natural aggregates to check their availability for use in structural concrete. 6 different batches were collected from different parts of the

Table 4.2. Aggregate crushing value (ACV) results

	Crushing Value (%)	
	Natural Aggregates	Recycled Aggregates
Batch #1	13.45	16.78
Batch #2	15.04	25.81
Batch #3	17.36	18.1
Batch #4	17.45	23.12
Batch #5	16.16	17.95
Batch #6	14.96	27.45
Std. Dev.	1.42	4.14
Average	15.74	21.54

aggregate stocks and tests were conducted to see the mean and deviations.

Flakiness of aggregates is generally based on crusher type used in production phase. In this study, similar processes and especially same crushers were facilitated to see the effects rather than geometrical deficiencies caused by the basic simple crushers that are being used to crush recycled aggregates. When results are analyzed, differences between flakiness indices are less with respect to other aggregates test since shape of the aggregates are mainly related to the crushing process. Recycled aggregates showed higher indices that may be linked to their composite structure. When recycled aggregates are investigated after crushing process, especially aggregates that have bigger aggregates from source concrete are most likely to crush from mortar-aggregate interface releasing the natural aggregate part into outer surface of the newly formed recycled aggregate (Table 4.3).

4.1.4. Aggregate Water Absorption and Unit Weight

Water absorption capacities of aggregates are extremely important for concrete production. Proper determination of water absorption will contribute to better results

Table 4.3. Flakiness Index Test Results

	Flakiness Index (%)	
	Natural Aggregates	Recycled Aggregates
Batch #1	3.97	5.72
Batch #2	4.42	5.64
Batch #3	4.35	6.57
Batch #4	5.36	6.76
Batch #5	4.63	6.42
Batch #6	4.68	7.48
Std. Dev.	0.42	0.63

in both durability and mechanical properties of concrete.

Recycled aggregates due to their structural composition are prone to water absorption and if they are to be used in structural concrete, it has to be dealt carefully. Water absorption and unit weight tests are conducted simultaneously as prescribed in TS EN 1097-6 [49]. Picnometer method was selected to test specimens that have maximum diameter sizes between 4-25 mm. As described in experimental study section, specimens were screened in different diameter sizes (4-8, 8-16, 16-25 mm). Water absorption studies were conducted for both natural and recycled aggregates in different size groups so in that manner, effect of aggregate sizes on water absorption and unit weight were also investigated. Five batches from all specimen sizes from both natural and recycled aggregates were subjected to tests simultaneously under same laboratory conditions. Water absorption results of natural and recycled aggregates according to diameter sizes are given in Table 4.4 and Table 4.5, respectively.

Natural aggregate specimens had grand mean of 1.21 % whereas recycled aggregate specimens had 4.88%. The water absorption capacity of recycled aggregates is higher than that of normal aggregates as they contain adhered cement paste which may absorb high amounts of water. Variation of water absorption capacity found in

Table 4.4. Water absorption results of natural aggregates

	Results	Means	Grand Mean
NA 4-8mm Set #1	1,28%	1,27%	1,21%
NA 4-8mm Set #2	1,31%		
NA 4-8mm Set #3	1,21%		
NA 8-16mm Set#1	1,21%	1,19%	
NA 8-16mm Set#2	1,19%		
NA 8-16mm Set#3	1,16%		
NA 16-25mm Set#1	1,14%	1,16%	
NA 16-25mm Set#2	1,16%		
NA 16-25mm Set#3	1,19%		

Table 4.5. Water absorption results of recycled aggregates

	Results	Means	Grand Mean
RA 4-8mm Set #1	5.12%	5,12%	4.88%
RA 4-8mm Set #2	5.21%		
RA 4-8mm Set #3	5.02%		
RA 8-16mm Set#1	4.82%	4.83%	
RA 8-16mm Set#2	4.64%		
RA 8-16mm Set#3	5.02%		
RA 16-25mm Set#1	4.67%		
RA 16-25mm Set#3	4.65%		

different specimen sets is due to the variation of cement paste content on aggregates due to different diameter sizes. Aggregates that contain higher amount of attached mortar on had more absorption capacity. Smaller sized specimens were found to have higher absorption capacity with respect to bigger diameter sizes.

Table 4.6. Density of natural aggregates (kg/m³).

	Results	Means	Grand Mean
NA 4-8mm Set #1	2775	2767	2764
NA 4-8mm Set #2	2755		
NA 4-8mm Set #3	2771		
NA 8-16mm Set#1	2778	2761	
NA 8-16mm Set#2	2755		
NA 8-16mm Set#3	2750		
NA 16-25mm Set#1	2759	2763	
NA 16-25mm Set#2	2765		
NA 16-25mm Set#3	2765		

As seen in Tables 4.6 and 4.7, density of recycled aggregates is lower than that of natural aggregates. This is principally caused by the porous and less dense cement paste on the recycled aggregates structure. Densities of recycled aggregates may differ depending on the attached mortar content and that may be why density varied with aggregate diameter size. Smaller size specimens were found to have lower density. This may be related to higher cement content on smaller size specimens.

4.2. Fresh Concrete Properties

Concrete mixture design was done according to specifications given in experimental study and concrete was cast by the help of a laboratory mixer. When casting concrete, fresh concrete tests were conducted to have preliminary information on the specimens. Slump tests, fresh state unit weight and air content determination tests were conducted and noted.

Table 4.7. Density of recycled aggregates (kg/m³).

	Results	Means	Grand Mean
RA 4-8mm Set #1	2452	2452	2522
RA 4-8mm Set #2	2421		
RA 4-8mm Set #3	2484		
RA 8-16mm Set#1	2571	2539	
RA 8-16mm Set#2	2515		
RA 8-16mm Set#3	2531		
RA 16-25mm Set#1	2558	2576	
RA 16-25mm Set#2	2579		
RA 16-25mm Set#3	2591		

4.2.1. Workability

Prior to determining the concrete mixture compositions, preliminary concrete casts were done to have information on slump values of specimens to create mixes that show similar slump values that is how the superplasticizer ratios were decided. For this study, a slump value of 140 mm was targeted for all mixtures.

In order to maintain the target slump values, trials were conducted for all mixtures. In trial mixes, when slump value was found lower than the target value, the superplasticizer amount was increased or vice versa. Finding superplasticizer amount for natural aggregates were relatively easier. Since recycled aggregate specimen had various porosity values for each mix, several batches were cast to decide on the average amount of superplasticizer for each series. Average of the results were taken to have better optimization of the superplasticizer amount. In Figure 4.1, superplasticizer to binder amount ratios are given for 4 different replacement levels (0, 50, 75, 100 %) and for 2 water-to-cement ratios (0.45 and 0.70).

When Figure 4.1 is examined, it may be seen that with the increasing replacement level superplasticizer amount increases since higher amount of recycled aggregates lead to higher water loss in the mix water. When effect of water-to-cement ratio is assessed, it is seen that with the increasing replacement level increase in the superplasticizer amount was seen to be higher for lower water-to-cement ratio specimens. Also it may be noted that lower water-to-cement ratio specimens had 37% higher slope with respect to higher water-to-cement ratio specimens.

Unit weight of concrete mixtures in fresh state were also taken and given in Figure 4.2 to compare the results. With increasing replacement level of recycled aggregates, decrease in unit weight results are seen since recycled aggregates have lower unit weight than natural aggregates. There was no significant effect of water-to-cement ratio observed. Highest decrease was seen at 100 % replacement level for both water-to-cement ratios. RA45 specimens had 4.82% decrease in unit weight whereas RA70 specimens had 4.02 %.

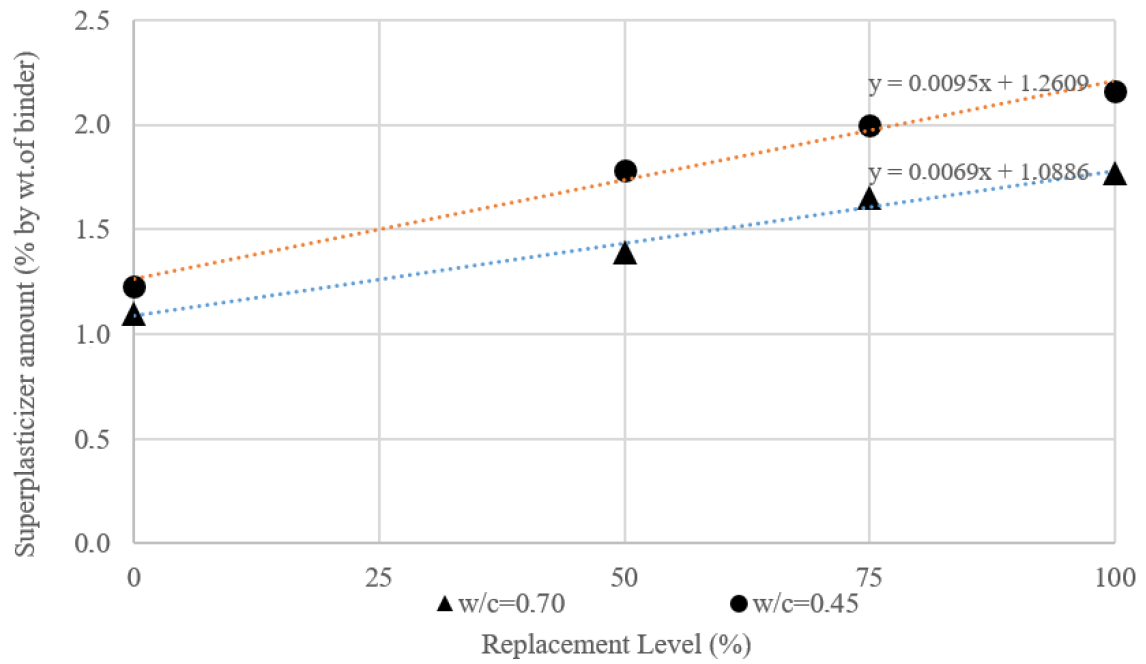


Figure 4.1. Superplasticizer to binder ratio for both water-to-cement with the increasing replacement level.

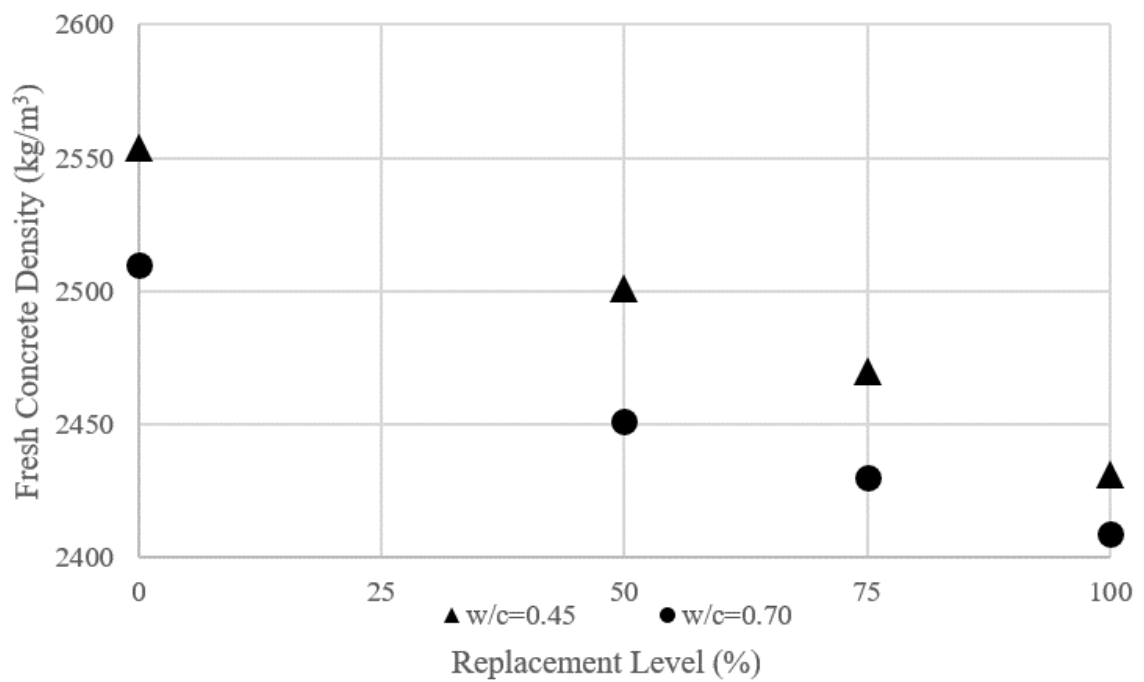


Figure 4.2. Fresh state unit weight with increasing replacement level.

4.2.2. Air content

Air content of each mix was also determined by the apparatus and prescriptions given in TS EN 12350-7. Air content determination of specimens was also efficient to check if the newly designed concrete mixture recipe supplied a satisfactory packed formation. Recycled aggregate concretes exhibited higher amount of air content with respect to natural concrete. Air content increased with the increasing amount of recycled aggregates as can be viewed From Figure 4.3.

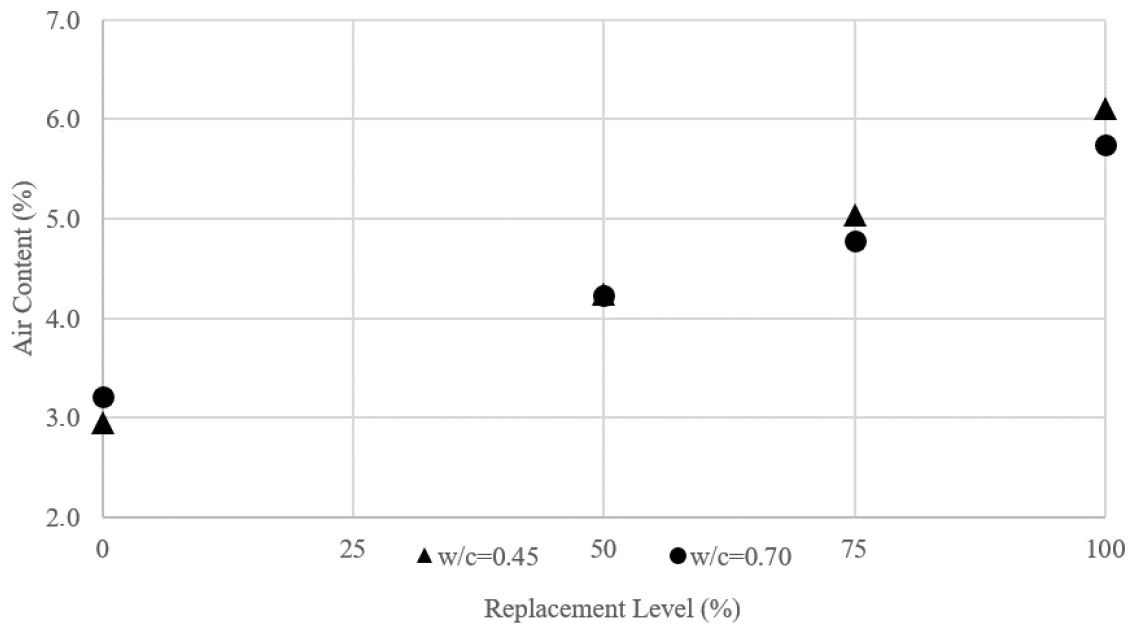


Figure 4.3. Fresh state unit weight with increasing replacement level.

Increase in air content with the replacement level also differed due to water-to-cement ratio. Natural aggregate 0.45 water-to-cement ratio specimens had 44, 71, 107% increase when 50, 75, 100 % replacement levels were supplied respectively. Amount of increase was limited for higher water-to-cement ratio. 0.70 water-to-cement ratio specimens had 32, 49 and 79% increase when 50, 75, 100 % replacement level was conducted. When results were compared with the other studies in literature, it may be said that these values were relatively low which may be attributed to good proportioning of the materials when designing the mixes [34].

4.3. Hardened Concrete Properties

Hardened concrete tests were done according to details given in experimental study. In this study, there were two water-to-cement ratios (0.45 and 0.70) and four replacement levels. There were eight different types of concrete cast which mechanical performance tests were conducted to clarify the effects of replacement level with different new mortar quality.

4.3.1. Compressive Strength Analysis

Compressive strength analysis on eight different mixes are conducted on 100x200 mm cylindrical specimens. Differences in compressive strength results are examined and results are discussed throughout this chapter.

Compressive strength tests are done under uniaxial compression loading in MTS servo hydraulic closed loop system. Cylindrical specimens are loaded until crushing under a force-controlled loading increasing with a 4.8kN/sec loading rate. During compressive strength test, longitudinal deformations were also measured by the help of a compression ring system with two LVDTs for the purpose of calculating the modulus of elasticity.

Compressive strength tests were done on 2,7 and 28 days. Three specimens for 2 day and 7-day and 5 specimens for 28-day specimens were crushed. Test results may be seen from Tables 4.8 and 4.9.

When compressive strength results are compared, effect of replacement ratio may easily be seen for both water-to-cement ratios. Compressive strengths of concretes containing different levels of recycled aggregate concrete normalized with compressive strength of concrete containing only natural aggregates are given in Figure 4.4.

In Figure 4.4, normalized compressive strength test results may be viewed for concrete with 0.70 water-to-cement ratio. For this water-to-cement ratio specimens,

Table 4.8. Compressive strength test results for w/c=0.70 specimens.

				Compressive Strength (MPa)			
NA	RA	W/C	ID	2-day	7-day	28-day	90-day
100%	0%	0.70	NA70	10.34	15.11	21.57	23.51
50%	50%	0.70	50RA70	10.07	14.56	19.16	20.55
25%	75%	0.70	75RA70	09.85	14.02	18.21	19.96
0%	100%	0.70	RA70	09.58	13.84	17.71	19.21

Table 4.9. Compressive strength test results for w/c=0.45 specimens.

				Compressive Strength (MPa)			
NA	RA	W/C	ID	2-day	7-day	28-day	90-day
100%	0%	0.45	NA45	19.37	25.75	36.80	40.85
50%	50%	0.45	50RA45	17.31	23.76	32.68	35.45
25%	75%	0.45	75RA45	16.35	21.85	30.55	32.21
0%	100%	0.45	RA45	16.06	20.88	28.82	30.76

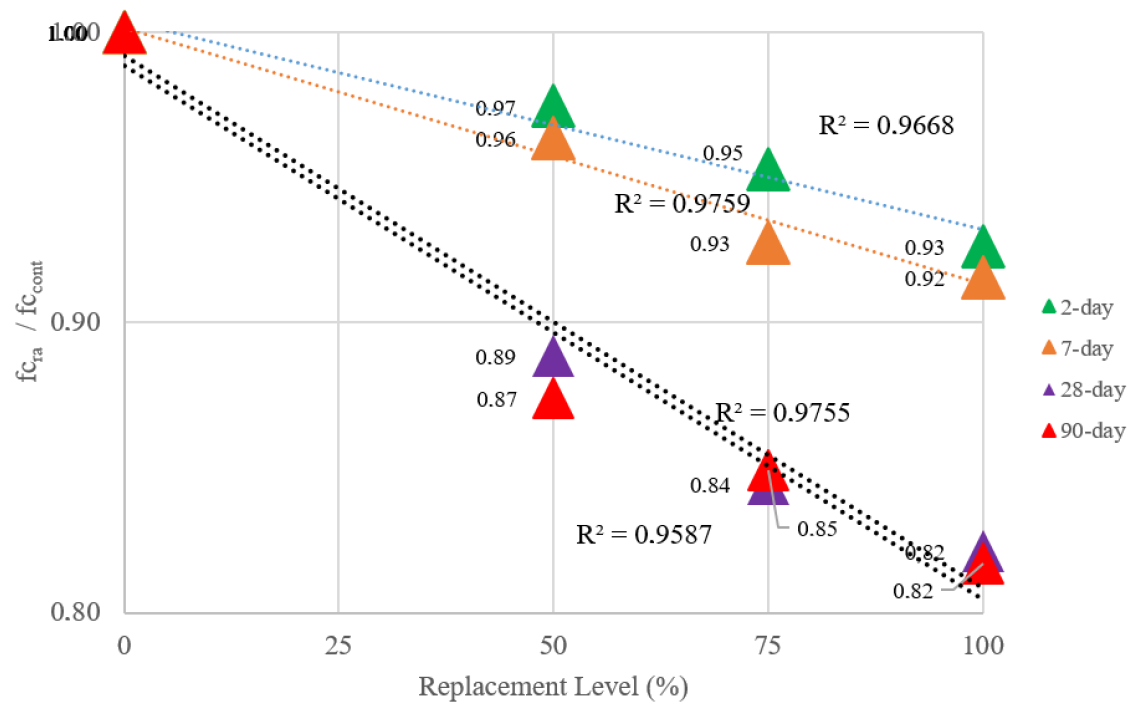


Figure 4.4. Compressive Strength Test Results Normalized with conventional concrete results ($w/c = 0.70$)

concrete containing recycled aggregates showed less compressive strength as expected. If curing period is assessed, it is seen that 2 and 7 days results showed less decrease with respect to 28 and 90-day results. For 50% addition of recycled aggregates into mix showed negligible decrease for 2 and 7-day results however after replacement at higher levels its effect on compressive strength gained significance. When R^2 values of 2 and 7-day results are inspected, it is clear that increase of replacement level attributed to a certain decrease in compressive strength. Since concrete strength is generally referred as 28-day concrete strength, 5 specimens were used to create a bigger sample size for better determination. If 28-day strength results are investigated, full replacement of coarse recycled aggregates caused a 18% decrease in compressive strength.

When Figure 4.4 is examined, normalized values of 90-day and 28-day values are very similar to each other which is expected. If Tables 4.8 and 4.9 are investigated, increase after 28 days of curing are limited and especially recycled aggregate specimens showed less increase till 90 days. R^2 values show that 90-day results are slightly lower than 28-day results.

In Figure 4.5, normalized compressive strength test results may be viewed for concrete with 0.45 water-to-cement ratio. For this water-to-cement ratio specimens, concrete containing recycled aggregates also showed less compressive strength as expected. If curing period 2 and 7-day are examined, compressive strength is 17% and 19% less than conventional concrete at the same curing period for full replacement level whereas these values were only 7% and 8% for higher water-to-cement ratio specimens. R^2 values for the trendline of decreasing compressive strength with increasing replacement level is higher than 95%.

When water-to-cement ratio effect on earlier compressive strength is analyzed, it is seen that for higher water-to-cement ratio specimens earlier strengths (2 and 7 days) were not much influenced however, low water-to-cement ratio specimens experienced higher losses with the increasing replacement level. Since in the early days higher water-to-cement ratio specimens have low new mortar strength which may not be higher than adhered mortar strength which is the most probable cause of failure for

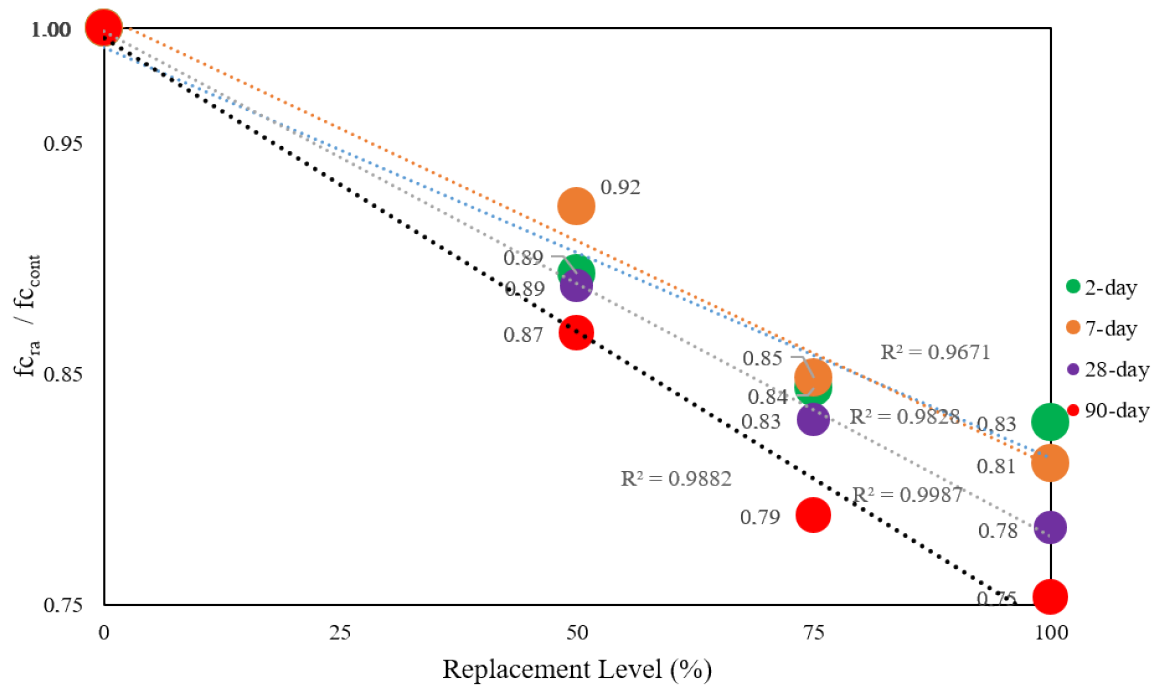


Figure 4.5. Compressive Strength Test Results Normalized with conventional concrete results ($w/c = 0.45$)

mixes containing recycled aggregates, this may have caused the natural specimens to fail under closer stresses to recycled aggregate concrete specimens failed. However, lower water-to-cement ratio specimens may have higher earlier new mortar strength than the adhered mortar on the recycled aggregates.

28-day compressive strength of samples seems to be highly affected by the increasing replacement level. 22% percent decrease in compressive strength after full replacement of coarse aggregates from natural to recycled aggregates. Increase after 28-day period to 90-day period is highly limited in recycled aggregate concretes since concrete containing natural aggregates showed an increase of 11% in this period whereas concrete containing 100% coarse recycled aggregates showed an increase only 6%. R^2 values for these findings is also all above 90%.

When water-to-cement ratio effect on increasing replacement level is analyzed, first point to emphasize should be that lower water-to-cement ratio specimen is more prone to increasing recycled aggregate replacement level. Failure mechanism is most probably about interface mechanisms which are more complicated with respect to conventional concrete that has only one interface between aggregate and mortar. Conversely concrete containing recycled aggregates has more than once interfacial transition zone;

- (i) ITZ between old mortar and old aggregates
- (ii) ITZ between old mortar and new mortar
- (iii) ITZ between new mortar and new aggregates
- (iv) ITZ between new mortar and old aggregates

Source concrete has compressive strength of 20 MPa that is close to specimens with $w/c = 0.70$. Also same natural aggregates were used in both concrete, moreover, recipes of source concrete and $w/c = 0.70$ specimens were very similar to each other. On the other hand, source concrete was ready-mixed concrete whereas concrete with $w/c = 0.70$ were laboratory made. This similarity between old mortar and new mortar might have enhanced the connection between the mortars. Since recycled aggregate concrete

consists of more than one mortar, it may be considered as a composite material that is to fail from its weaker portion when loaded. Due to this fact, recycled concrete aggregates with lower water-to-cement ratio exhibited higher decrease when replacement level was increased.

4.3.2. Modulus of Elasticity

Modulus of elasticity was measured under force-controlled uniaxial compression loading. Since concrete containing recycled aggregates unlike conventional concrete has more than one interface mechanism, modulus of elasticity is suspected to be highly affected from this phenomenon.

Average results of modulus of elasticity is given in Table 4.10 and Table 4.11 for both water-to-cement ratios.

Table 4.10. Modulus of elasticity results for $w/c=0.70$ specimens

				Modulus of Elasticity (MPa)			
NA	RA	W/C	ID	2-day	7-day	28-day	90-day
100%	0%	0.70	NA70	13885	20027	24451	25421
50%	50%	0.70	50RA70	12904	19072	20801	21768
25%	75%	0.70	75RA70	12950	18155	19802	19988
0%	100%	0.70	RA70	12543	17850	18566	18900

Modulus of elasticity results of concretes containing recycled aggregates are normalized with the modulus of elasticity values of natural concretes and given in Figures 4.6 and 4.7.

If specimens with 0.70 water-to-cement ratio are compared, it can be easily said that especially 28 and 90-day results are highly different from early strength results as it was for compressive strength analysis. Modulus of elasticity decreased with the increasing replacement level and at 100% replacement of coarse aggregates, modulus

Table 4.11. Modulus of elasticity results for w/c=0.45 specimens

NA	RA	W/C	ID	Modulus of Elasticity (MPa)			
				2-day	7-day	28-day	90-day
100%	0%	0.45	NA45	18269	24843	29244	29591
50%	50%	0.45	50RA45	17066	23597	24589	25012
25%	75%	0.45	75RA45	16455	22889	22993	22880
0%	100%	0.45	RA45	16166	22680	20388	21088

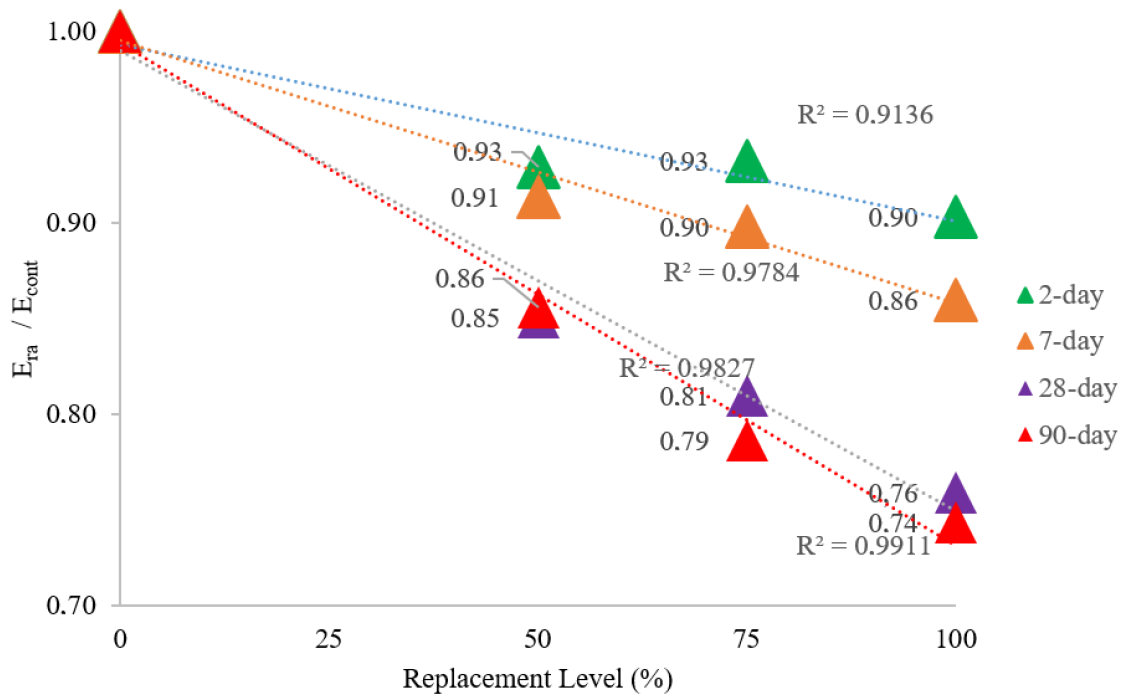


Figure 4.6. Modulus of elasticity test results normalized with conventional concrete results (w/c =0.70)

of elasticity decreased 24% at 28 days. If 50% values are inspected, a loss of 15% is seen, when used for structural purposes this may be a tolerated level of loss.

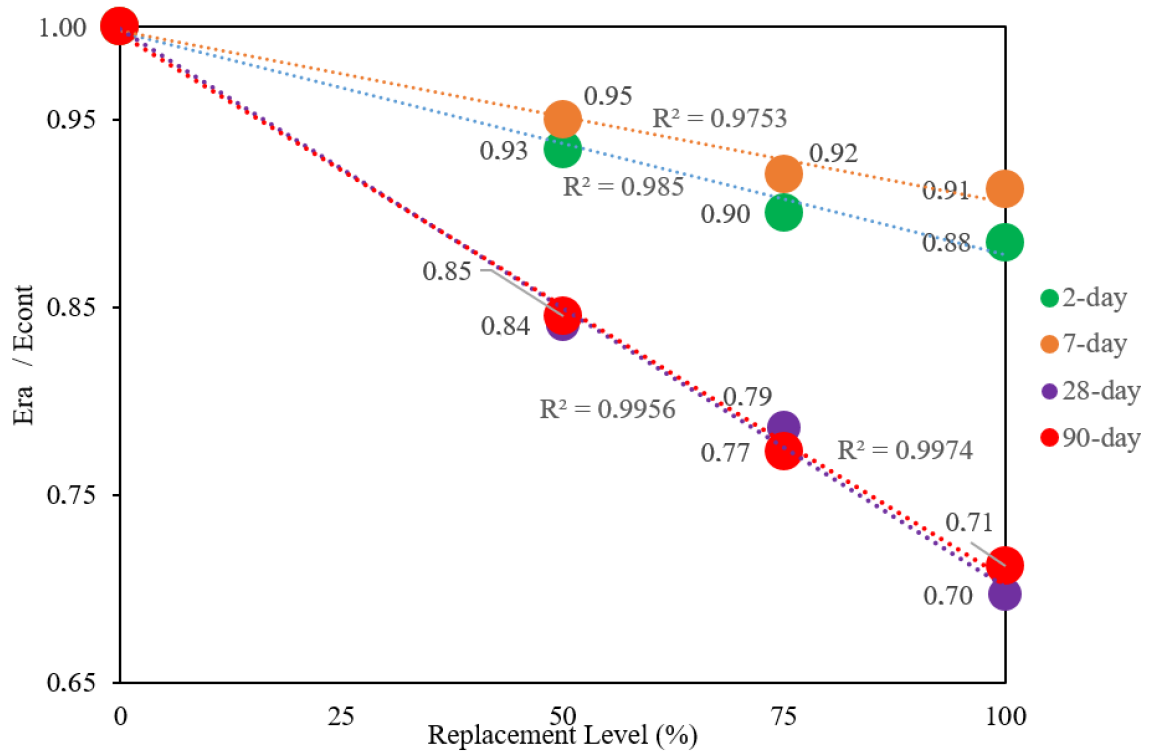


Figure 4.7. Modulus of elasticity test results normalized with conventional concrete results ($w/c = 0.45$)

When 0.45 water-to-cement ratio specimens are viewed (Figure 4.7), it can be said that decrease in modulus of elasticity is higher for higher quality specimens as it was for compressive strength. Interfacial transition zone occurring between aggregates and mortar seems to be more affected from this. Concrete containing recycled aggregates have more than one interfacial transition zone and one of them is cast and formed before the new mix which means it does not depend on new concrete quality. Surely that does not mean that if quality of the new and the source concrete of the recycled aggregates concrete are closer, then there will be no decrease in the modulus. Since natural aggregates are plain materials that does not contain any bonding or composite behavior, their effect in concrete is highly different than recycled aggregates. Decrease in early strength values are relatively lower with respect to 28 and 90-day results

contradictory to compressive strength results which may be attributed to different mechanisms when elasticity of recycled aggregate concrete is concerned. Since concrete containing recycled aggregate has interior cracks, they do less elastic deformation with respect to natural concrete. For 28 and 90-day results, decrease in elasticity with increasing replacement level are nearly the same. Loss of elasticity modulus for 50% replacement level is 15% for both 28 and 90-day results which is similar with the losses in lower water-to-cement ratio specimens. So for this replacement level regardless of concrete quality, similar losses were monitored.

4.3.3. Splitting Tensile Strength

Splitting tensile analysis were also done on specimens with 2 different water-to-cement ratios and four replacement levels. Decreases with increasing replacement level were monitored and behaviors of different concrete qualities were analyzed.

Table 4.12. Splitting tensile strength test results for w/c=0.70 specimens

				Splitting Tensile Strength (MPa)			
NA	RA	W/C	ID	2-day	7-day	28-day	90-day
100%	0%	0.7	NA70	0.82	1.72	2.94	3.09
50%	50%	0.7	50RA70	0.8	1.63	2.77	2.95
25%	75%	0.7	75RA70	0.76	1.56	2.58	2.72
0%	100%	0.7	RA70	0.74	1.54	2.53	2.61

Table 4.13. Splitting tensile strength test results for w/c=0.45 specimens

				Splitting Tensile Strength (MPa)			
NA	RA	W/C	ID	2-day	7-day	28-day	90-day
100%	0%	0.45	NA45	1.39	2.88	3.93	4.21
50%	50%	0.45	50RA45	1.26	2.68	3.62	3.77
25%	75%	0.45	75RA45	1.22	2.62	3.31	3.44
0%	100%	0.45	RA45	1.2	2.6	3.2	3.38

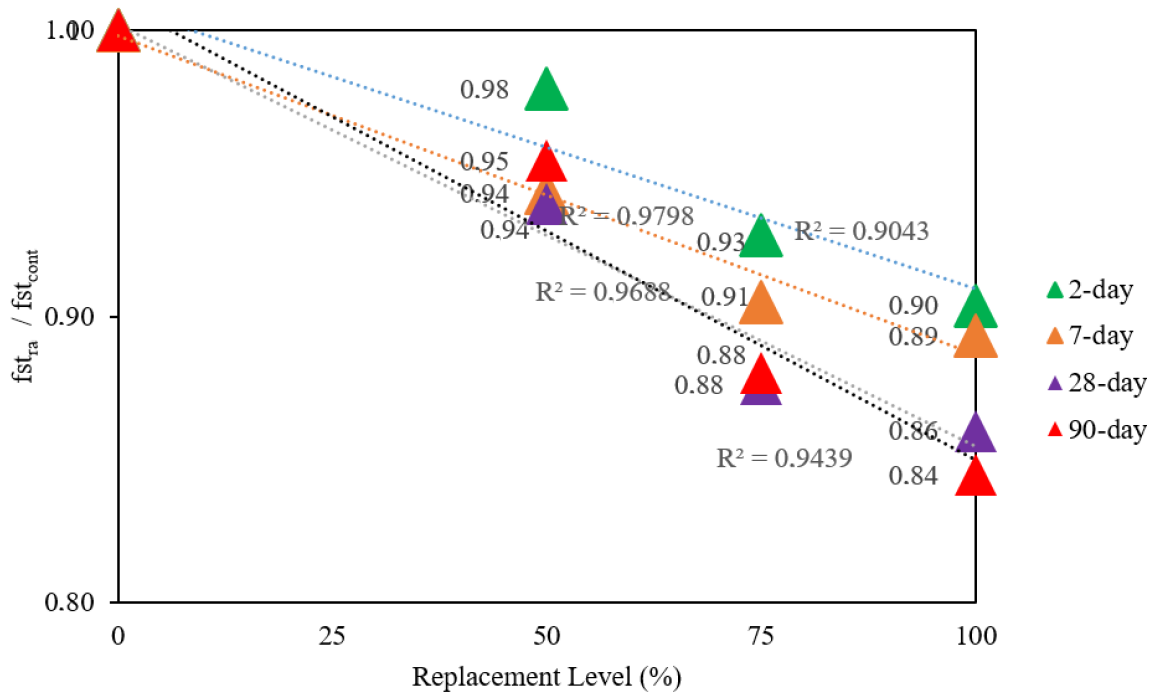


Figure 4.8. Splitting tensile strength test results normalized with conventional concrete results ($w/c = 0.70$)

Splitting tensile strength values may be viewed from Tables 4.12 and 4.13 for both water-to-cement ratio concrete specimens. Figure 4.8 and 4.9 are also given to exhibit the decrease in splitting tensile strength with increasing recycled aggregate in normalized values. When Figure 4.8 is viewed, all specimens with $w/c = 0.70$ showed decrease in splitting tensile strength as expected. In early periods, effect of recycled aggregate addition was less with respect to 28 and 90-day results. It is mainly related to newly strengthening of the matrix structure since differences between old mortar quality and new mortar quality was not much. That phenomenon may also be proved with the differences of decreases between two different water-to-cement ratios. R^2 values of splitting tensile tests are relatively low with respect to compressive strength values.

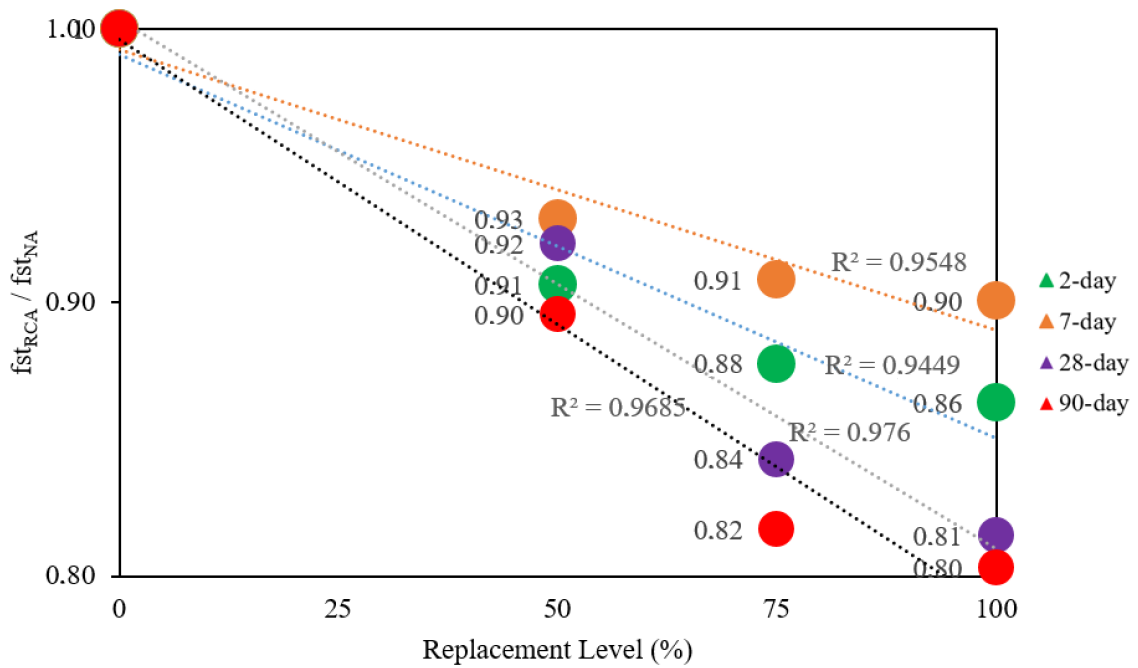


Figure 4.9. Splitting tensile strength test results normalized with conventional concrete results ($w/c = 0.45$)

Splitting tensile test results normalized with conventional concrete test results can be viewed in Figure 4.9. For both concrete qualities it is easy to say that early concrete strengths showed less decrease with respect to 28 and 90-day results. For $w/c = 0.45$ specimens, the decrease in splitting tensile strength for 28-day specimens

are 20% whereas it is 14% for higher water-to-cement ratio specimens. That difference is relatively small when same difference was analyzed for compressive strength. Since recycled aggregate concrete has more than one interfacial zone, tensile forces may be affecting the overall specimen integrity less with respect to compressive forces. Tensile forces inhibiting the disintegration may be more influenced with the surface texture of recycled aggregates which delayed the crushing of the concrete.

4.3.4. Flexural Tensile Strength

Flexural tensile tests were conducted on all 8 mixes and results are given in Table 4.14 and Table 4.15.

Table 4.14. Flexural tensile strength results for w/c=0.70 specimens

NA	RA	W/C	ID	Modulus of Rupture (MPa)			
				2-day	7-day	28-day	90-day
100%	0%	0.7	NA70	1.27	3.09	4.34	4.67
50%	50%	0.7	50RA70	1.22	2.78	4.03	4.22
25%	75%	0.7	75RA70	1.2	2.69	3.7	3.88
0%	100%	0.7	RA70	1.17	2.63	3.45	3.59

Table 4.15. Flexural tensile strength results for w/c=0.45 specimens

NA	RA	W/C	ID	Modulus of Rupture (MPa)			
				2-day	7-day	28-day	90-day
100%	0%	0.45	NA45	1.95	3.94	6.37	6.87
50%	50%	0.45	50RA45	1.83	3.71	5.81	5.89
25%	75%	0.45	75RA45	1.75	3.51	5.52	5.57
0%	100%	0.45	RA45	1.68	3.34	5.31	5.51

Flexure tests results are normalized with conventional concrete and may be viewed in Figure 4.10 and Figure 4.11 for w/c=0.70 and w/c=0.45 respectively.

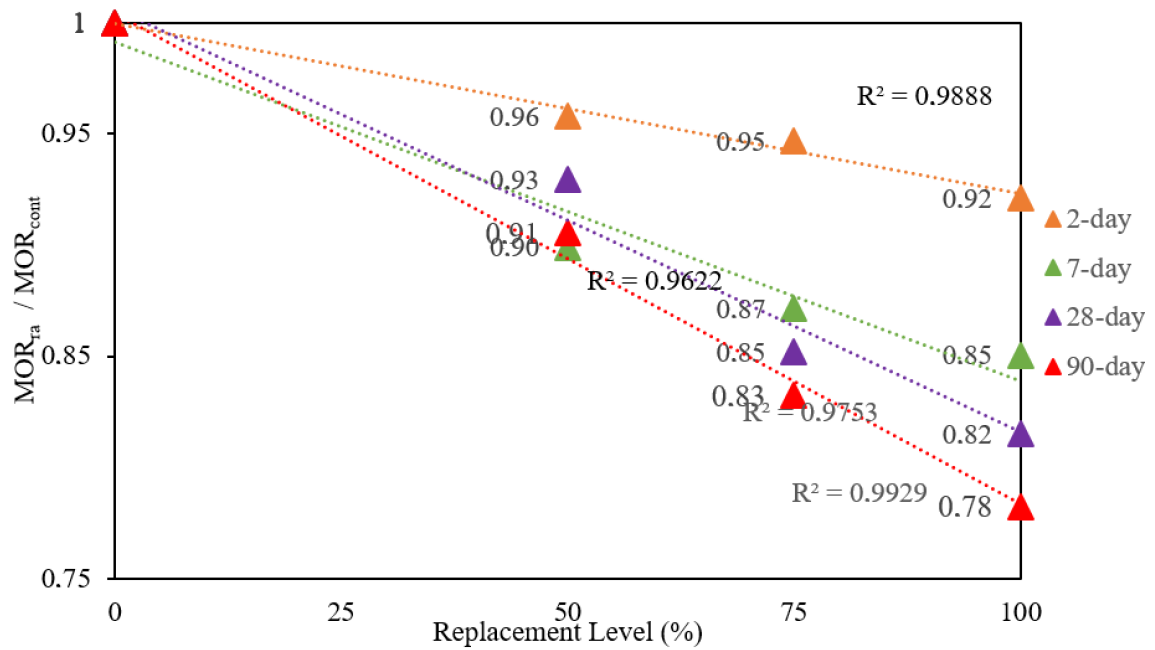


Figure 4.10. Flexural strength test results normalized with conventional concrete results ($w/c = 0.70$)

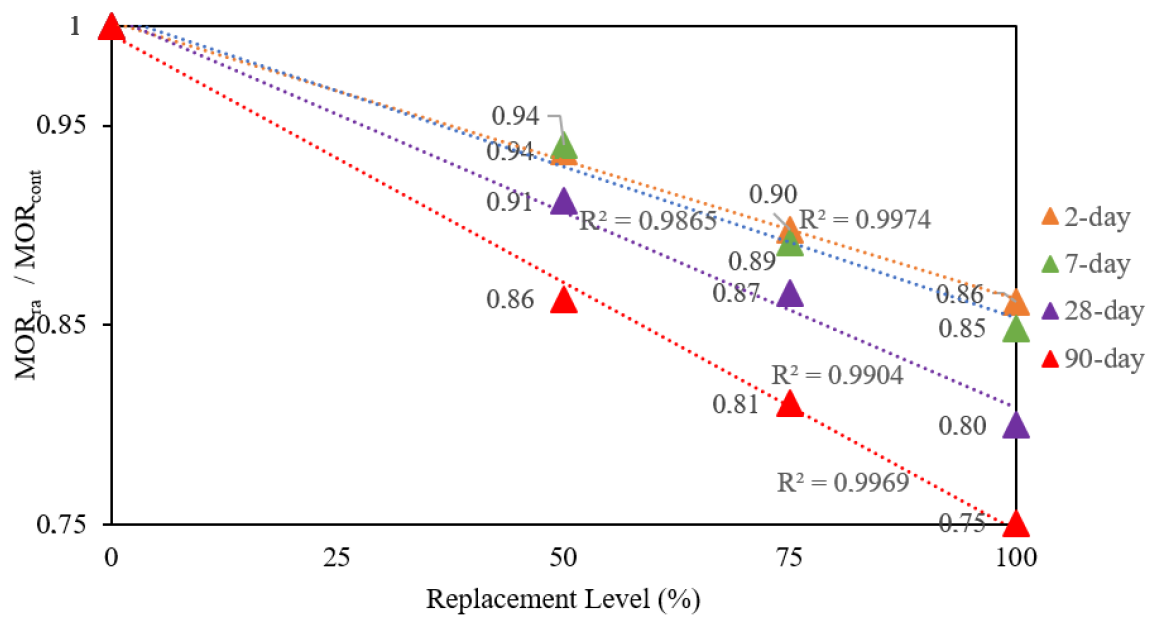


Figure 4.11. Flexural strength test results normalized with conventional concrete results ($w/c = 0.45$)

When flexural strength results are inspected, decreases are similar with the findings in compressive and splitting tensile test results however losses for all specimens are comparatively higher than both compressive and split tensile tests. It has to be noted that difference between 28-day and 90-day results were found to be higher for these type of loading with respect to other strength tests. This may be attributed to complexity of flexural stresses with respect to stresses in splitting tensile and compressive strength tests.

Lower water-to-cement ratio specimens experienced higher decreases whereas higher water-to-cement ratio specimens with 50% replacement had acceptable losses since they were all above 90% of the flexural strength of conventional concrete.

Both flexural and splitting tensile test results demonstrate that increasing replacement level disturbs the concrete capacity to withstand tensile stresses. When considering the use of recycled aggregates in structural concrete, recycled aggregates should be treated somehow to enhance their bonding with the new matrix.

4.3.5. Surface Treatment of Recycled Aggregates with Slurry Method

Recycled aggregates have disabilities that concern structural integrity of the concrete composed of them. In order to use those aggregates in concrete, several studies have been made to enhance the properties of recycled aggregates to be used in structural concrete. Many methods cheap or expensive, practical or not have been tried and there is no consensus on a certain type of treatment that shows stable results. In this study, first a method simply called slurry method was used to decrease the adverse effects of recycled aggregates in concrete.

Slurry method is a mixing methodology more than a special treatment on aggregates in contrast with the other method applied in this study. Slurry method is especially tried for the convenience of applicability and also economical point of view that no extra expense is required other than personnel with enough knowledge to apply the mixing steps.

The procedure for this method was given in Section 3.3.5. Slurry method was applied on concrete cylinder specimens of 100 x 200 mm for compressive and splitting tensile tests and also 100 x 100 x 500 prismatic specimens were casted for flexural tests. All mechanical tests are done with the same loading devices and conditions in this stage of the study. Also concrete prisms of 100 x 100 x 500 mm (20 fatigue, 12 static) were casted for fatigue tests. Also 75 x 100 x 400 mm prismatic specimens were cast for freeze-thaw durability test.

Fresh concrete tests conducted for mixes in the previous section were also conducted for concrete mixes in this stage of the study.

4.3.6. Fresh Concrete Properties

Determination of fresh concrete properties of concrete specimens were done on all concrete casting sessions. Slump, air content determination and unit weight tests were conducted and noted. Fresh concrete unit weight results were not much different with respect to untreated recycled aggregates as expected. However, surface coating of the coarse aggregates was found to be useful for workability. Since slurry treated specimens had better workability, superplasticizer amounts were adjusted to have the target 150 mm slump value as for the mixes throughout the project. In Figure 4.12, superplasticizer amounts by weight of binder ratios are given for treated specimens.

RAT 0.45 and RAT 0.70 specimens resemble the slurry method mixes. When 4.12 is inspected it is easily seen that treated specimens had better workability, therefore, superplasticizer amounts were decreased to have the target slump value of 150 mm. If linear relationship is to be assigned for all superplasticizer amount ratios with respect to replacement level, it can be seen that treated specimens had lower slopes than untreated versions. This exhibits that the effect of treatment on workability has higher significance with increasing replacement level. 100% replacement level specimens for both water-to-cement ratios performed relatively better workability features when treated.

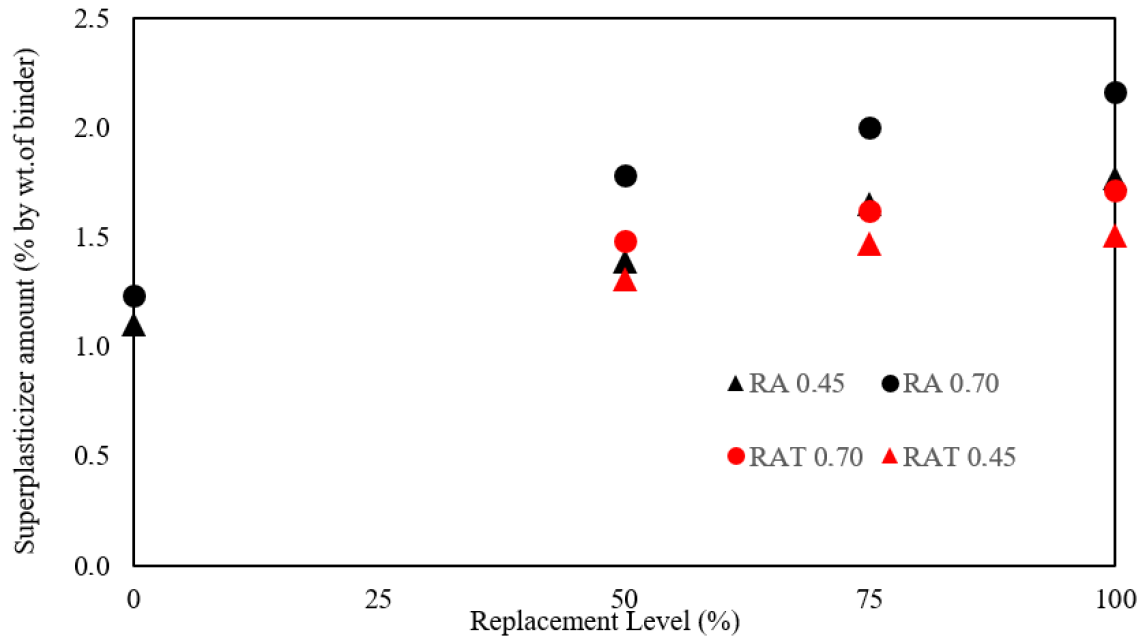


Figure 4.12. Superplasticizer amount by weight of binder ratio with increasing replacement level.

4.3.7. Hardened Concrete Properties

Hardened concrete tests were conducted on treated specimens with all 4 replacement level and 2 water-to-cement ratios. This method was also applied on concrete mixes containing natural aggregates to detect if there is any contribution also on natural aggregates.

4.3.7.1. Effect of Treatment on Compressive Strength. Specimens were loaded until crushing under force-controlled loading with a loading rate of 0.6 MPa/sn. Compressive stress strain data were acquired with data acquisition and stress-strain graphs were drawn for each specimen that also helps finding the modulus of elasticity. Test results may be viewed from Table 4.16 and 4.17 for specimens with water-to-cement ratio of 0.70 and 0.45 respectively.

Table 4.16. Effect of treatment on compressive strength (w/c=0.70)

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA70	10.34	10.57	15.11	15.32	21.57	21.38	23.51	22.95
Tre-Eff	2.27%		1.39%		-0.88%		-2.38%	
50RA70	10.07	10.12	14.56	15.72	19.16	20.41	20.55	21.45
Tre-Eff	0.41%		7.97%		6.50%		4.38%	
75RA70	9.85	10.09	14.02	15.02	18.21	19.25	19.96	21.07
Tre-Eff	2.44%		7.13%		5.71%		5.56%	
RA70	9.58	9.56	13.84	14.89	17.71	19.35	19.21	20.65
Tre-Eff	-0.23%		7.63%		9.25%		7.50%	

Table 4.17. Effect of treatment on compressive strength (w/c=0.45)

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA45	19.37	20.55	25.75	25.82	36.8	36.61	40.85	40.11
Tre-Eff	6.10%		0.27%		-0.53%		-1.81%	
50RA45	17.31	18.1	23.76	25.14	32.68	35.52	35.45	36.88
Tre-Eff	4.61%		5.82%		8.70%		4.03%	
75RA45	16.35	16.88	21.85	23.85	30.55	33.55	32.21	34.56
Tre-Eff	3.24%		9.15%		9.82%		7.30%	
RA45	16.06	16.53	20.88	22.91	28.82	33.41	30.76	35.2
Tre-Eff	2.90%		9.70%		16.00%		14.43%	

Table 4.17 shows compressive strength test results of specimens with water-to-cement ratio of 0.45 and increase of the compressive strength due to effect of treatment. For higher quality specimens, specimens suffered higher losses with increasing replacement level. Since losses were higher, effect of treatment was more pronounced for higher quality concrete specimens. For 28-day results maximum increment for treated concrete mixes is 16% which is higher than the maximum increment for the specimens with water-to-cement ratio of 0.70 which was 10%. If early strength of specimens is inspected, for these specimens the effect of treatment is more visible for higher quality concrete specimens. 10% increase is seen for high level of recycled aggregate replacement. 28-day compressive tests results are normalized with compressive test results of natural concrete and given in Figure 4.14.

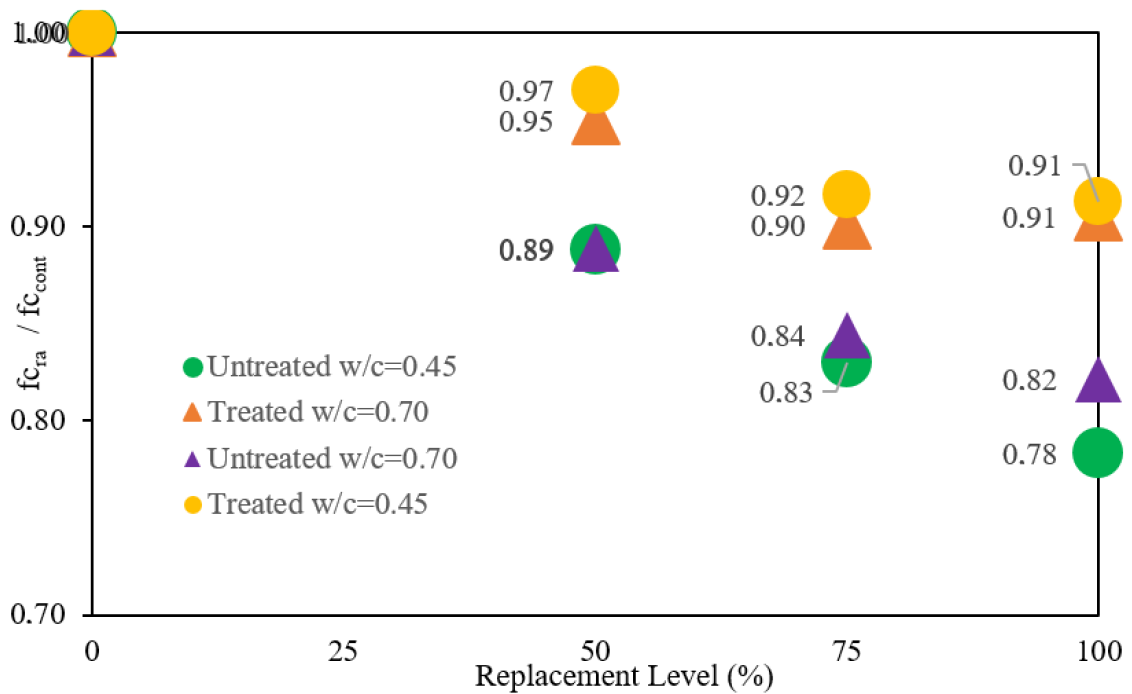


Figure 4.13. Normalized compressive strength test results with increasing replacement level for both treated and untreated specimens

To better monitor the results, normalized values of compressive strength with respect to natural concrete are given in Figure 4.13. Specimens of both water-to-cement ratios gained strength after treatment procedure. Specimens with 0.45 water-to-cement ratio are increased from 78% to 91% of normal aggregate concrete. Especially speci-

mens with 50% replacement level after treatment gained strength and reached 97% and 95% for specimens with 0.45 and 0.70 water-to-cement ratio specimens, respectively. Since their compressive strength values are very close to that of natural concrete, this replacement level may be used for structural applications when treated. But compressive strength is not the only aspect that shows the performance of a concrete mix to be used in structural applications. Other mechanical properties and also durability aspects should be investigated to come to a more accurate conclusion.

4.3.7.2. Effect of Treatment on Flexural Strength. Flexural strength tests until crushing were conducted on specimens with 100 x 100 x 500 mm dimensions under a four-point loading with a pace rate of 0.5 kN/ sec. 3 prism specimens for each mix were crushed and modulus of rupture data were recorded precisely. Modulus of rupture values may be viewed for both treated and untreated specimens and the ratio of the change between the untreated and treated versions of same mixes.

Table 4.18. Effect of treatment on flexural strength ($w/c=0.70$)

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA70	1.27	1.24	2.88	2.88	4.34	4.39	4.81	4.79
Tre-Eff	-2.37%		-0.29%		1.31%		-0.42%	
50RA70	1.25	1.29	2.78	2.83	4.10	4.40	4.46	4.59
Tre-Eff	3.41%		1.74%		7.31%		2.91%	
75RA70	1.20	1.23	2.69	2.80	3.94	4.17	4.32	4.41
Tre-Eff	2.49%		3.90%		5.80%		2.08%	
RA70	1.17	1.19	2.63	2.75	3.82	4.14	3.98	4.22
Tre-Eff	1.71%		4.63%		8.37%		6.03%	

When Table 4.18 is examined, it may be concluded that treatment also affected the flexural capabilities of concrete specimens containing recycled aggregates.

Table 4.19. Effect of treatment on flexural strength (w/c=0.45)

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA45	1.95	1.93	3.94	3.90	6.37	6.47	6.95	6.90
Tre-Eff	-1.28%		-0.97%		1.52%		-0.72%	
50RA45	1.83	1.93	3.71	3.95	5.81	6.13	6.24	6.57
Tre-Eff	5.34%		6.61%		5.54%		5.29%	
75RA45	1.75	1.83	3.51	3.72	5.52	5.85	6.01	6.22
Tre-Eff	4.29%		5.93%		5.98%		3.44%	
RA45	1.68	1.80	3.34	3.50	5.31	5.88	5.46	5.87
Tre-Eff	7.14%		4.74%		10.84%		7.51%	

When Tables 4.18 and 4.19 are inspected, it may be concluded that treatment also affected the flexural capabilities of concrete specimens containing recycled aggregates. However, it may be said that contribution of treatment is less pronounced when compared to compressive strength tests. Difference may be originated of the mechanical differences of both tests. Also one should mention that effect on water-to-cement ratio is less pronounced with respect to compressive test results. Similar increments are seen for both water-to-cement ratios.

Treatment demonstrated its effect on early day values as well as 28 and 90-day values. Unlike compressive strength, treatment showed its effect on earlier days. Maximum treatment effect on flexural tests were to be seen as 11%.

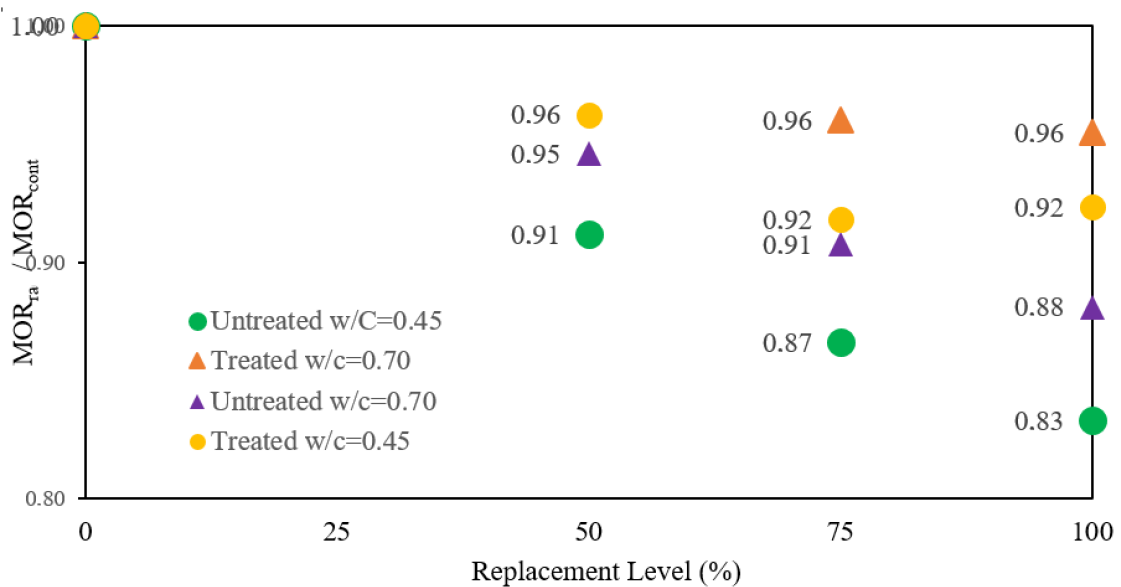


Figure 4.14. Normalized flexural test results with increasing replacement level for both treated and untreated specimens (28 days).

Normalized flexural test results with increasing replacement level for both treated and untreated specimens can be viewed in Figure 4.14. For water-to-cement ratio of 0.45, treated specimens showed better properties with respect to untreated specimens.

4.3.7.3. Effect of Treatment on Splitting Tensile Strength. Splitting tensile tests were conducted until crushing under force-controlled loading with a pace rate of 0.01 kN/sec. 100 x 200 mm cylindrical concrete specimens were tested mixed with the treatment methodology proposed. Results are given in Tables 4.20. and 4.21 for specimens with water-to-cement ratio of 0.70 and 0.45 consecutively.

Table 4.20. Effect of treatment on splitting tensile strength (w/c=0.70)

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA70	0.82	0.83	1.72	1.72	2.94	2.94	3.09	3.02
Tre-Eff	1.13%		-0.18%		-0.22%		-2.27%	
50RA70	0.80	0.81	1.63	1.68	2.77	2.85	2.95	3.02
Tre-Eff	3.41%		1.74%		7.31%		2.91%	
75RA70	0.76	0.77	1.56	1.61	2.58	2.65	2.72	2.80
Tre-Eff	2.49%		3.90%		5.80%		2.08%	
RA70	0.74	0.74	1.54	1.59	2.53	2.58	2.61	2.69
Tre-Eff	0.00%		3.25%		2.02%		3.07%	

Table 4.21. Effect of treatment on splitting tensile strength ($w/c=0.45$).

	2-day		7-day		28-day		90-day	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
NA45	1.39	1.38	2.88	2.84	3.93	4.01	4.21	4.12
Tre-Eff	-0.72%		-1.53%		2.16%		-2.14%	
50RA45	1.26	1.30	2.68	2.78	3.62	3.76	3.77	3.81
Tre-Eff	3.17%		3.61%		3.87%		1.06%	
75RA45	1.22	1.29	2.62	2.67	3.49	3.67	3.44	3.62
Tre-Eff	5.74%		1.91%		5.16%		5.23%	
RA45	1.20	1.26	2.60	2.65	3.20	3.45	3.38	3.59
Tre-Eff	5.00%		2.01%		7.81%		6.21%	

When Tables 4.20 and 4.21 are inspected, treatment effect on specimens with water-to-cement ratio of 0.70 is quite low. Effect on 28-day and 90-day specimens is only 2% and 3% with full replacement level. But at 50% replacement level specimens had an increase of 7%. When considered in this aspect, in all the other mechanical tests effect of treatment was increasing with the increasing of replacement level but this behavior was not seen in this test. If specimens with water-to-cement ratio of 0.45 is inspected, effect of treatment increased with the increment in replacement level and this is compatible with all the other mechanical test results. Maximum effect of treatment on these specimens was 7.81% which was seen for full replacement level at 28-day and also for 90-day specimens this increment was 6.21%.

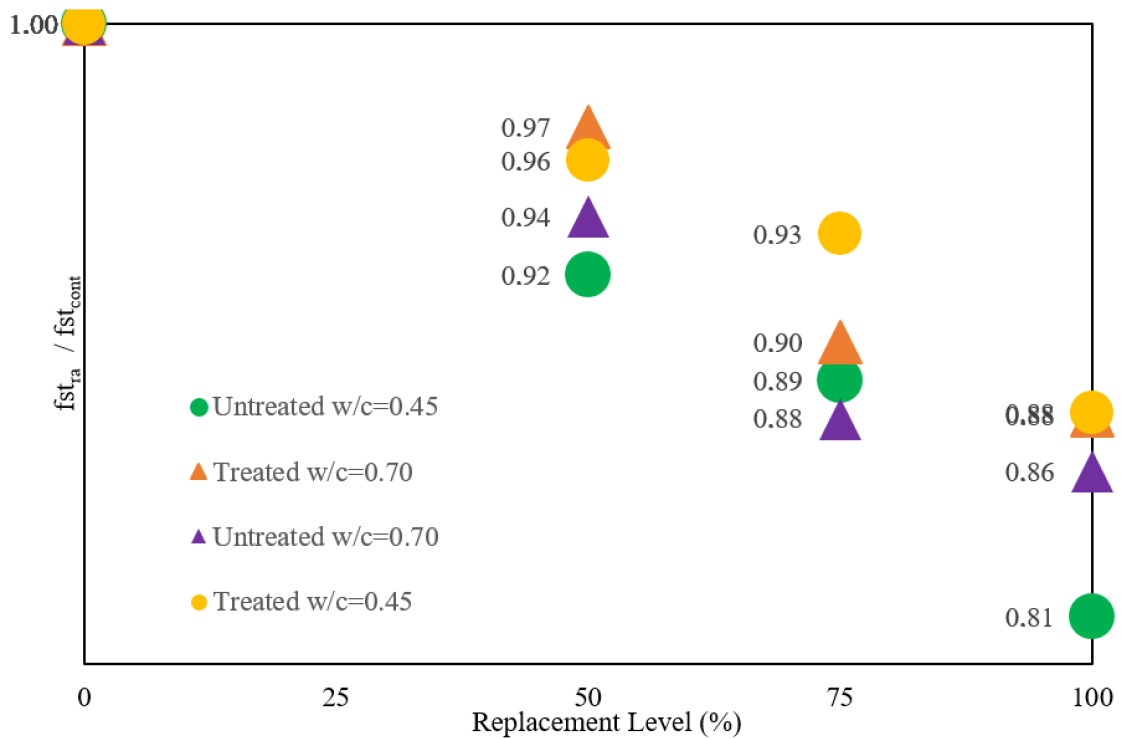


Figure 4.15. Normalized flexural test results with increasing replacement level for both treated and untreated specimens (28 days).

In order to better present the effect of treatment on splitting tensile strength results Figure 4.15 is given. For specimens with water-to-cement ratio of 0.70, there is not adequate increase in strength to speak of positive effect of treatment but it is seen

that all the results were higher than untreated specimens. For low water-to-cement ratio specimens, treatment seemed more effective.

When all mechanical test results are compared, compressive test results have been the one that was most affected after the treatment methodology applied whereas, splitting tensile test results were also increased but in very low percentages.

Slurry treatment was found to be effective since coating of the specimen surfaces of recycled aggregates contributed to better workability, strength and a denser interfacial transition zone. When recycled aggregates are used in concrete, the absorption of recycled aggregate causes absorption of water from mortar to recycled aggregates. The absorption results in cracks in interfacial transition zone subsequent to evaporation of water. However, coating of the recycled aggregate surfaces reduces this inner absorption mechanism by forming a barrier and therefore workability is enhanced and weak interfacial transition zone is strengthened. Relatively lower water-to-binder ratio of slurry contributes to denser interfacial transition zone thus resulting a higher strength for recycled aggregate concrete.

4.4. Biodeposition Treatment on Recycled Aggregates

The second method used for the treatment of recycled aggregates is the microbiological treatment. The procedure for this method is given in Section 4.4. Due to limited resources and high cost of microorganisms limited amount of treated recycled aggregates is tested for water absorption of aggregates and compressive strength of mixtures.

4.4.1. Microorganism Growth

The highest concentration of microorganisms tested was observed after the use of culture medium containing urea-peptone medium. *S. Pasteurii* cells reached 2.8×10^8 CFU/mL after 24 h of incubation. Also culture medium containing urea-yeast extract exhibited similar performance when growing *S.pasteurii* bacteria. Given these points,

it was decided to continue study with peptone-urea medium since similar results were monitored for both types of mediums. Relationship of bacteria cells with time is given in Figure 4.16.

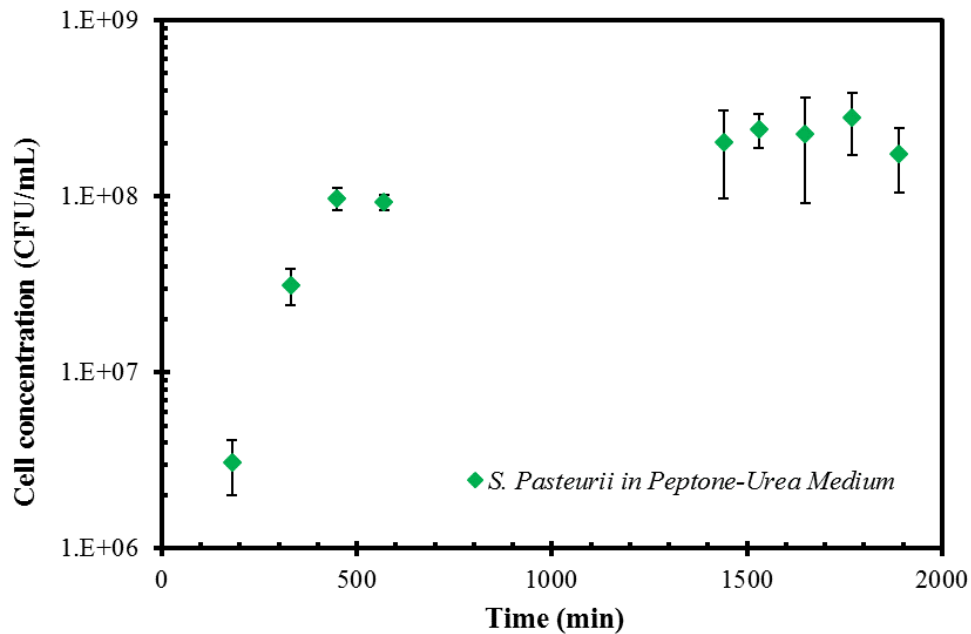


Figure 4.16. Number of bacteria cells (*S. pasteurii*) with time.

4.4.2. Water absorption

One of the major negative effects of using recycled aggregates in concrete is the high water absorption of these aggregates. Water absorption results of recycled aggregates before and after biodeposition treatment are given in Figure 4.17.

Evaluation of the effect of the treatment was done by the water absorption of the aggregates after the treatment. It was seen that biodeposition treatment decreased the water absorption of the recycled aggregates as can be viewed from Figure 4.17. Two different batches were used in the findings of the recycled aggregates and for better analyses, effect of biodeposition treatment is assessed on the same samples by conducting test procedure before and after the treatment. When results are inspected, it may be seen that absorption capacity of both samples were reduced where batch 1

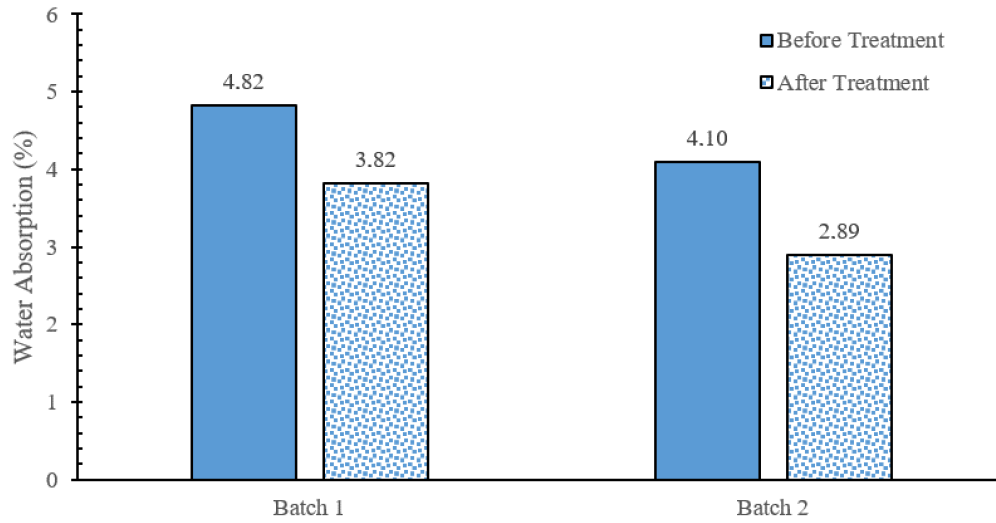


Figure 4.17. Water absorption of recycled concrete aggregates before and after treatment of biodeposition.

had 21 % and batch 2 had 30 % less water absorption with respect to their original untreated conditions.

Decrease in water absorption was found to be quite effective provided that effect of treatment was proved to act on the porosity of the samples and filled the outer pores and ways to the inner pores. Formation of CaCO_3 particles after biodeposition is highly important in this plugging behavior.

Reduction in water absorption points out the promising opportunity here in treatment of recycled aggregates for enhancing the quality and use in concrete. Generally speaking, this effect may be translated as the positive effect of bacteria on the properties of aggregates.

4.4.3. SEM Investigations

Emission scanning electron microscope and energy-dispersive X-ray spectroscopy (EDX) were used to identify the morphology and the chemical composition of the

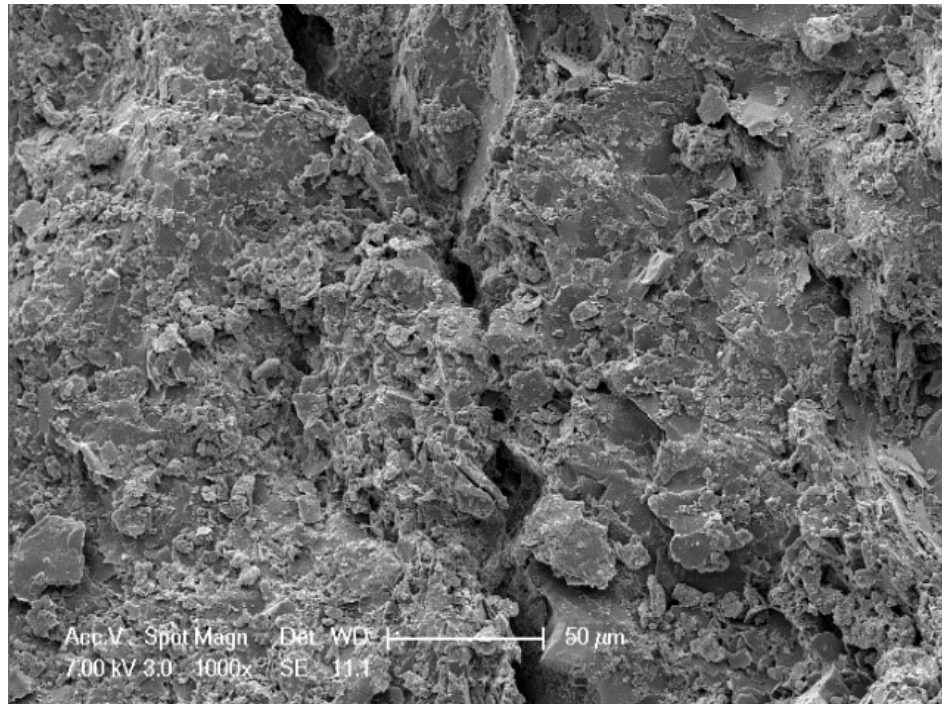


Figure 4.18. SEM view from cracked parts of recycled aggregate before biodeposition precipitates. Gold coating was applied before applying biodeposition.

Before biodeposition process, SEM investigations were conducted to view the surface cracks and morphology of the recycled aggregate specimens (Figures 4.18 and 4.19).

After the biodeposition process specimens were investigated for the formation of bacterial treatment. In Figure 4.20, crack plugging of cubic particles of CaCO_3 can be viewed. High amount of cubic particles plugged the cracks on the surface of recycled aggregate.

In Figure 4.21, cubic formations of CaCO_3 particles may be viewed in a closer level and this level of magnification it is also possible to see the imprints of bacteria.

Bacteria create layers when constructing CaCO_3 cubes which may be seen in Figure 4.22. Also bacterial imprint can be seen in the same figure.

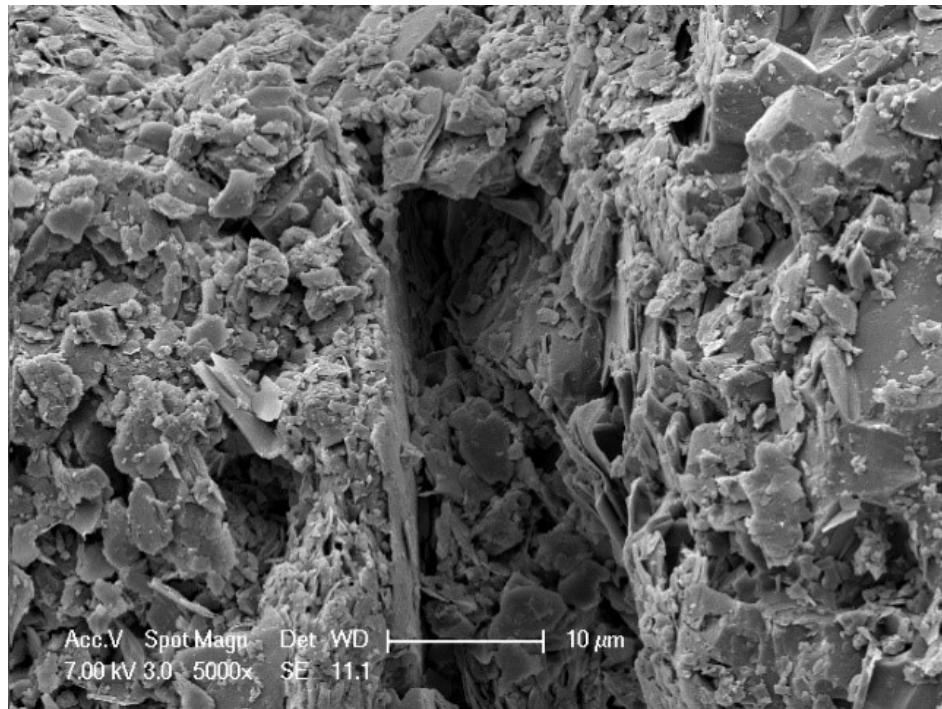


Figure 4.19. Magnified SEM view from cracked parts of recycled aggregate before biodeposition

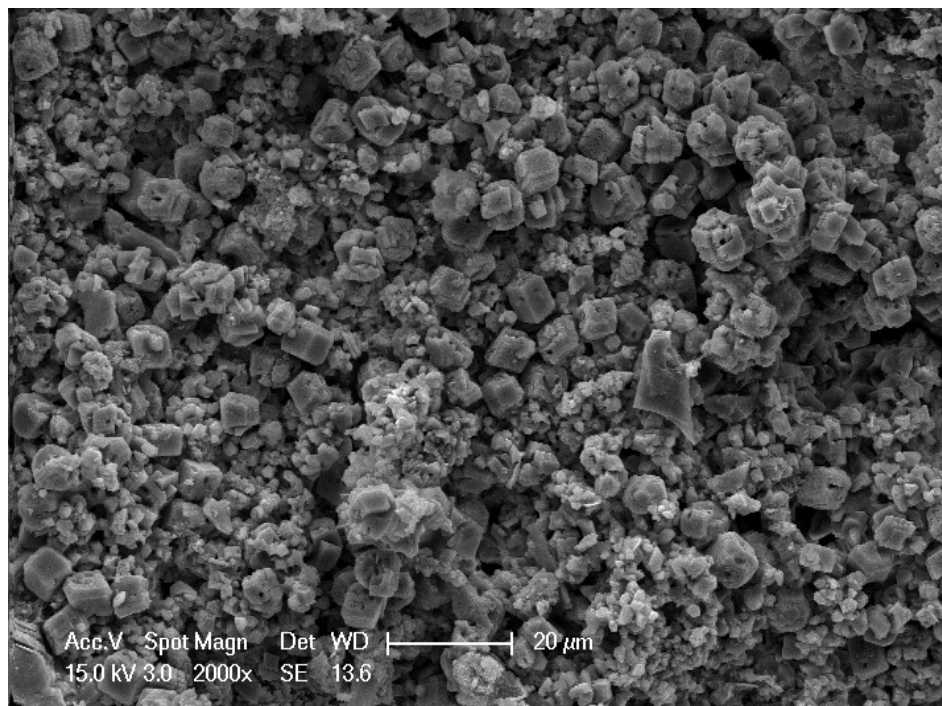


Figure 4.20. High amount of assembled cubic CaCO_3 particles.

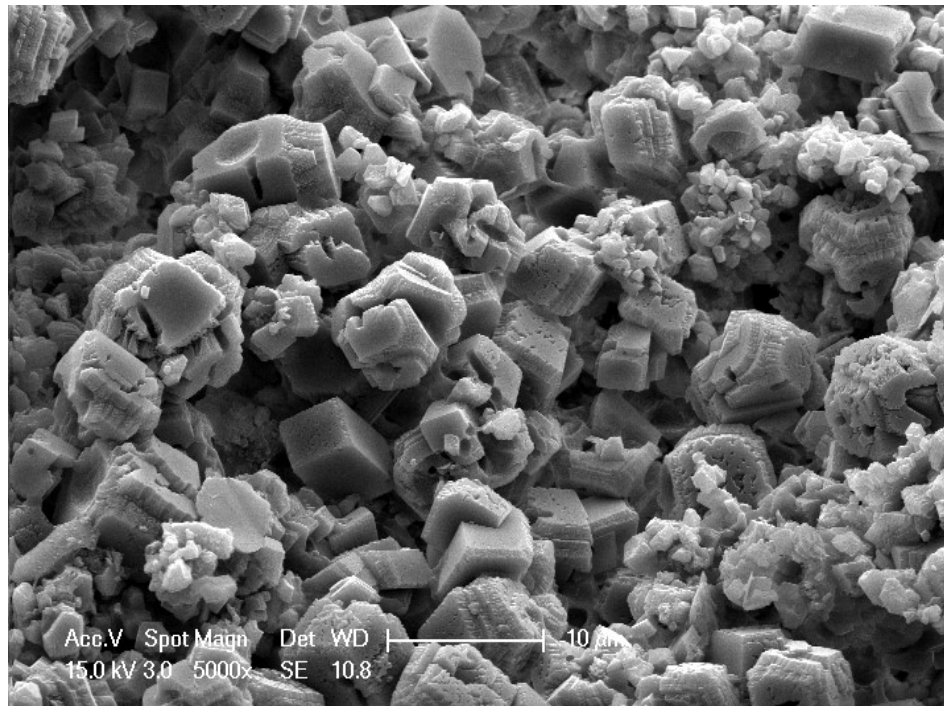


Figure 4.21. CaCO_3 particles at a higher magnification level.

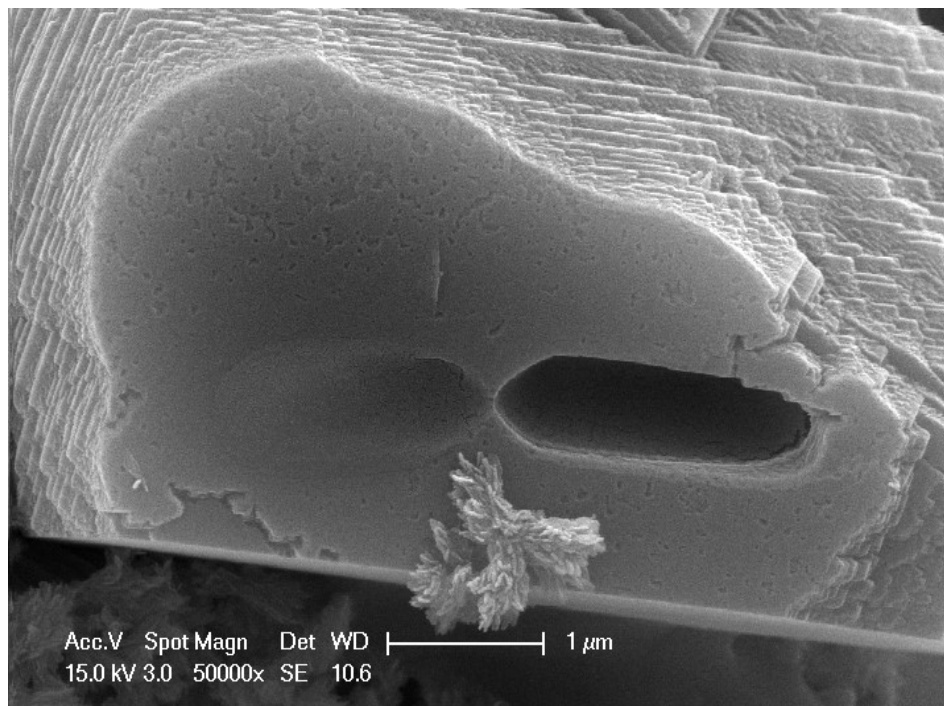


Figure 4.22. Layers of CaCO_3 and bacterial imprint.

After the biodeposition process, surfaces of the aggregates were verified with the scanning electron microscopy observations and also EDS analysis were conducted simultaneously on same specimens to ensure the presence of biodeposition products on the surface of treated specimens. High amount of calcium carbonate precipitation was detected when scanning the aggregate surfaces and especially it has been noted that cracks on the surfaces of these recycled aggregates were clearly filled with the crystals of calcium carbonate that has the cubic formation. Bacterial imprints with likely $2.7\ \mu\text{m}$ of length can be clearly seen on the particles (Figure 4.23).

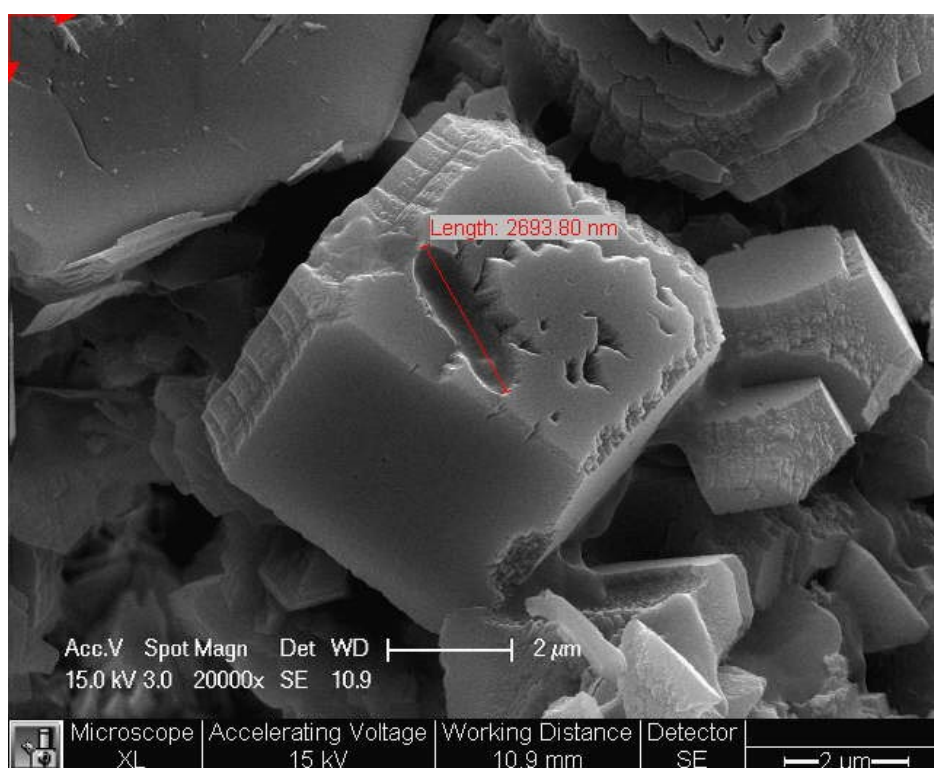


Figure 4.23. Bacterial imprint on CaCO_3 particles

Cubic formed particles were also analyzed with EDS and it was concluded that they were all CaCO_3 particles that were produced by precipitation. Also spherical formations were observed and they were found to be vaterite (Figures 4.4.3 and 4.4.3).

Crack plugging of vaterite formation may be seen in Figure 4.26. Closer magnification shows different sizes of vaterites in a crack zone on the surface of the recycled aggregates.

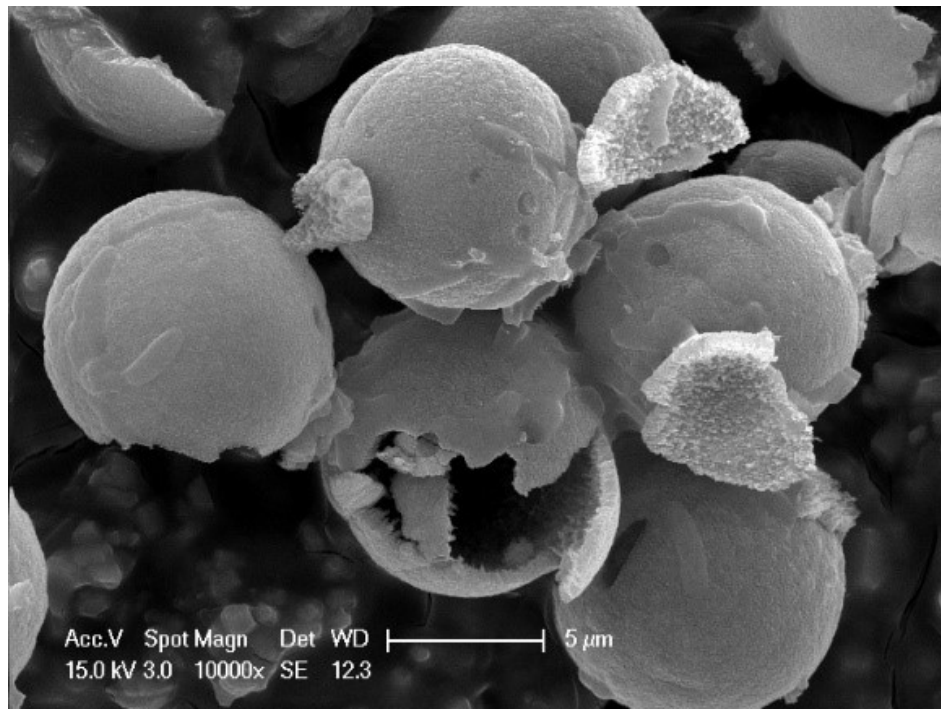


Figure 4.24. Close look at spherical forms of CaCO_3 polymorphs (vaterite)

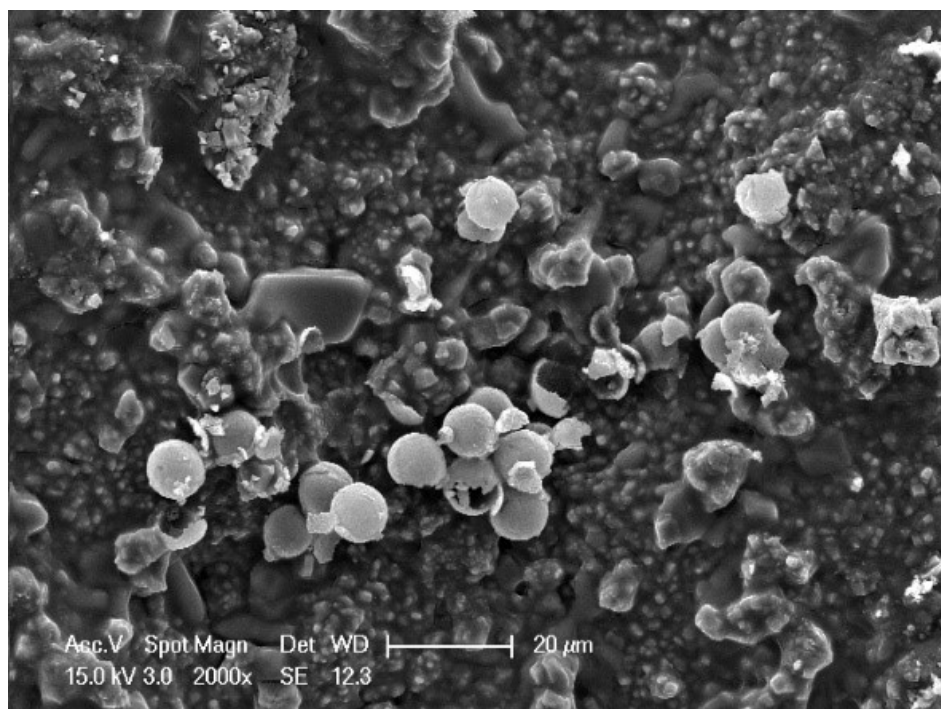


Figure 4.25. Spherical forms of CaCO_3 polymorphs (vaterite)

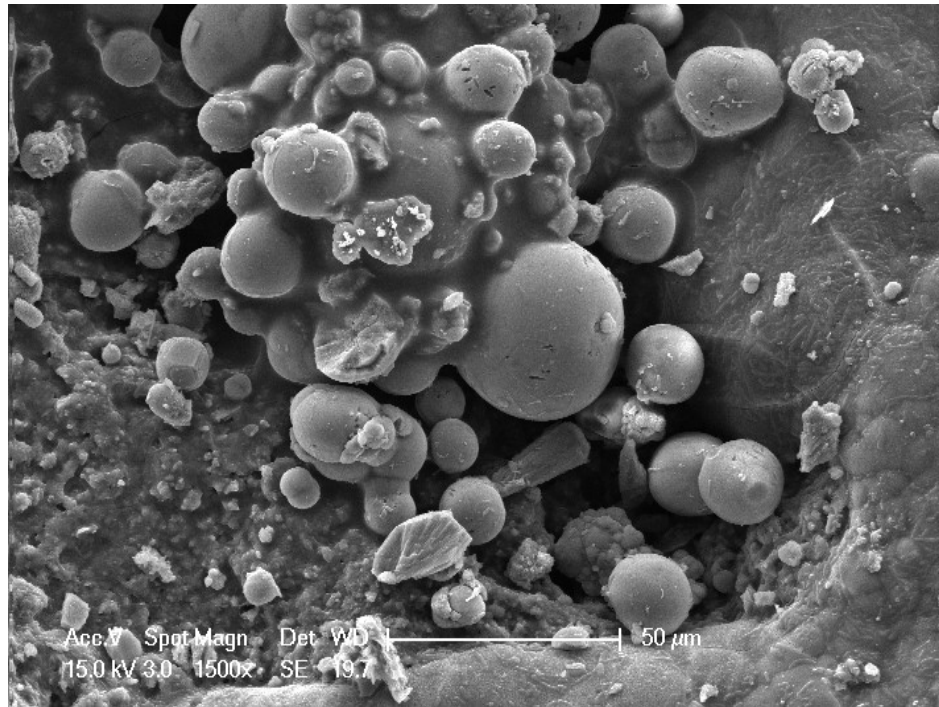


Figure 4.26. Formation of vaterites plugging a surface crack.

4.4.4. Compressive strength analysis

24 units of 50x50x50 mm cubic specimens were produced with 4-8 mm coarse aggregates using natural aggregates, recycled aggregates and bacteria treated recycled aggregates. 8 cubes were produced for each type of aggregates and tested after 7 days and 28 days of curing in water tank. Results of the compressive strength tests are given in Table 4.22.

When Table 4.22 is inspected, it can be seen that natural aggregates had the highest ultimate strength whereas with 100% replacement there was a decrease in strength of 9.6%. This decrease was slightly lower (6.2%) when bacteria treated specimens were used. This may be related to lower water absorption capacity of these specimens.

When 7-day results are inspected, it can be said that strength gain was relatively slower in early period since bacteria treated specimens had lower 7-day results

Table 4.22. Compressive strength test results of 50x50x50 mm cubic specimens

	7-day			28-day		
	Load(kN)	Comp. Strength (MPa)	Change	Load(kN)	Comp. Strength (MPa)	Change
NA	103.12	41.25	0%	160.20	64.08	0%
RA	91.33	36.53	-11.40%	144.90	57.96	-9.60%
Bacteria Treated	89.44	35.78	-13.30%	149.30	60.11	-6.20%

with respect to both natural and untreated recycled aggregates. Untreated recycled specimens also had slower strength gain with respect to natural aggregate specimens.

4.5. Durability of Concrete

In this study, freeze-thaw cycling tests were done according to prescriptions given in ASTM C666 [54] to inspect the durability of recycled aggregate concrete. Specimens with dimensions of 75x100x400 mm are cast and stored in curing for 28 days. After 28 days, immediately freeze-thaw cycles are started. Five specimens from each specimen type were tested under freeze-thaw cycling conditions and every week mass losses and dynamic resonance frequency measurements were done. After all freeze thaw tests on all specimen types were ended, with these findings residual flexural tests were conducted on every specimen type tested in standard freeze-thaw tests. In these tests, surface treated specimens were also tested and effect of treatment was investigated in durability perspective after mechanical test performance.

4.5.1. Freeze Thaw Tests of Concrete with Recycled Aggregates

4.5.1.1. Mass Losses. Freeze-thaw tests data were collected every week which is equal to 42 cycles. Every 42 cycles (a week period) freeze-thaw cabinet was stopped and specimens were weighed and tested with ultrasonic pulse velocimeter. Measurements of same specimens were continued till the disintegration of the first specimen from that

batch. If a specimen of any batch is disintegrated all the same specimens from that batch are accepted as disintegrated and cycles are stopped for that batch but specimens from other batches are continued to be exposed to freeze-thaw cycles. In Figure 4.27 ultimate number of freeze-thaw cycles that specimens had encountered during the mass loss measurements are given.

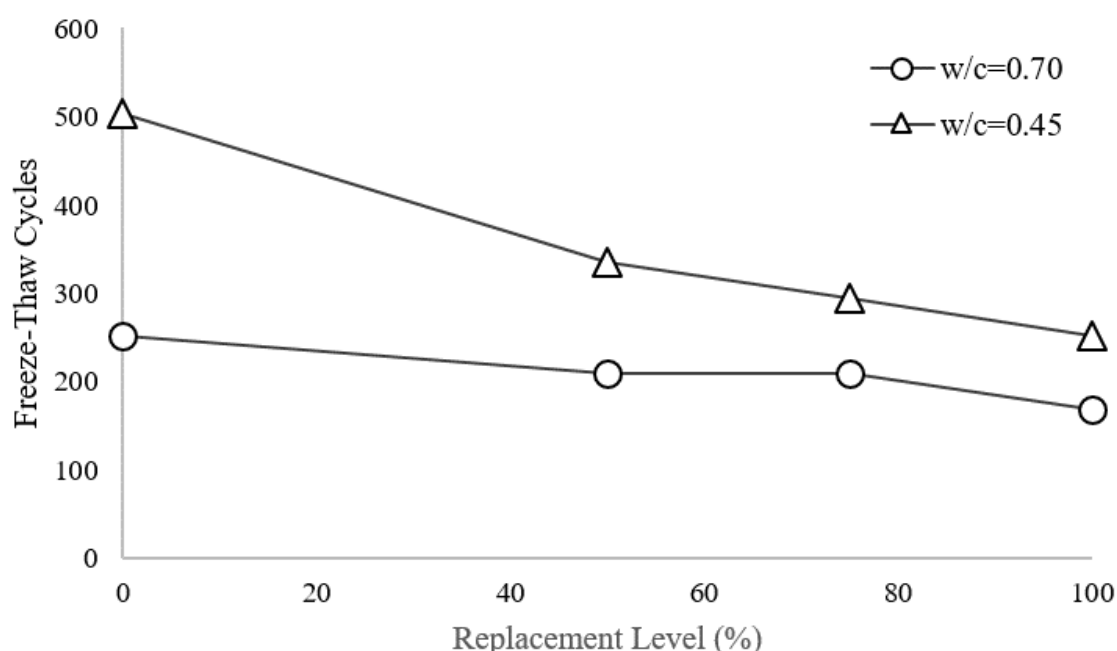


Figure 4.27. Number of freeze-thaw cycles till disintegration with increasing number of replacement level.

Mass loss measurements were continued till one of the specimens of the same series has lost integrity and split into parts. Specimens with lower water-to-cement ratio survived more freeze-thaw cycles with respect to higher water-to-cement ratio specimens. Specimens containing only natural aggregates survived highest number of cycles and it may be also seen easily that with the increasing number of replacement level freeze thaw cycle numbers are also decreased since replacement of recycled aggregates affect the concrete quality lowering the freeze-thaw resistivity of the concrete.

Average mass losses of specimens may be viewed in Figures 4.27 and 4.28 for specimens with water-to-cement ratio of 0.70 and 0.45, respectively.

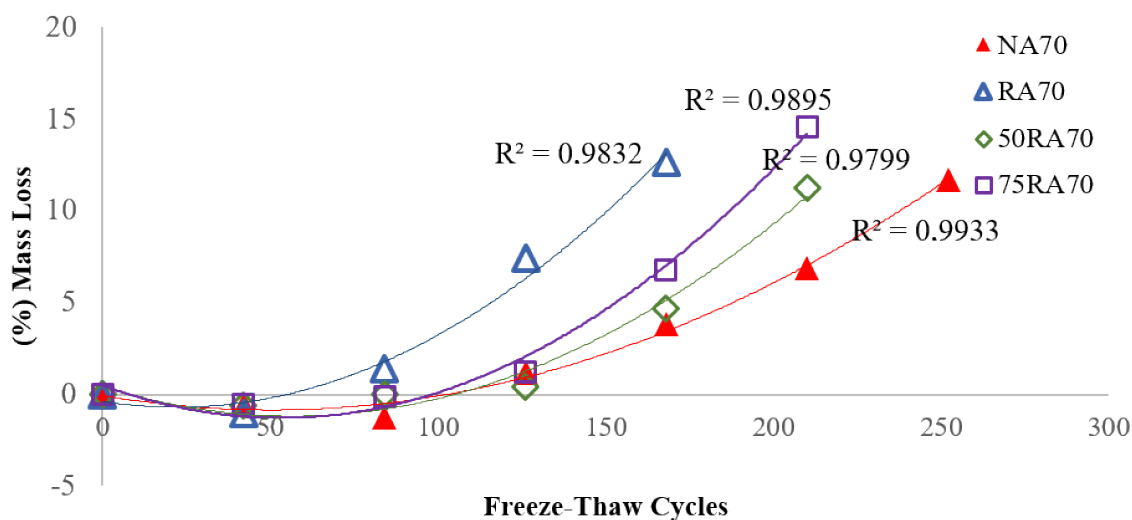


Figure 4.28. Mass loss of specimens with 0.70 water-to-cement ratio with increasing freeze-thaw cycles.

Mass losses of specimens with water-to-cement ratio of 0.70 are normalized with the initial masses of the specimens at saturated surface dry condition and given in Figure 4.28. When results are inspected, obviously all specimens had mass increases in the first week and specimens containing recycled aggregates had more increase with respect to natural concrete. Especially specimen with 100% replacement level experienced the highest mass increase in the first week (2%). All the specimens had this increase in the first week but in the second week measurements it has been seen that increase was replaced with decrease for specimens containing recycled aggregates. Weight of natural concrete increased till the second week different from the other specimens. This may be attributed to water absorption of specimens without any disintegration in two weeks but specimens containing recycled aggregates had mass losses because of the disintegration caused by the freezing of water absorbed in the first week of the cycles especially in the old adhered mortar. All specimens experienced mass losses in the third week, highest decrease observed was in RA70 specimens with 100% replacement level, when other specimens showed no mass loss with respect to original starting weights. In the coming weeks, all specimens experienced mass losses which increased with an increasing slope and all mass losses are fitted a second degree trend curve.

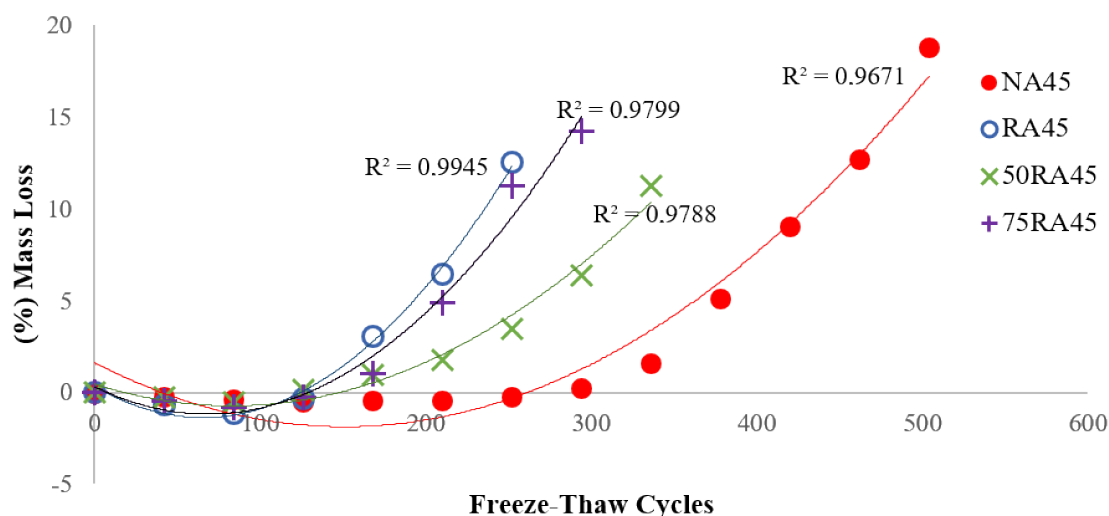


Figure 4.29. Mass losses of specimens with 0.45 water-to-cement ratio with increasing freeze-thaw cycles.

Specimens with a water-to-cement ratio of 0.45 survived more cycles with respect to specimens with 0.70 water-to-cement ratio. For lower water-to-cement ratio specimens, mass losses started late with respect to higher water-to-cement ratio specimens. Natural concrete specimens experienced first mass loss in the 294th cycle, whereas RA45 specimens (100% replacement level) exhibited first loss from original weight in the 168th week. Low water-to-cement ratio specimens showed increased rate of mass losses with increasing replacement level as the high water-to-cement ratio specimens. Natural concrete specimens survived 504 cycles (12 week) and exhibited the most durable behavior against severe freeze-thaw cycles. 75RA45 specimens showed closer behavior to RA45 specimens, mass loss rate with increasing freeze-thaw cycles was similar to each other. Basically, this shows lower water-to-cement ratio specimens are more affected when higher replacement levels are used. 50RA45 specimens with %50 recycled aggregates showed more tolerable behavior against freeze-thaw cycles. Regardless of percentage used, it is seen that use of recycled aggregates significantly affect the freeze-thaw behavior.

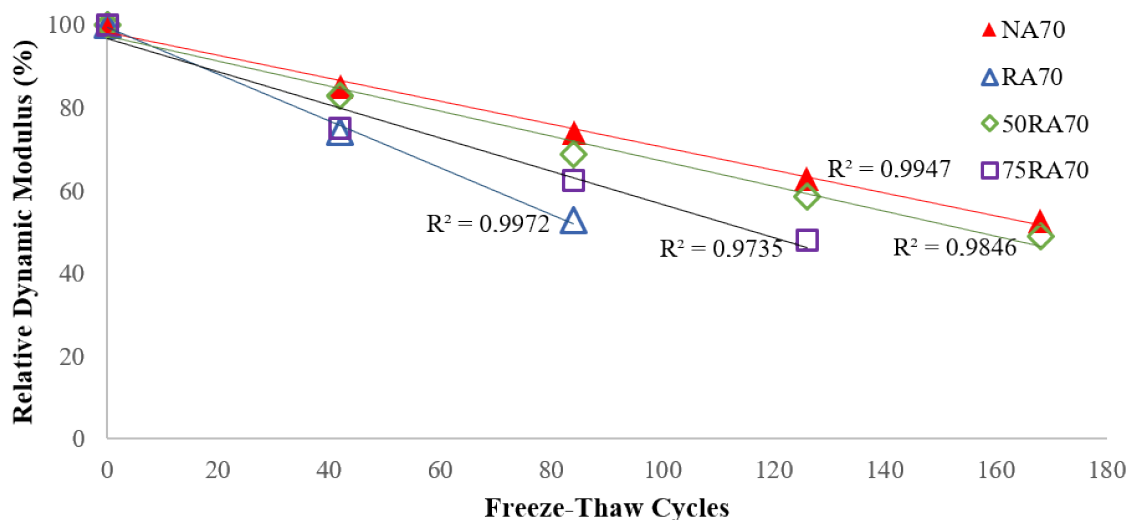


Figure 4.30. Relative Dynamic Modulus of specimens with 0.70 water-to-cement ratio with increasing freeze-thaw cycles.

4.5.1.2. Relative Dynamic Modulus. Every week with the weight measurements ultrasonic wave measurements were also taken. With data taken, changes in relative dynamic modulus results were obtained and shown in Figure 4.30 and 4.31. Measurements were continued until no wave measurement could be taken practically. This data may give direct information about how much concrete specimens degraded with the increasing number of freeze thaw cycles. Natural concrete specimens showed similar degradation with the 50RA70 specimens. RA70 specimens with 100% replacement level had low relative modulus in all weeks and also rate of the decline was also higher with respect to other specimens. In three weeks, RA70 specimens degraded to 52% of its original relative dynamic modulus. All the specimens with water-to-cement ratio of 0.70 exhibited a linear decrease in relative dynamic modulus.

Lower water-to-cement ratio specimens experienced degradation with the increasing freeze-thaw cycles. Natural concrete specimens had degraded in longer duration and also measurements could be taken for longer duration which indicates that specimens resisted freeze-thaw cycles without significant disintegration. RA45 specimens showed rapid degradation and relative dynamic modulus decreased to 60% in 168 cy-

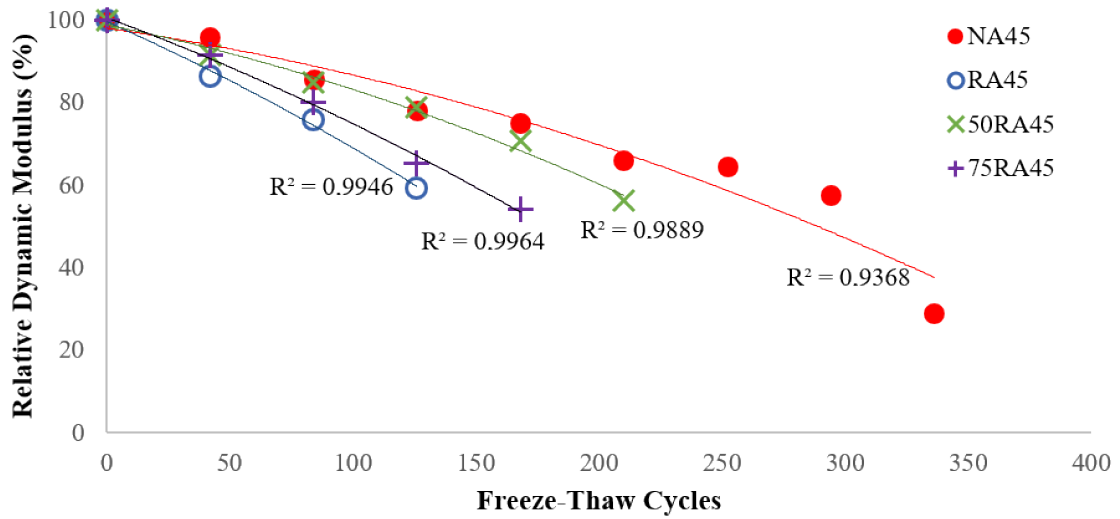


Figure 4.31. Relative Dynamic Modulus of specimens with 0.45 water-to-cement ratio with increasing freeze-thaw cycles.

cles. When Figure 4.30 and 4.31 are compared, it may be seen that, performance of natural concrete is quite significant with respect to especially higher amount of replacement level specimens (RA45, 75RA45). Degradations of specimens were completed one more week after for lower water-to-cement ratio specimens. All 0.45 water-to-cement ratio specimens were fitted by a trend curve of second degree with a negative increasing slope.

4.5.2. Freeze-Thaw Test of Concrete with Slurry Treated Recycled Aggregates

4.5.2.1. Number of Freeze-Thaw Cycles Resisted. Slurry method was described in Section 4.3.3 was also applied to beam specimens to assess the effectiveness of slurry method on durability when exposed to freeze-thaw cycles. In Figure 4.32, it is seen that with the increasing replacement level, decrease in the number of freeze-thaw cycles were restrained. When specimens with water-to-cement ratio of 0.70 are inspected individually, it is seen that effect of slurry method is quite effective since all the replacement levels resisted same number of freeze-thaw cycles. For 50 and 75 replacement

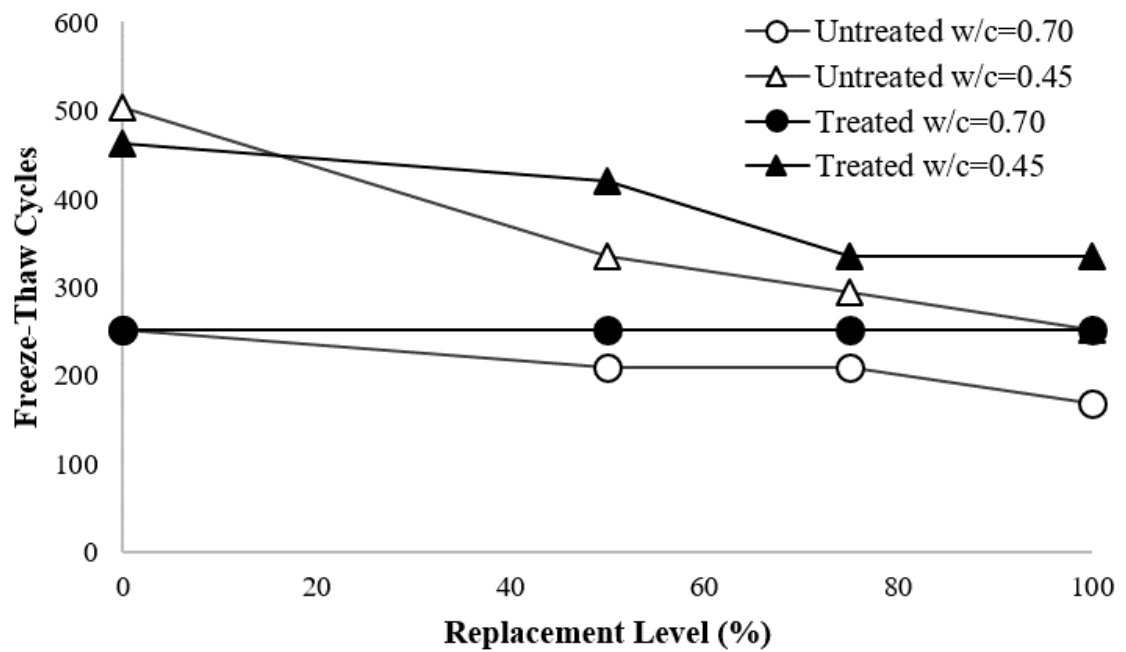


Figure 4.32. Relative Dynamic Modulus of specimens with 0.45 water-to-cement ratio with increasing freeze-thaw cycles.

levels, an improvement of 42 cycles was seen and for 100% replacement level there was 84 cycles progress in the results. When specimens with water-to-cement ratio of 0.45 was investigated, effect of slurry method was also positive. For all replacement levels, specimens were enhanced. Also for better assessment of the effectiveness of slurry methods, natural concrete specimens were also cast with this procedure and specimens were also exposed to freeze-thaw cycles. Effectiveness of slurry method on concrete specimens containing only natural aggregates seemed limited and any progress was not seen.

Photos of natural, recycled and treated recycled specimens subjected to 126 cycles are given in Figures 4.33 and 4.34. When visually inspected, at the same amount of cycles NA70 and RAT70 specimens were in similar conditions, on the other hand RA70 specimen was disintegrated already. Effect of slurry treatment was found to be highly visible and significant especially for higher water-to-cement ratio specimens.

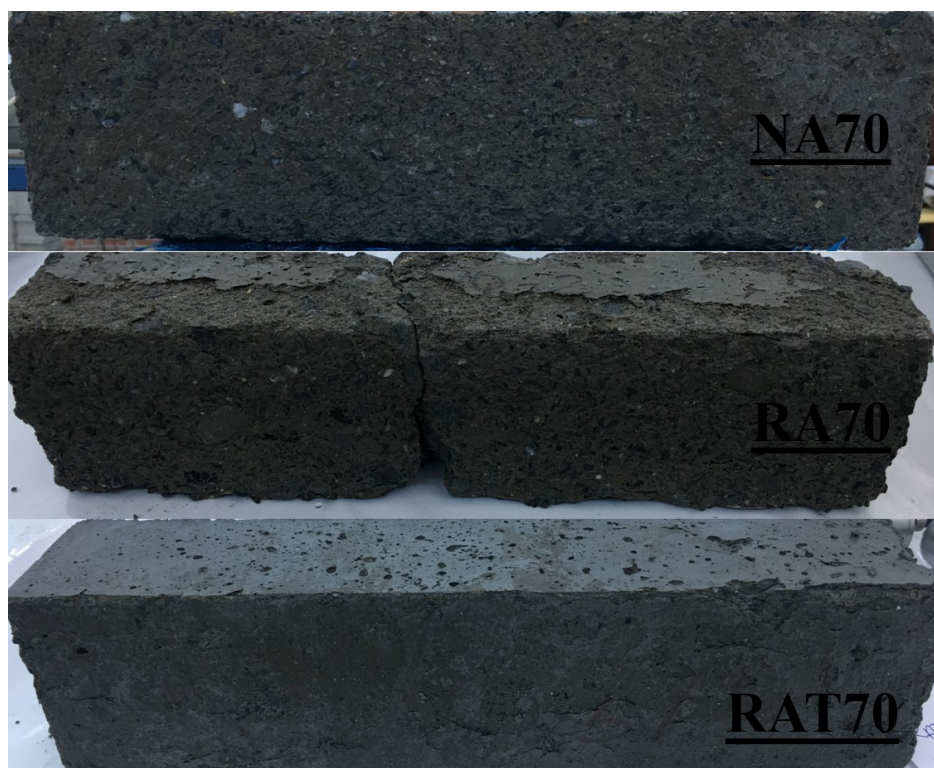


Figure 4.33. Photos of NA70, RA70 and RAT70 specimens after subjected to 126 cycles.

Same visual inspections were also done on lower water-to-cement ratio specimens and similar conditions were also visible. However, it was not pronounced as it was for higher water-to-cement ratio specimens (Figure 4.33).

Possible explanation of the contribution of slurry coating is the decreased water absorption of the recycled aggregates and cracks occurred by inner bleeding were minimized by the barrier formed after the slurry treatment [28]. So inner structure with less cracks performed better under freeze-thaw cycles. Also denser interfacial transition zone was supplied by the help of the slurry coating. Water-to-binder ratio of the coating slurry was relatively higher than that of higher water-to-cement ratio specimens whereas closer to that of lower water-to-cement ratio specimens and this may explain why higher water-to-cement ratio specimens were more enhanced with respect to lower water-to-cement ratio specimens.



Figure 4.34. Photos of NA45, RA45 and RAT45 specimens after subjected to 126 cycles.

4.5.2.2. Mass Losses. Mass losses were also measured on slurry method treated specimens and given in Figures 4.35 and Figure 4.36. Specimens were measured every week till disintegration and if one specimens from a batch is disintegrated that batch is removed from the cycles for all and measurement taken up to that week is taken into consideration.

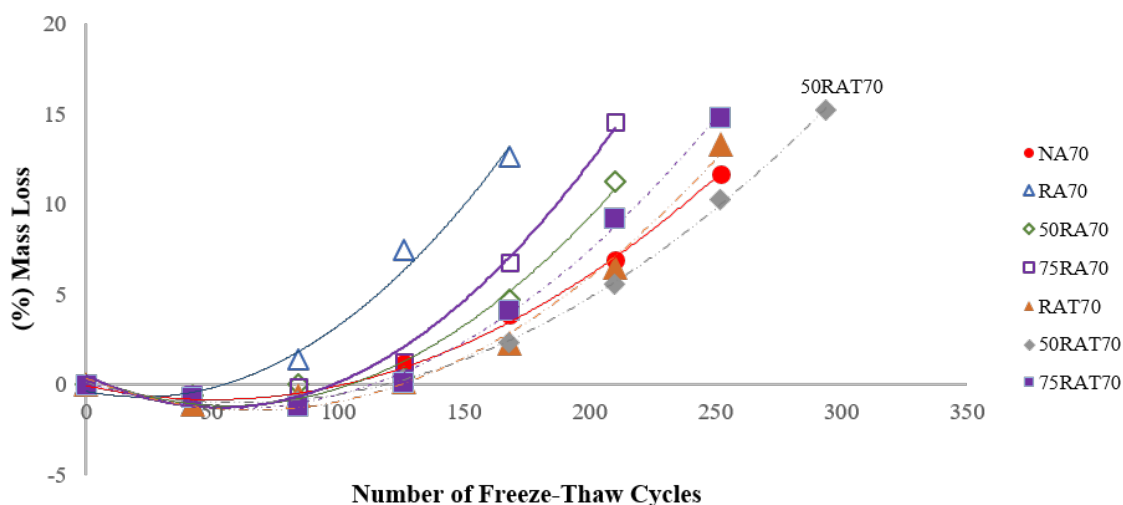


Figure 4.35. Mass losses of specimens with 0.70 water-to-cement ratio with increasing freeze-thaw cycles for both treated and untreated specimens.

When untreated specimens were compared with treated specimens, it is seen that influence of treatment is quite visible since treated specimens showed similar behavior to natural concrete specimens. Effect of treatment was seen on mass loss values of specimens. Specimens with all replacement levels showed similar values of mass values. RA70 specimens had shown 13% mass loss till disintegration in the 168th cycle whereas treated RAT70 specimens had shown only 4% mass loss in the 168th cycle. 50RAT70 specimens showed very good performance which is very close to natural concrete series and actually better than natural concrete series. Increase of mass losses of 50RAT70 specimens were also fitted with a trend curve which has an increasing slope as all the other specimens had but it is important to say that the increase in the slope is limited with respect to all the other specimens demonstrating the best performance in all the specimens with water-to-cement ratio of 0.70.

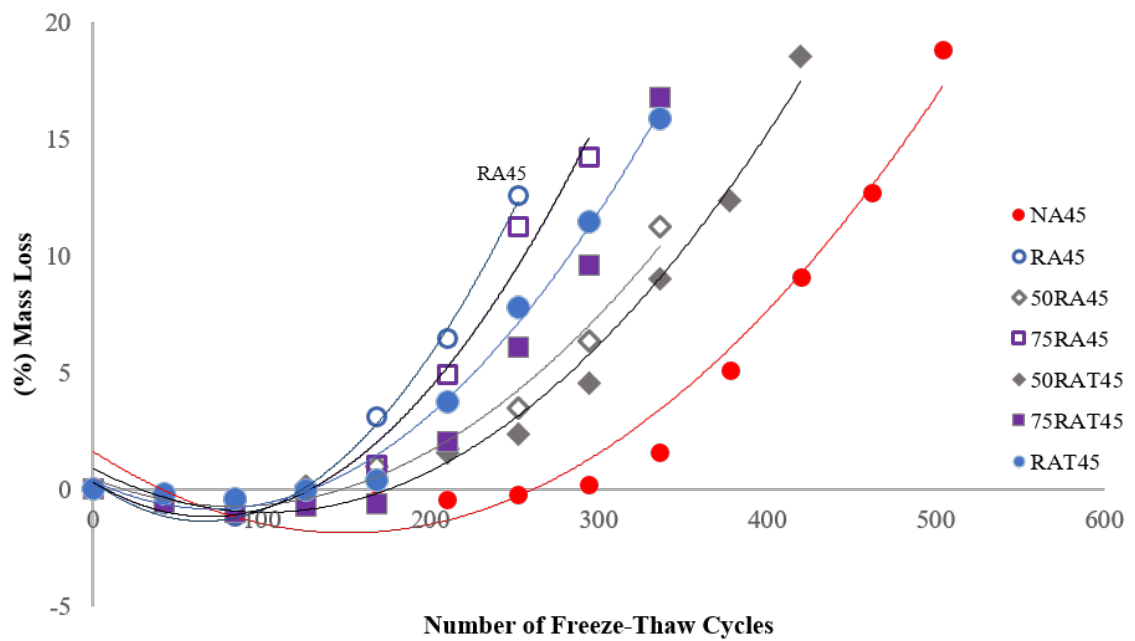


Figure 4.36. Mass losses of specimens with 0.45 water-to-cement ratio with increasing freeze-thaw cycles for both treated and untreated specimens.

When Figure 4.36 is inspected, it is seen that treatment of slurry method is also effective on specimens with water-to-cement ratio of 0.45. 50RAT45 specimens exhibited the best performance which is closest to natural concrete specimens containing only natural aggregates. 50RA45 specimens also showed good properties however 50RAT45 specimens survived more than 50RA45 specimens and suffered less mass losses in the same cycle amounts. When RA45 and RAT45 specimens are considered, it may be seen that RAT45 specimens survived more weeks and mass losses were likely 50% of RA45 specimens which demonstrates the effect of treatment significantly. Also, 75RAT45 specimens showed better performance with respect to untreated version 75RA45 specimens also they had less mass losses in same cycle amount with a ratio of likely 40%.

When Figures 4.35 and Figure 4.36 are inspected together to compare the effectiveness of treatment with different water-to-cement ratios, it may be seen that after treatment generally water-to-cement ratio of 0.70 specimens were more enhanced than specimens with water-to-cement ratio of 0.45. Treated $w/c=0.70$ specimens performed alike the natural concrete specimens whereas $w/c=0.45$ specimens performed better than untreated specimens however not as much as $w/c=0.70$ specimens.

4.5.2.3. Relative Dynamic Modulus (RDM). Relative dynamic modulus measurements were continued till it is impossible to take any measurements. It was not possible to take relative dynamic modulus measurements till the disintegration so RDM measurements were not the same amount as the mass losses or given in the resisted cycles results.

Specimens with water-to-cement ratio of 0.70 can be inspected from Figure 4.37. It is apparent that all treated specimens were better than all untreated specimens regardless of replacement level. Relative dynamic modulus values of untreated specimens decreased with increasing replacement level, but all treated specimens performed better however they also had the same sequence which is better performance with decreasing replacement level. 75RAT70 specimens were able to show dynamic modulus measurements two weeks more than untreated versions (75RA70). Apparently

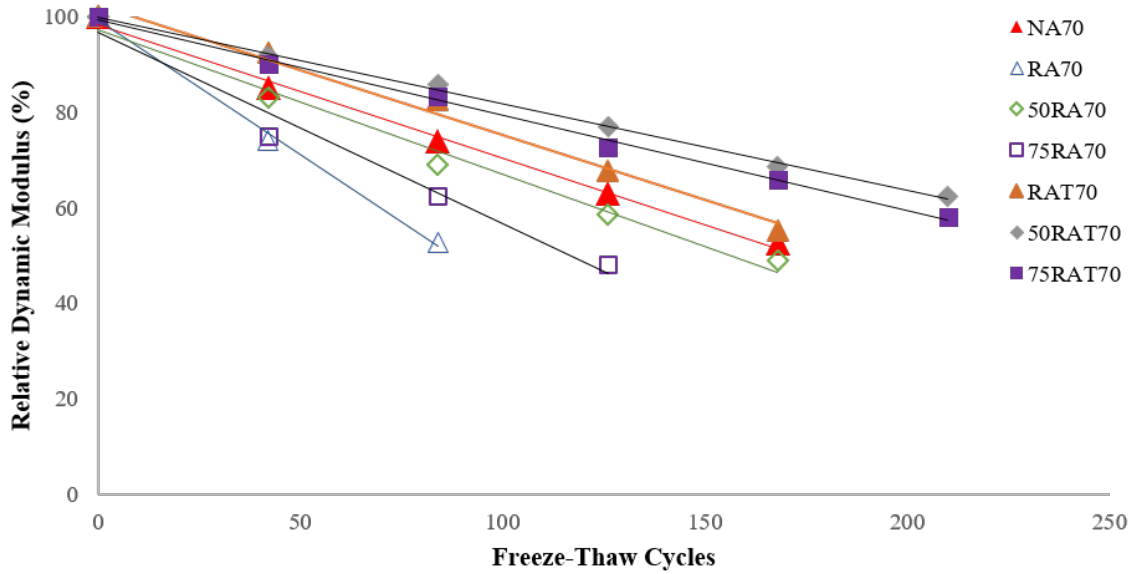


Figure 4.37. Relative Dynamic Modulus results for both treated and untreated specimens with $w/c=0.70$.

treated specimens resisted the freeze-thaw cycles better than untreated specimens by restricting the quick degradation.

In Figure 4.38 and 4.39, relative dynamic modulus results of $w/c=0.45$ specimens are given. Since these specimens exhibited closer levels of relative dynamic modulus, chart was separated with full replacement levels (0%,100%) and mid replacement levels (50%, 75%).

When relative dynamic modulus results are compared, it is visible that full replacement level specimens with water-to-cement ratio of 0.45 are enhanced since they had less losses with respect to untreated specimens. Natural concrete specimens performed better than both as expected. For mid replacement levels, it is also seen that treated specimens performed better with respect to their untreated versions. For 50% replacement level, modulus values for first weeks does not seem much influenced of the treatment however, in last week 50RAT45 specimens performed better and thus created difference in modulus measurements and correspondingly measurements could

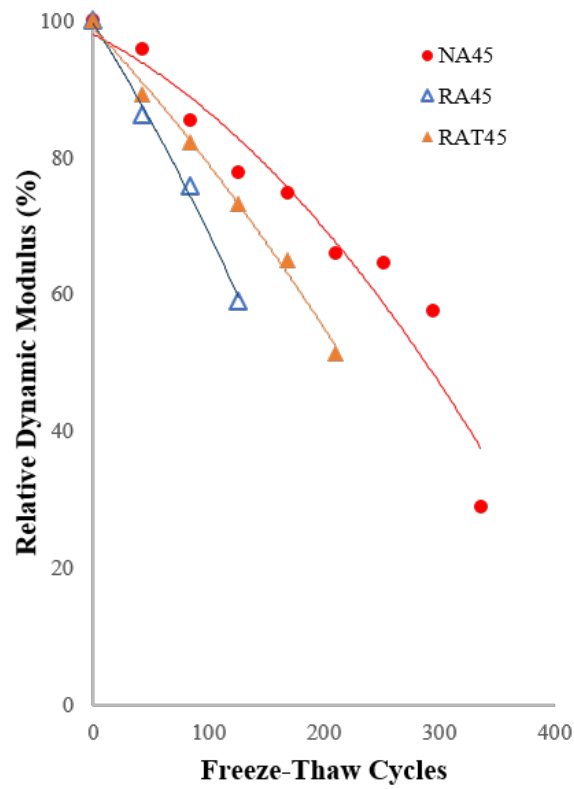


Figure 4.38. Relative Dynamic Moduli of specimens with 0% and 100%

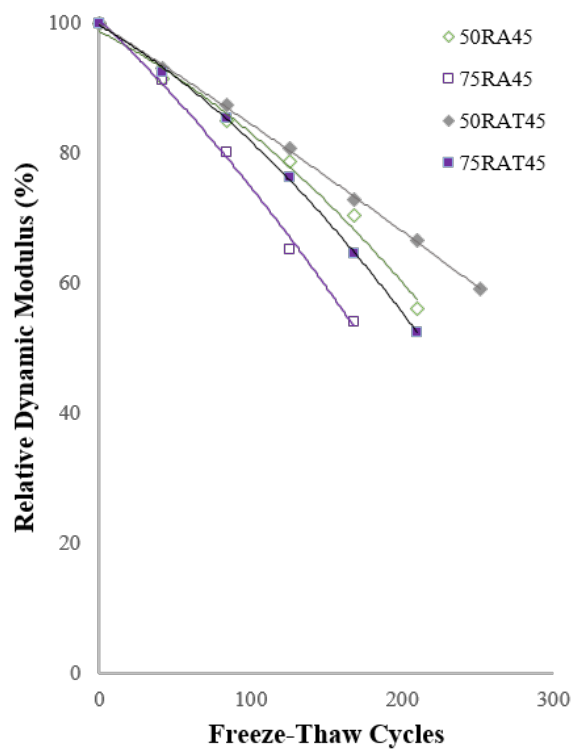


Figure 4.39. Relative Dynamic Moduli of specimens with 50% and 75%

be taken for one more week.

When Figures 4.37, 4.38 and 4.39 are investigated together, it is possible to see that effect of treatment is significantly apparent for $w/c=0.45$ specimens whereas, performance of treatment for $w/c=0.70$ is extremely good.

4.5.2.4. Residual Flexural Strength of Concrete with Recycled Aggregates. All series of specimens were tested under bending to determine the residual flexural capacity after each week. Three specimens from each batch were removed from the freeze-thaw cabinet and was exposed to four-point bending. Series that have one specimen that have disintegrated before flexural testing was found to be over and cycles were not continued if there is any specimen left in the cabinet for that series.

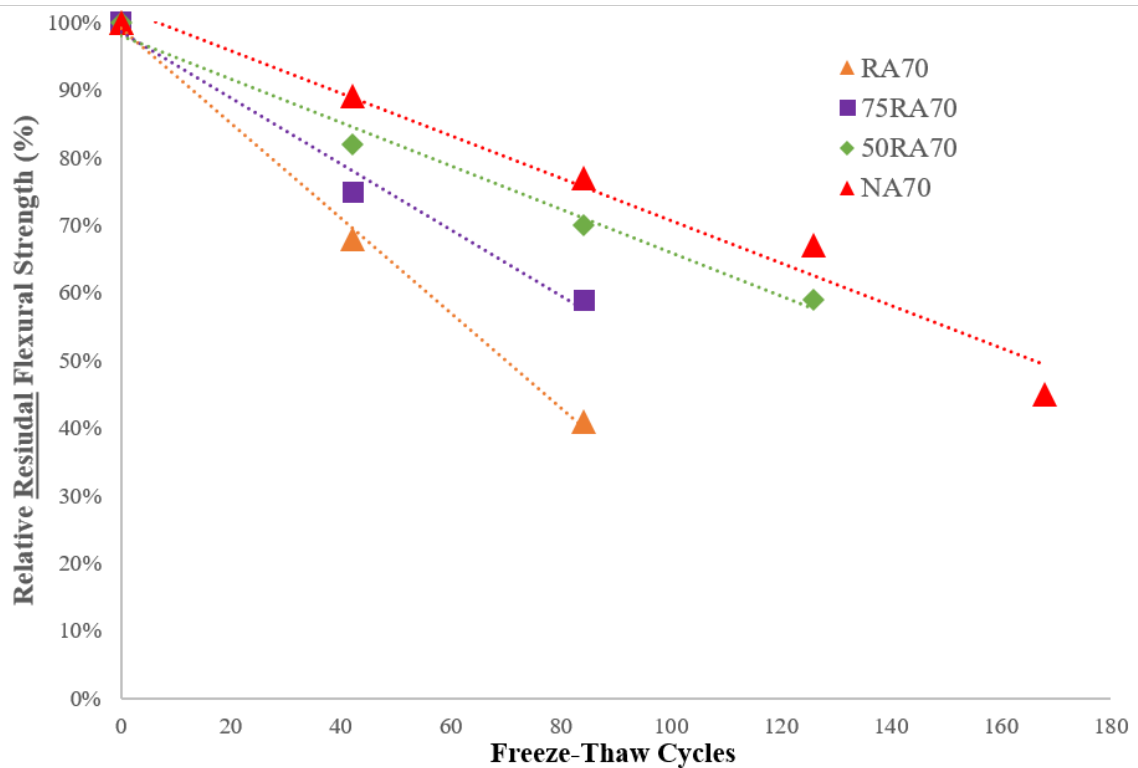


Figure 4.40. Residual flexural tests of $w/c=0.70$ specimens with different replacement levels.

When Figure 4.40 is inspected, first thing to mention is that recycled aggregates specimens have deteriorated much with respect to natural concrete specimens and it is easy to say that with the increasing replacement level this deterioration became more visible. Natural concrete specimens were able to withstand freeze-thaw cycles and flexural tests were done for more weeks than other specimens. Although they were assessed and normalized to their values in zero cycles, replacement level highly affected the concrete flexural strength and this is surely connected to low resistance of recycled aggregate specimens and sudden decreases in strength are seen for high level replacement of aggregates. In the 2nd week (84 cycles) RA70 specimens were found to be in the 41% of their initial flexural strength although NA70 specimens which contains only natural aggregates had residual strength as 45% after 168 cycles. This simply shows that use of recycled aggregate in concrete may differ the final situation when properties were analyzed in combination with each other. Here in this part of the study, effect of freeze-thaw cycles on flexural strength were tried to be understood. When previous mechanical properties were investigated, it may be said that use of 50% replacement level may seem applicable, but in severe conditions these tests demonstrate that this level of replacement may also affect the concrete properties which is structured to withstand a lifetime of 4-5 decades at least. Specimens with 50% replacement level (50RA70) showed decrease to 59% after 3 weeks of cycles and it is close to residual strength results of natural concrete specimens (RA70) for this water-to-cement ratio.

When Figure 4.41 is inspected, it may be seen that with residual flexural strength of all samples not only decreased with the increasing number of freeze-thaw cycles but also slope of these decreases decreased with the increasing replacement level. Since then biggest decrease in residual flexural strength was inspected in RA45 specimen as expected. RA45 specimens were out of the cycles in after 3 weeks in which their flexural strength fell to 45% of initial value. Other series of specimens were continued for more weeks. Natural concrete specimens decreased to 54% after 210 cycles (5 weeks) and flexural strength of 50RA45 specimens were reduced to 57% after 168 cycles (4 weeks). 75RA45 specimens decreased to a similar value in three weeks. Their residual strength at that week (62%) is better than RA45 specimens.

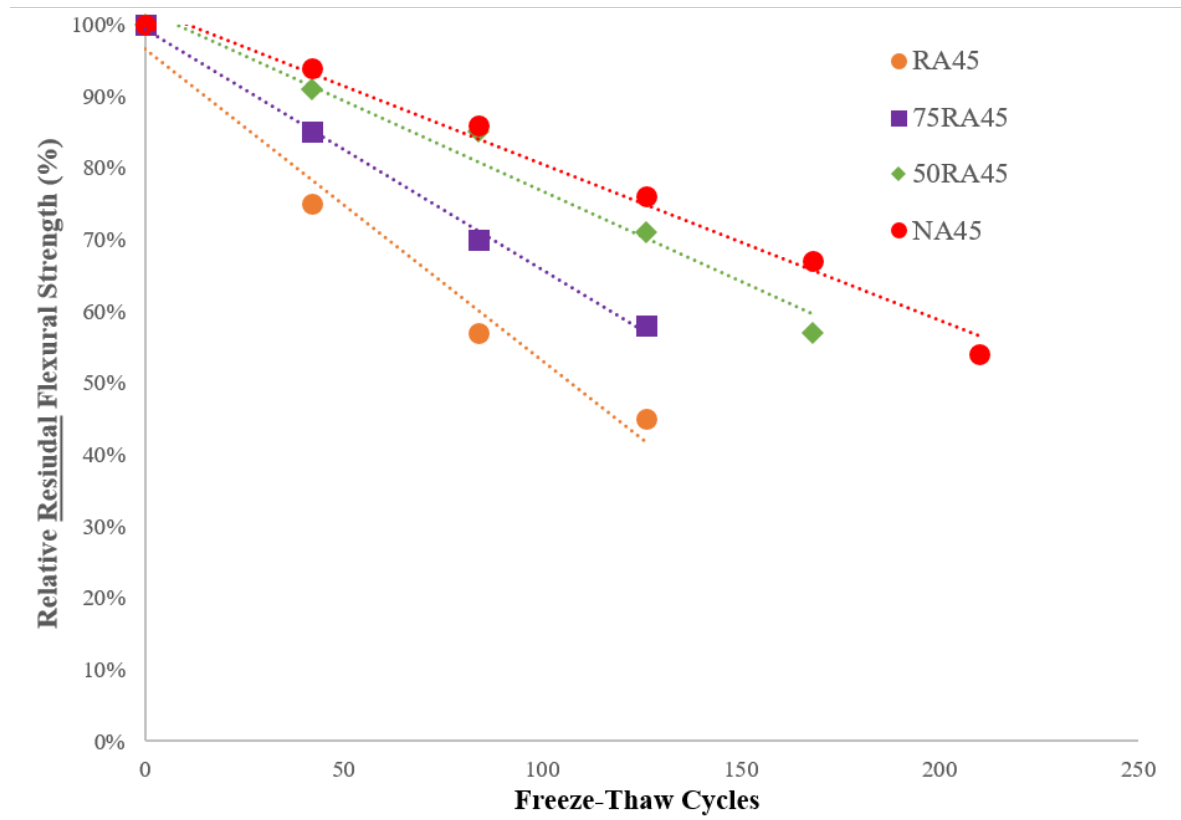


Figure 4.41. Residual flexural tests of $w/c=0.45$ specimens with different replacement levels.

When weekly values of strength were compared, after the first week of the cycles, only RA45 specimens exhibited a sudden decrease in strength, the other series were close to natural concrete NA45 series. In the second week, 50RA45 specimens were again very close to each other. In the third week, difference between all specimens were increased, natural concrete specimens were proved to have better resistance with respect to specimens that contain recycled aggregates. Equally important as natural concrete behavior, 50RA45 concrete demonstrated closer behavior to natural concrete specimen than other specimen series did.

4.5.2.5. Residual Flexure Strength of Specimens with Slurry Treatment. Flexural residual strength analyses were also conducted on treated specimens. In previous sections, mass loss and relative dynamic modulus values have proven that treated specimens performed better under freeze-thaw action. These tests were conducted to see how much their mechanical properties were affected from those freeze-thaw cycles.

When Figure 4.42 is inspected, it may be easily seen that treated specimens behaved very well with respect to untreated specimens. 50RAT70 series residual flexural strength results were very close to concrete series containing only natural aggregates which indicates that effect of treatment is intact and useful when use of recycled aggregates were considered. 50RAT70 specimens were 5% better than 50RA70 specimens when results of every week were compared. Since 50RA70 specimens also performed well and close to natural aggregate results this difference was not much. But for 75% and 100% replacement levels, differences with increasing number of cycles were getting bigger. 75RAT70 specimens showed 10% higher residual flexural strength in the first week cycles, in the 2nd week cycles difference was 12%. When 100% replacement level was compared, RAT70 series specimens had 83% of its initial value whereas RA70 specimens had only 68% of their initial strength. In the 2nd week measurements this difference was doubled. RA70 specimens lost 51% of their initial strength but treated specimens (RAT70) was down to 74% of their initial strength. This surely clarifies the effect of treatment increased with an increasing slope with the increasing level of replacement.

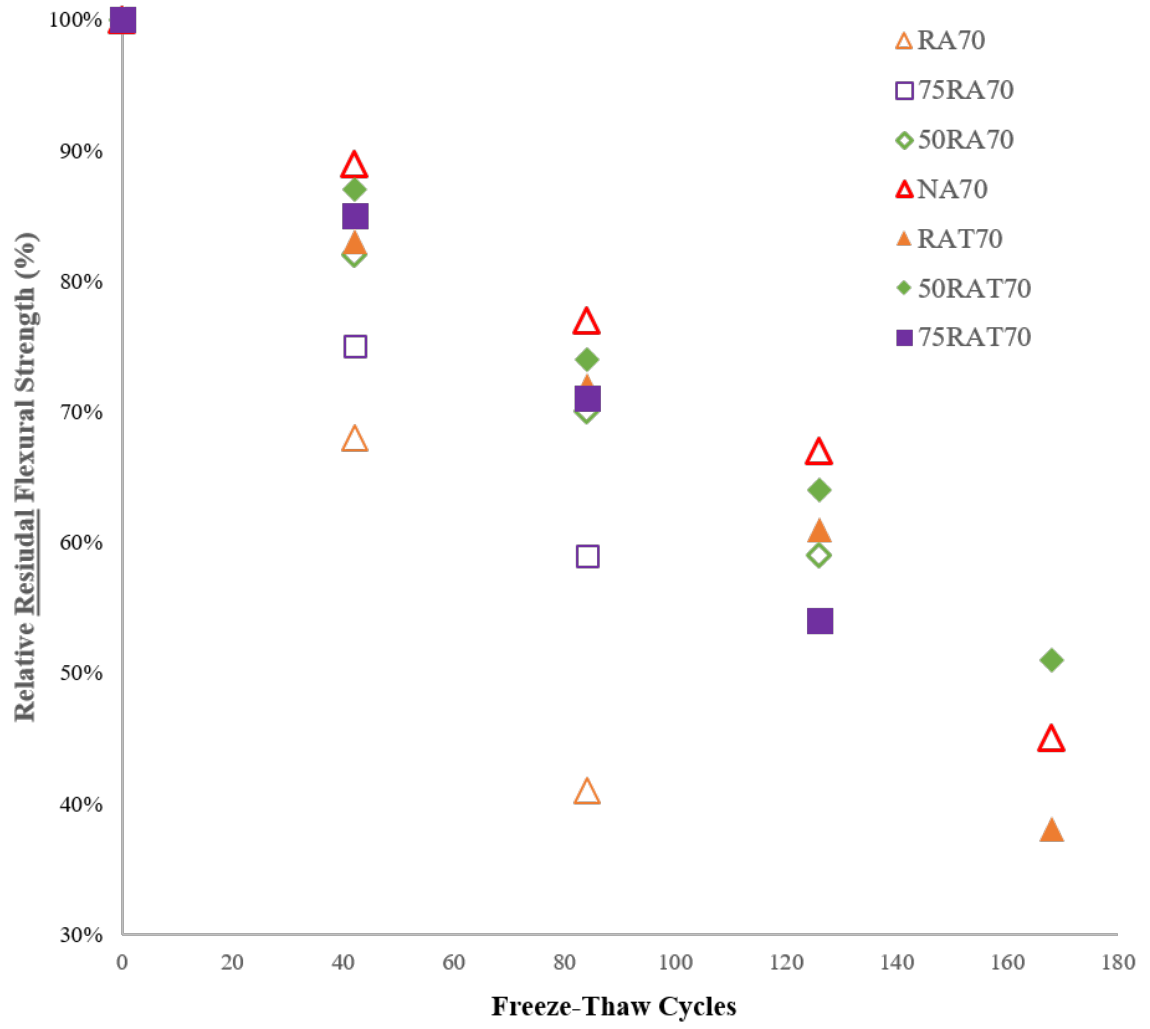


Figure 4.42. Residual flexural tests of $w/c=0.70$ for both treated and untreated specimens with different replacement levels.

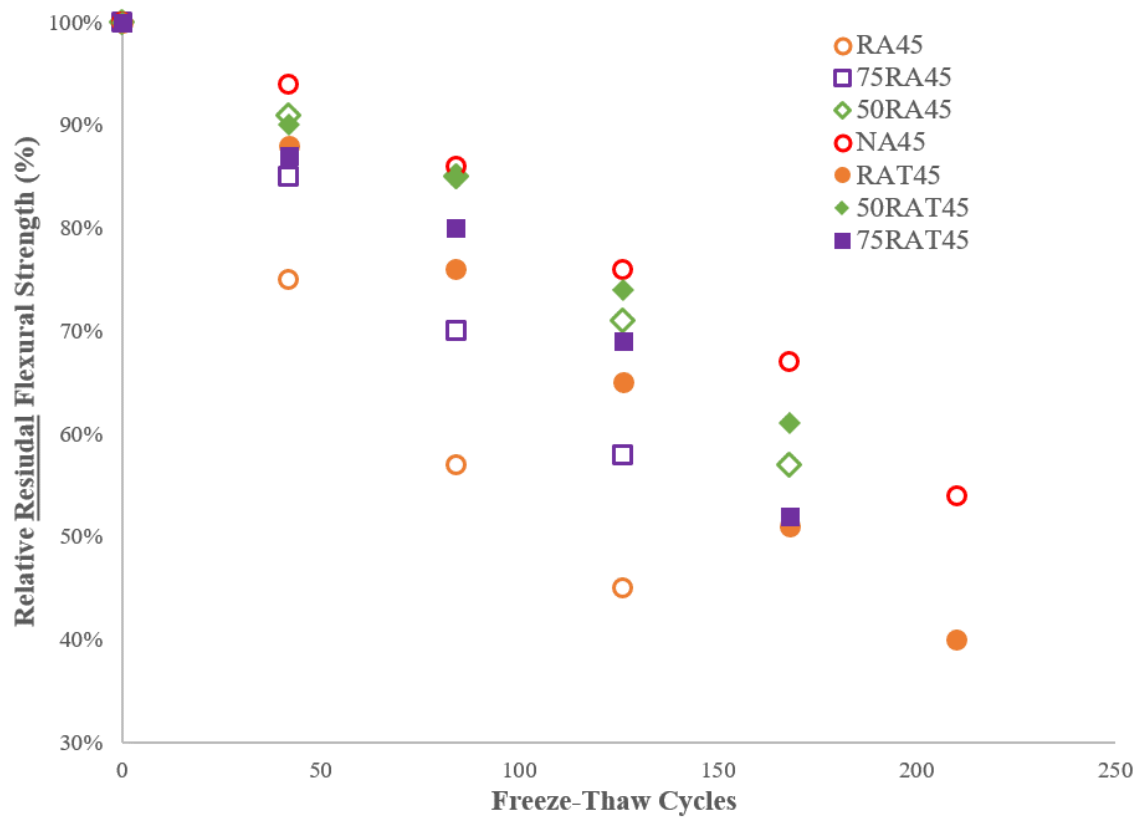


Figure 4.43. Residual flexural tests of $w/c=0.45$ for both treated and untreated specimens with different replacement levels.

When Figure 4.43 is inspected, for $w/c=0.45$ specimens, specimens containing only natural aggregate (NA45) demonstrated the best performance. Best performance after natural concrete specimens were 50RAT45 specimens which are treated specimens with 50% replacement level. For all 3 weeks' results, 50RAT45 specimens performed very close to natural concrete specimens. In the 4th week, 50RAT45 specimens deteriorated more than NA45 specimens. 75RAT45 and RAT45 specimens also showed good performance with respect to untreated versions. Difference of the flexural residual strength for RA45 and RAT45 specimens increased with increasing rate. In the first week, difference between them was 12%, in the second week it increased to 19% and in the third week it was 20%. No more tests could be done on RA45 specimens after 3rd week whereas RAT45 specimens remained intact for two more weeks and provided information for residual flexural strength. 75RAT45 specimens were also enhanced with treatment and showed similar results to RAT45 specimens whereas before treatment RA45 and 75RA45 specimens had more distinct results. Given these points it may be said that treatment effect was more apparent and beneficial for higher replacement levels.

When effect of treatment with respect to water-to-cement ratio of specimens were investigated, it may be said that it was more useful for $w/c=0.70$ specimens especially for 100% replacement level. After the second week, RA70 specimens were reduced to 41% of their initial residual strength whereas their treated version series RAT70 specimens were reduced to 71%. This difference 30% is the biggest enhancement viewed in entire series. Enhancement for other replacement levels (50%, 75%) exhibited closer results.

4.6. Fatigue Strength of Concrete

Fatigue tests has been investigated based on the number of load cycles and starting from this, resistance of concrete to fatigue is generally assessed by the number of cycles. However, the number of cycles to crushing are not the only aspect to analyze for behavior of concrete under fatigue loadings. There are other essential aspects which are the stiffness and strain developments but these aspects are not much concerned as

cycle numbers resisted. In this study, besides numbers of cycles to failure, the developments of stiffness and strain were focused on for a more mechanism-orientated analysis of concrete fatigue [59]. Fatigue stress differ from monotonically increasing stresses and creep loads due their complex load characteristics. Each load cycle alters formation of the concrete and thus influencing fatigue behavior. Concrete fatigue strength and number of cycles may not demonstrate actual fatigue resistance attitude of concrete and may not present any information about concrete condition until failure. Therefore, concrete behavior against fatigue should be investigated in-depth by approaching the situation inspecting the strain developments throughout the specimen history under cyclic loads. Strain developments and stiffness evolution is absent in the database for fatigue loading of concrete. Exploring these aspects in detail when recycled concrete aggregates are used in the composition of concrete is going to be the first in the literature. And also 2 different water-to-cement ratio with 4 different replacement level are considered, this study seemed to give quite illuminating information on comparison of different levels of recycled aggregates usage. This little knowledge in literature may be expanded substantially.

Continuous cyclic loads are characterized by 3 primary parameters: (a) stress, (b) load frequency, (c) waveform. In this study, two of these parameters were fixed whereas there were 2 different maximum stress levels.

4.6.1. Number of cycles to failure

Influences of the maximum stresses on the number of cycles until failure is highly important and also load frequency had major influence on number of cycles to failure [60], [61]. For this study, load frequency was selected as 10 Hz with the previous findings [10, 11, 56, 62] on normal strength concrete. Generally, it has been seen that for normal strength concrete specimen's higher frequency of loading generated higher number of cycles to failure. Although number of cycles to failure were higher with respect to lower frequency loadings, test durations were found to be lower.

Stress levels were also decisive in the number of cycles to failure as can be expected. Higher maximum stress levels caused less number of cycles to failure and also lower minimum stress levels also caused less number of cycles as given in the literature.

In our study, normal concrete strength specimens were tested under 10 Hz cyclic loadings with two different maximum stress levels (75% and 85%) and one minimum stress level (5%).

In literature, fatigue tests were conducted however especially investigators focused on the number of cycles to failure since accurate sampling of deformation data in such high frequencies was out of capabilities for earlier investigations. Given these points, strain and stiffness developments were not sampled in much studies in literature [62]

Although number of cycles to failure results give information about the performance of specimens, since they are noticeably scattered, it is not wise to use them as single value from one specimen. That is why in this study, number of specimens tested were maximized as much as possible.

Number of cycles until failure were considerably scattered so data obtained from fatigue tests were given with error bars to see the fluctuation in the results in Figure 4.38. Error bars show maximum and minimum number of cycles as well as means of the results. Number of cycles to failure for specimens with water-to-cement ratio of 0.70 for both maximum stress level ratios (0.75 and 0.85) are given in Figure 4.44.

When Figure 4.44 is examined, probably first thing to mention is that increasing replacement level affected the means of the number of cycles to failure since for both 0.85 and 0.75 maximum stress levels specimens survived less cycles with the increasing replacement level. RA70 specimens exhibited the minimum mean among all specimen series. When 85% stress level is examined, means of NA70, 50RA70 and 75RA70 specimens are highly similar. 75RA70 specimens survived less cycles and showed higher deviation within the results with respect to lower replacement levels. For this level of maximum loading, RA70 specimens showed the highest level of deviation. When

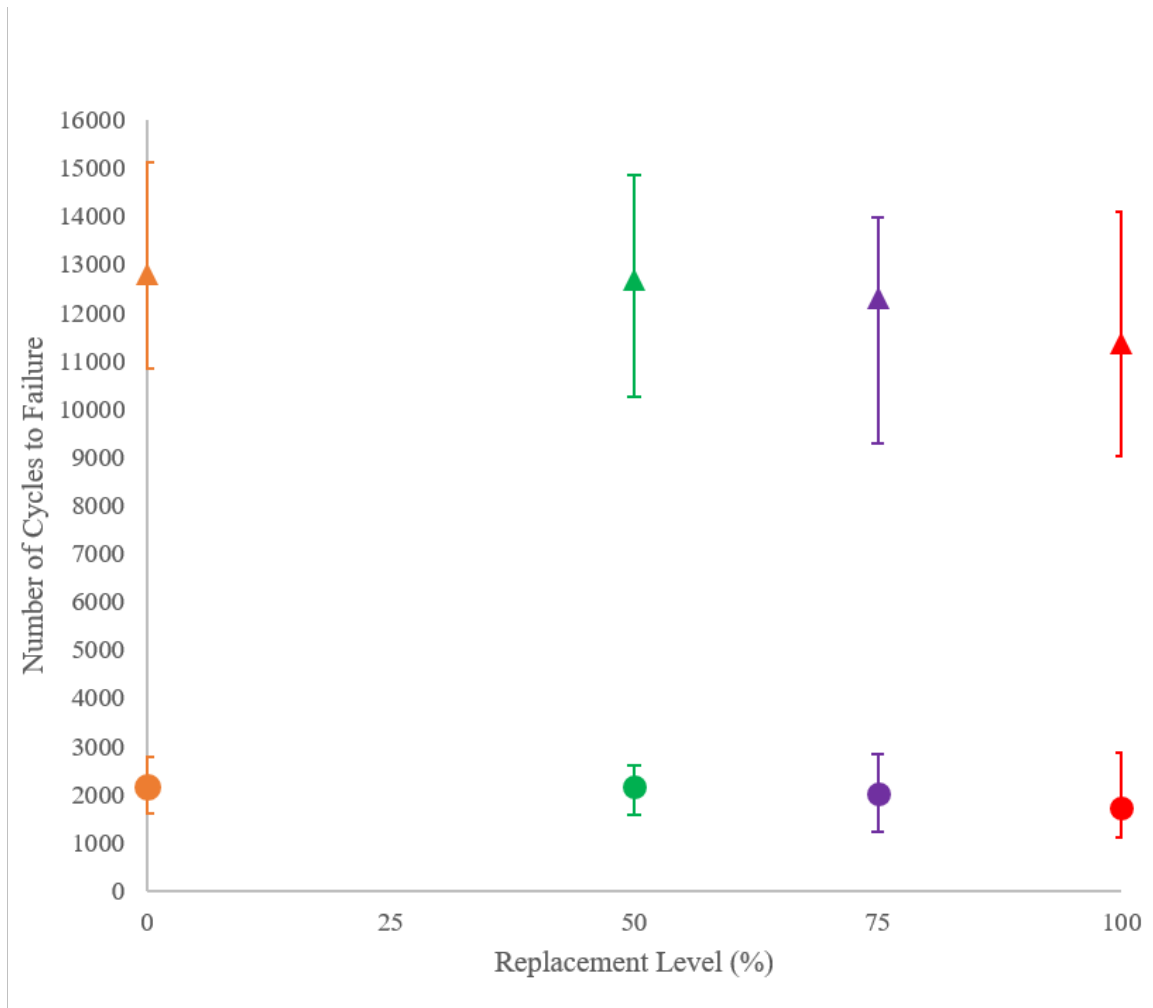


Figure 4.44. Number of cycles to failure of $w/c=0.70$ specimens with increasing replacement level of specimens.

75% stress level is analyzed, natural aggregate specimen series (NA70) endured higher number of cycles with respect to other series under same stress ratios and other series accordingly endured less cycles with the increasing replacement level. Deviation of the results are considerably high but quite similar for each specimen series. With the help of the error bars, it may be seen that specimen that have endured most cycles is from NA70 specimen set whereas specimen that have endured the minimum number of cycles is from RA70 specimens set.

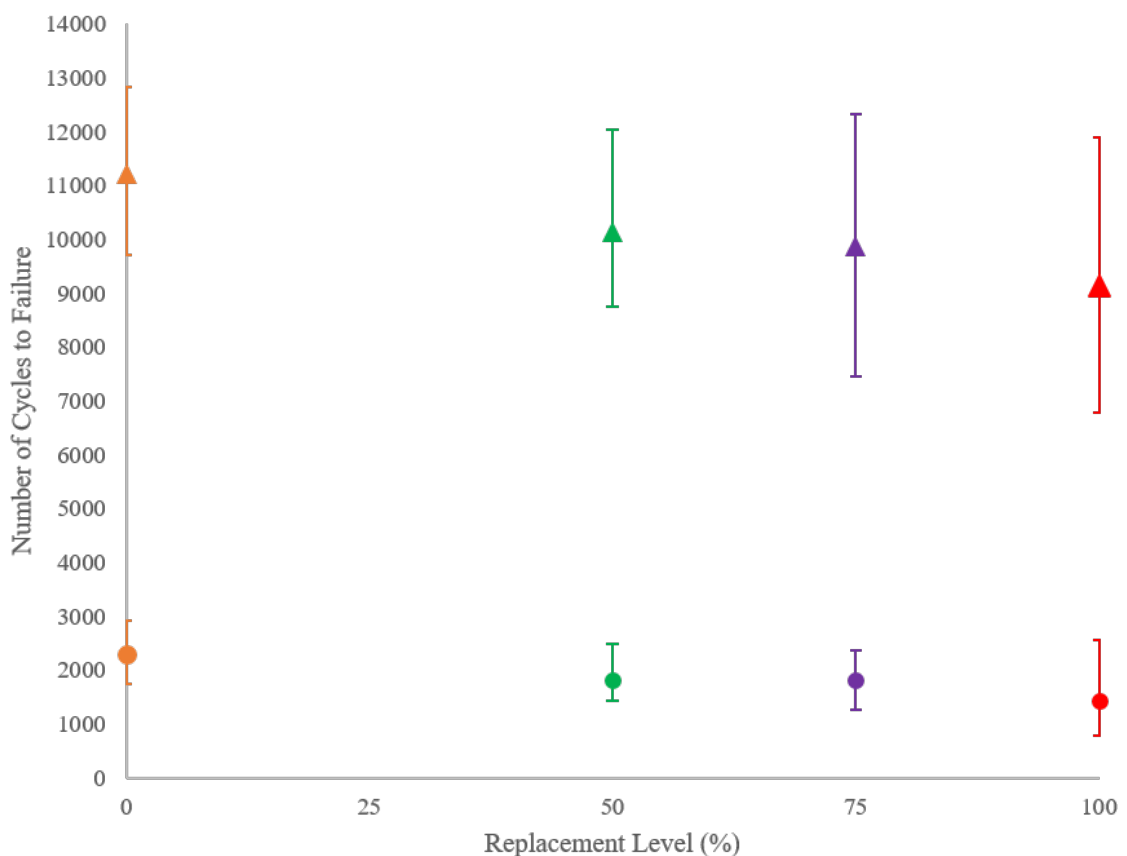


Figure 4.45. Number of cycles to failure of $w/c=0.45$ specimens with increasing replacement level of specimens.

When number of cycles to failure values are compared in Figure 4.45, it may easily be said that mean of the results are decreasing with the increase of the replacement level however this reduction is not very apparent to conclude on. Since all specimens were tested under their own mean compressive strength that is why performance of

specimens is not much affected as much as in the decrease in the compressive strength results with the increasing replacement level. In several studies, normal strength concrete specimens did not show much explicit differences when number of cycles to failure were compared in the same level of maximum and minimum stresses.

If error bars are examined, maximum and minimum number of cycles of those specimen series have survived can be assessed. Under 85% maximum stress level ratio, natural concrete specimens have endured highest number of cycles which is likely 3000 cycles and minimum number of cycles to failure was observed from a specimen from RA45 series. When the length of the error bars for each series are inspected, it is seen that RA45 specimens experienced the highest deviation which may contributed to more complex matrix system in these specimens. Also 50% and 75% percent specimens showed scatter but not as much as full replacement level specimens. Deviation of these specimens were not more than natural concrete specimens but also to be noted set of these specimens were formed with 3 samples however sets of NA45 and RA45 samples were formed with 5 samples.

When effect of water-to-cement ratio was assessed, it can be said that number of cycles to failure does not differ when concrete quality changes. Both water-to-cement ratio specimens endured approximately 2000 cycles under 85% maximum loading whereas for specimens under %75 maximum stress level of loading some effect of water-to-cement ratio was monitored. Lower water-to-cement ratio specimens endured less cycles with respect to higher water-to-cement ratio specimens which was also similar to findings in a study by Thomas *et al.* [11]. The decrease in the number of cycles is greater when natural concrete quality is higher whereas decrease is minimal when concrete quality is closer to the old concrete quality of the adhered mortar on the recycled aggregates.

4.6.2. Strain and Stiffness Developments

4.6.2.1. Maximum strain at maximum stress. All specimens were exposed to cyclic loads till failure. Strain data were found to be maximum at maximum stress levels

since strain values were always increasing with the increase of the number of cycles. Maximum strain at maximum stress data was collected to observe the amount of strain any specimen can endure under fatigue loading. Higher the strain values, higher the specimens were able to resist failure due to fatigue.

Here in Figure 4.46, maximum strain levels for specimens with 0 and %100 replacement level are given for each individual specimen and average of those specimens are also given separately.

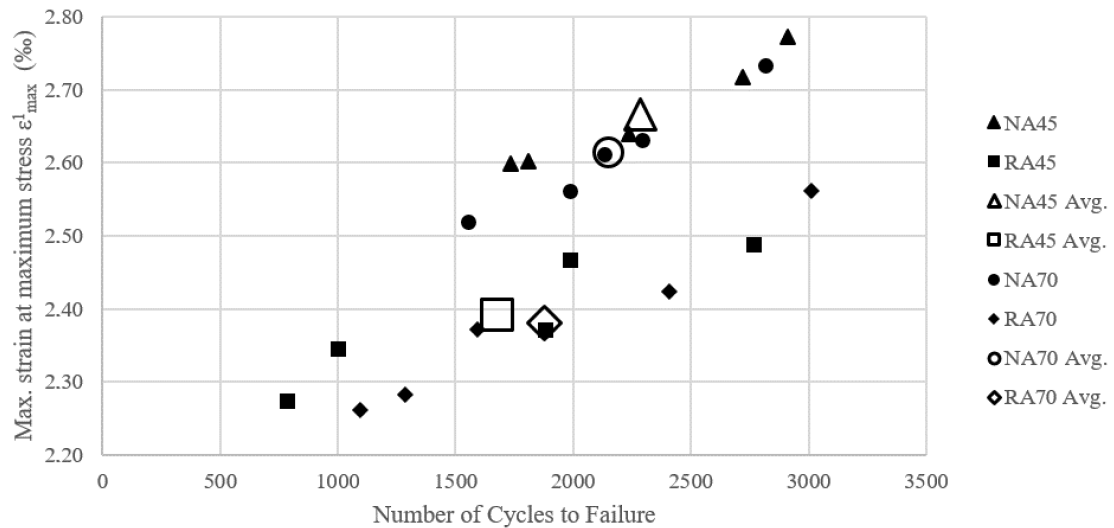


Figure 4.46. Maximum strain at maximum stress of $S=0.85$

When results are viewed from Figures 4.46, 4.47, natural concrete specimens have sustained more strain till failure with respect to recycled aggregate concrete specimens for both water-to-cement ratios and for both stress levels. It is also seen that for lower maximum stress level differences between natural and recycled aggregate concrete specimens were less. When higher level of stress is considered, this situation presents deficiency for fatigue loading of recycled aggregates and a major difference if recycled aggregates were to be used in structural concrete.

When a comparison was to be made for water-to-cement ratio, also for higher level of stress, NA45 specimens had sustained higher amount of strain with respect to NA70

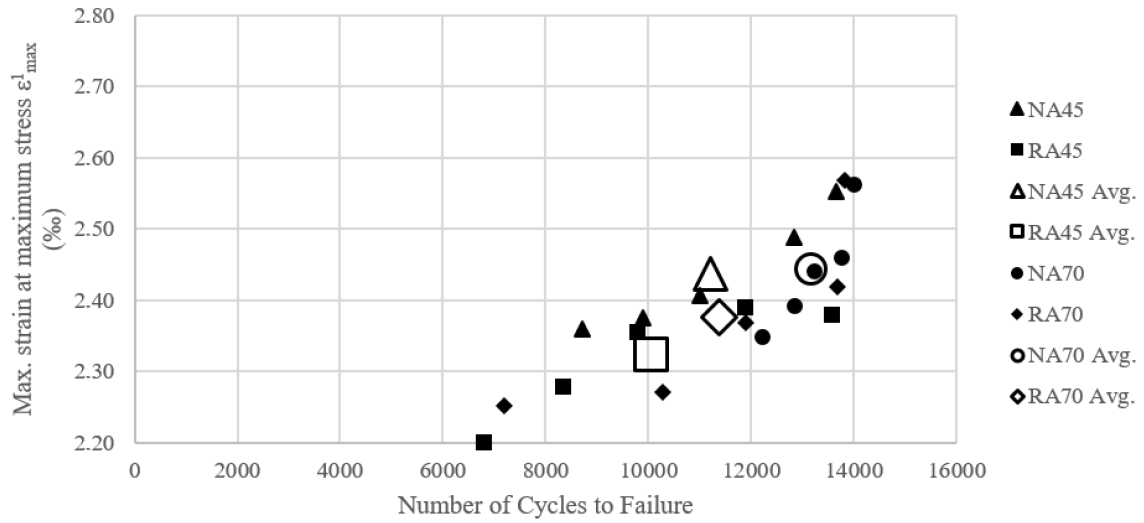


Figure 4.47. Maximum strain at maximum stress of $S=0.75$

specimens but this difference was not seen for lower stress level. This variety because of the water-to-cement ratio is not valid when recycled aggregates are considered, for lower stress level it is seen that RA45 specimens were not able to endure more strain with respect to RA70 specimens however, for higher level they were able to endure closer values of strain. This may be an information when using recycled aggregates with lower water-to-cement ratio that performance of the concrete is affected adversely with the decreasing lower water-to-cement ratio. Natural concrete specimens also did not show much deviation in number of cycles to failure (N_f) as was also given in previous sections and herein also individual strain results are closer to each other with respect to recycled aggregate concrete results. But it should be also noted that this condition is highly significant for high stress rather than low stress level. When lower stress fatigue results are inspected, it is seen that natural concrete specimens also deviate as much as recycled aggregate concrete specimens which may be related to higher duration of the test when maximum stress level is lower. Or it may be connected to the behavior of recycled aggregates that were less predictable when under higher stress level of cyclic loads.

When specimens were observed individually, it is explicitly seen that with the increasing number of cycles to failure (N_f), maximum strain under maximum stress values were increasing. When linearity of the results for each specimen set was viewed, it is seen that for both stress level, natural concrete specimens had displayed higher fit whereas recycled aggregate specimens were also linear but R^2 values of these specimen sets were lower.

Recycled aggregate specimens endured similar amounts of strain for both maximum stress levels whereas natural concrete specimens were able to resist cyclic loads up to higher levels of strain under higher stress level. Contradictory to recycled aggregate concrete results, natural concrete strain levels resisted decreased under lower level of stress and fell to strain levels that are closer to recycled aggregate results. This may be concluded as a limit for maximum strain level for recycled aggregates as strain level do not increase more after maximum stress level of 75%.

Most probable cause of this discrepancy between natural and recycled aggregate concrete is the complicated structure of the interfaces in concrete containing recycled aggregate specimens. Although they were subjected to lower amount of stress with respect to natural concrete (since their maximum compressive strength is lower) they proved to perform worse underneath cyclic loads and this phenomenon should be considered when recycled aggregates were to be used in structural applications especially in which dynamic loads are more involved. Thomas *et al.* [11] also found that the negative effect of the recycled aggregates on the dynamic properties is greater than that caused on the compressive strength. However, Xiao *et al.* [10] concluded that there was no effect of recycled aggregates on dynamic behavior of concrete.

4.6.2.2. Strain at first cycle at maximum stress (ε_{max}^0). Strain data were collected all the test duration so that all strain data at maximum stress increasing with the number of cycles are recorded. It is the strain value that were formed at the first peak load, in other words, highest strain in the first cycle of the fatigue loading. Results of the strain values that all natural and recycled aggregate concrete specimens experienced are given

in Figures 4.48 and 4.49. These strain values are significant since they give idea about the first behavior to the loading which is up to the maximum stress level which are 0.75 and 0.85. Generally speaking when a concrete specimen is loaded up to this level of its compressive capacity, its behavior is going to change since these levels of loading correspond to plastic deformation region. Any behavior beyond elastic region will not be easily predicted because of the loss of the linearity and the permanent deformation occurred.

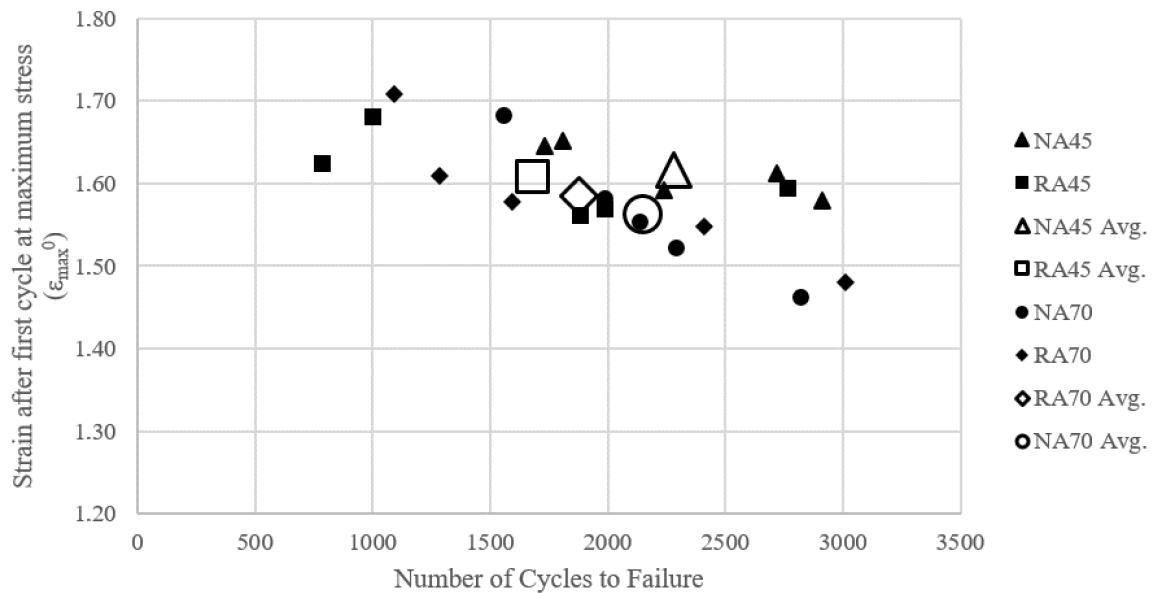


Figure 4.48. Strains at first cycle at maximum stress level of 0.85

When Figures 4.48 and 4.49 are inspected, effect of incorporation of recycled aggregates, water-to-cement ratio and level of maximum stress and their combined effects at first cycles may be compared and investigated deeply. When average values (big markers) are inspected, all 4 specimen series had experienced similar average strains at the start for $S_{max} = 0.85$. When high level stress is applied in the first cycle, it is acceptable to have specimen behavior somehow complex. Also for these specimens there is not a strong correlation between the individual results except NA70 specimens.

When lower stress level results are investigated, similarly it is seen that average results of all series are close to each other. Also there is not much linearity between

the results generally. If there had been a linear relation, that would give a quick idea about the number of cycles to failure just within the first cycle which does not seem very coherent. Since these measurements are the start of a loading sequence and does not bear any information about the latter parts of the study, it is more convenient to analyze these results as if they are monolithic loadings. However, it may be said that when specimens are inspected individually, it can be said that they bear some information about number of cycles to failure because as specimens that had higher first strain endured less number of cycles. But a linear proportionality is not valid since all specimens do not fit but generally first strain values are decreased when going to the right part of the graph.

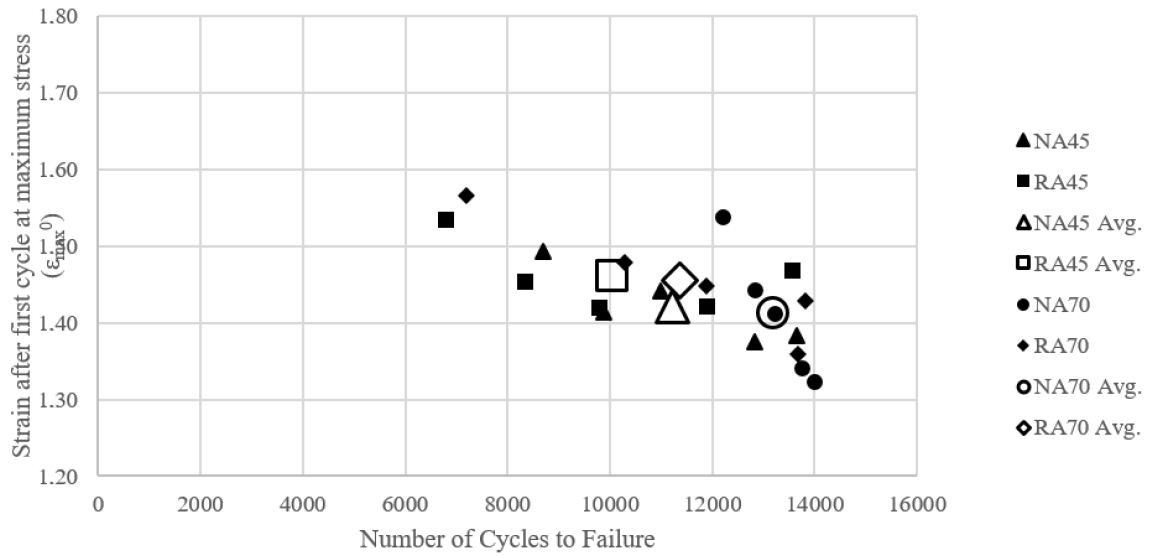


Figure 4.49. Strains at first cycle at maximum stress level of 0.75

4.6.2.3. Strain development at maximum stress ($\Delta\epsilon_{max}^1$). Strain data are collected for all the test duration so that all strain data at maximum stress increasing with the number of cycles are recorded. For the evaluation of the result, another important result is the development of strain, in other words, difference of the maximum strains between the first and the last cycles. Results of the strain development at maximum stress level for natural and recycled aggregates concrete are given in Figures 4.50 and 4.51.

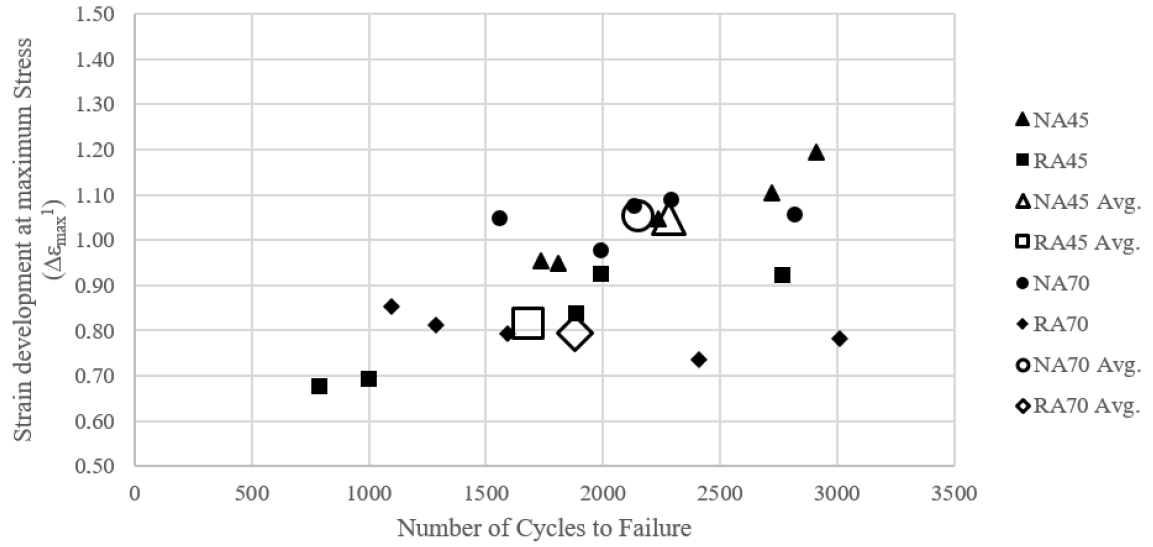


Figure 4.50. Strain development at maximum stress level of 0.85 ($\Delta\epsilon_{max}^1$)

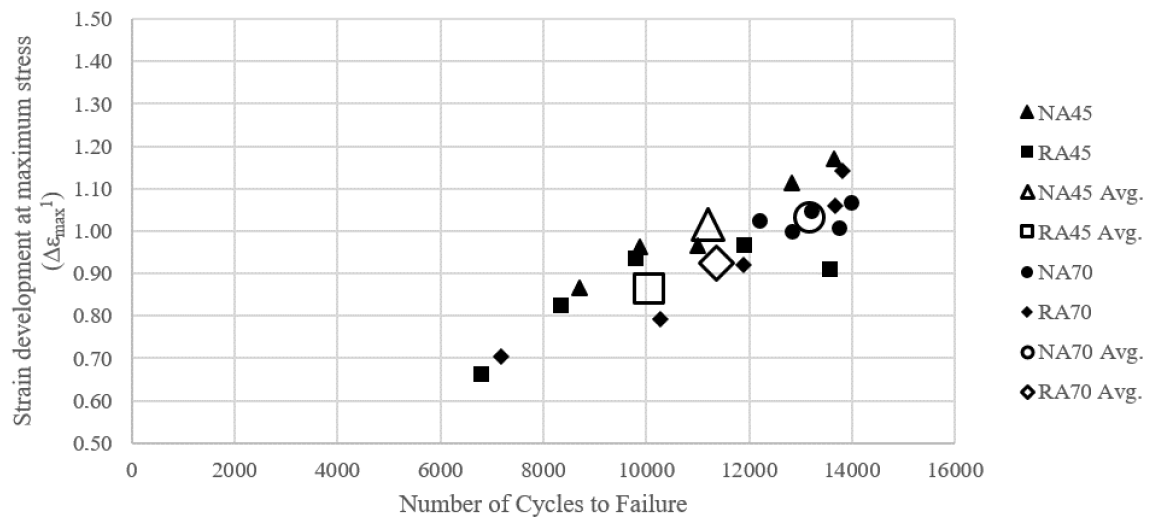


Figure 4.51. Strain development at maximum stress level of 0.75 ($\Delta\epsilon_{max}^1$)

When strain development results are inspected from Figures 4.50 and 4.51, first thing to mention about strain values is the difference that originates from the maximum stress level. The most significant parameter is the maximum stress level since strain developments of series differed when maximum stress level is higher. When $S_{max} = 0.85$, natural concrete specimens had more strain development and did not fail till higher strain formation but recycled aggregate specimens could not endure much number of cycles because of the amount of strain that they can endure seemed to be less with respect to natural concrete specimens. When $S_{max} = 0.75$, this difference between the natural concrete and recycled aggregate concrete are less but again natural concrete specimens had experienced more strain development.

When results from the both stress levels are investigated individually, it is hard to see any correlation of the results with respect to number of cycles to failure (N_f). Except one specimen, all specimens experienced strain developments between 0.80-1.10 for lower stress level, however under higher stress level specimens had wider range which is between 0.70-1.15. This may be commented as higher stress level causes more scatter in the results.

4.6.2.4. Loss of stiffness. With the strain data collected from the tests, evaluation of stiffnesses for all specimens were assessed. Stiffnesses of the specimens are obtained from the secant modulus that are calculated from the unloading branch of each fatigue cycle which is given in Figure 4.52. Effect of parameters are analyzed on loss of stiffness results.

In Figure 4.53 and Figure 4.54, residual stiffness results can be viewed.

When Figure 4.53 is viewed, it is seen that recycled aggregate specimens failed relatively earlier without losing much of their stiffness. Recycled aggregates specimens were able to retain their integrity till stiffness values decreased to 82% for RA45 and 79% for RA70 specimen series whereas natural concrete specimens were able to decrease to 72% for both NA45 and NA70. When results are assessed individually, for 85% ratio

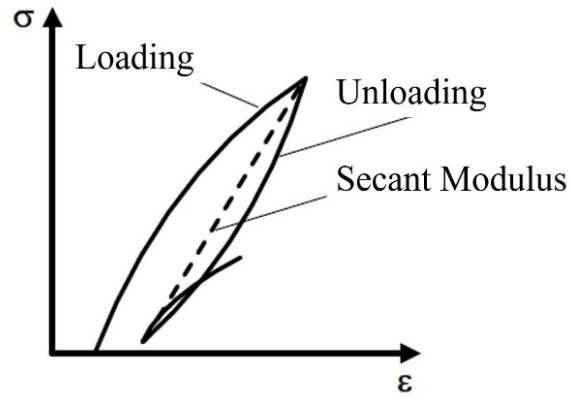


Figure 4.52. Calculation of stiffness for after a cycle.

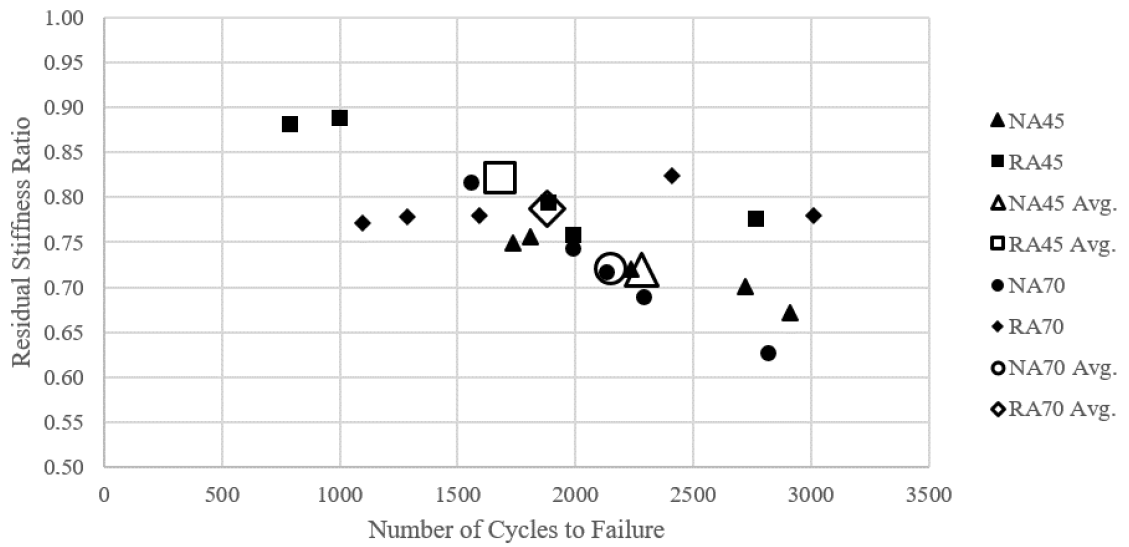


Figure 4.53. Residual stiffness ratio of specimens under $S_{max} = 0.85$.

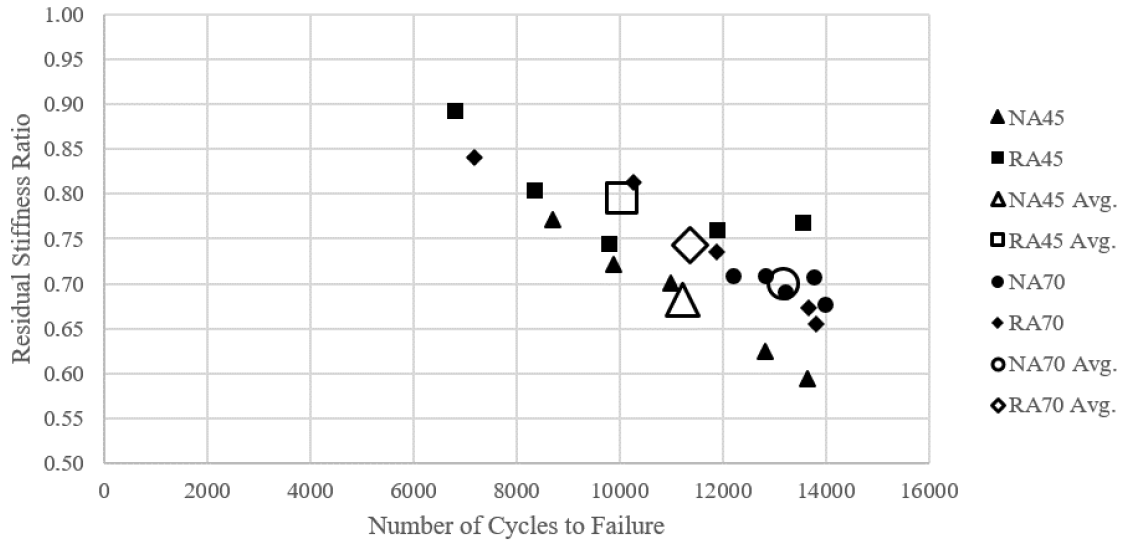


Figure 4.54. Residual stiffness ratio of specimens under $S_{max} = 0.75$.

of maximum stress, higher deviation for RA45 results is seen. Two of those specimens were failed at 90% and these specimens had also lesser number of cycles to failure. Three other specimens of RA45 were found to decrease below 80% of original stiffness value. When RA70 specimens were to be assessed individually, it is hard to mention of a relation between residual stiffness and number of cycles to failure (N_f) since all specimen residual stiffness results were close to each other and so also deviation of the results was found to be less for RA70 specimens. When NA45 specimens were assessed, results did not show much deviation but there seemed to be a relation with the increasing number of cycles to failure with a good fit of $R^2 = 0.96$. Individual NA70 results were likewise NA45 results and minimum residual stiffness ratio for all data set for 85% maximum stress level was found for a NA70 specimen which was 63%. NA70 specimens were also found to be linearly related with increasing number of cycles to failure (N_f) with a good fit of 0.98.

When Figure 4.54 is inspected, it is seen that recycled aggregate specimens crushed relatively earlier with respect natural concrete specimens as were in 85% maximum stress level. Recycled aggregates specimens were able to retain their integrity till stiffness values decreased to 79% for RA45 and 74% for RA70 specimen series whereas

natural concrete specimens were able to decrease to % 68 for both NA45 and 70% for NA70. These values were higher for 85% level with respect 75% level of stress. When RA45 specimens were analyzed individually, highest residual stiffness ratio is again from this series (89%). Two specimens with lower N_f values were not able to resist and their residual stiffness ratio is higher. Other 3 RA45 specimens have closer values that does not give any relation of residual stiffness ratio to number of cycles to failure. When NA45 series specimens were analyzed, it is seen that they show a linear relation with the increasing number of cycles to failure (N_f) values whereas NA70 specimens had very close values and had minimal deviation in the results also RA70 specimens showed a linear relationship with a relatively good fit.

When both maximum stress level results are analyzed together, effect of water-to-cement ratio is visible since performance of RA70 specimens increased significantly where RA45, NA45, NA70 specimens also increased but not as much as RA70. With the lowering of maximum stress level RA70 specimens had closer values to natural concrete specimens accordingly this may refer to a good recommendation for the use of recycled aggregates in concrete. When higher and lower stress values were compared, it can be said that lower stress results deviate less with respect to higher stress results which is also highly rational since higher amount of maximum stress deteriorate the specimen with higher amount of plastic deformation in every cycle. Higher plastic deformation per cycle causes the specimen to behave less foreseeable.

4.6.3. Effect of Slurry Treatment on Strain and Stiffness Developments

4.6.3.1. Maximum strain at maximum stress. Slurry treated recycled aggregate concrete specimens were also exposed to cyclic loads till crushing. Strain data were found to be maximum at maximum stress levels since strain values were always increasing with the increase of the number of cycles. Here in Figure 4.55, maximum strain levels for slurry treated specimens are given for each individual specimen and average of all specimen series (6 series) are also given as big markers. Maximum strain at maximum stress data was collected to observe the amount of strain any specimen can endure under fatigue loading.

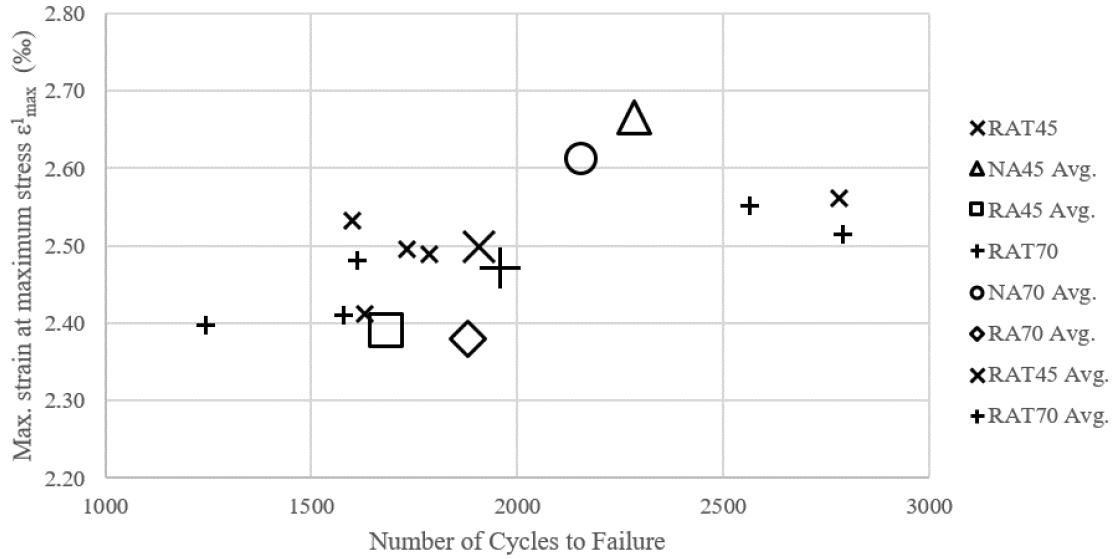


Figure 4.55. Maximum strain at maximum stress of $S_{max}=0.85$.

In Figure 4.56, maximum strain values at maximum stress of 0.75 is given. When average results of all series are compared, RAT70 specimens were able to strain more than every other specimen series. RAT45 specimen also performed higher with respect to untreated version. When effect of water-to-cement ratio is sought, it is seen that for this level of maximum stress specimens with higher water-to-cement ratio is better influenced. When deviation in the results are considered, treated specimens deviated less with respect to untreated specimens due to denser interfacial transition zone formation in the treated specimens.

4.6.3.2. Strain development at maximum stress ($\Delta\epsilon_{max}^1$). Strain development at maximum stress were all calculated from the difference of maximum strain at maximum stress level and maximum strain at first cycle. This value clarifies the effect of cyclic loads on strain values. In Figure 4.55, strain developments at maximum stress for slurry treated specimens are given for each individual specimen and average of all specimen series (6 series) are also given as big markers.

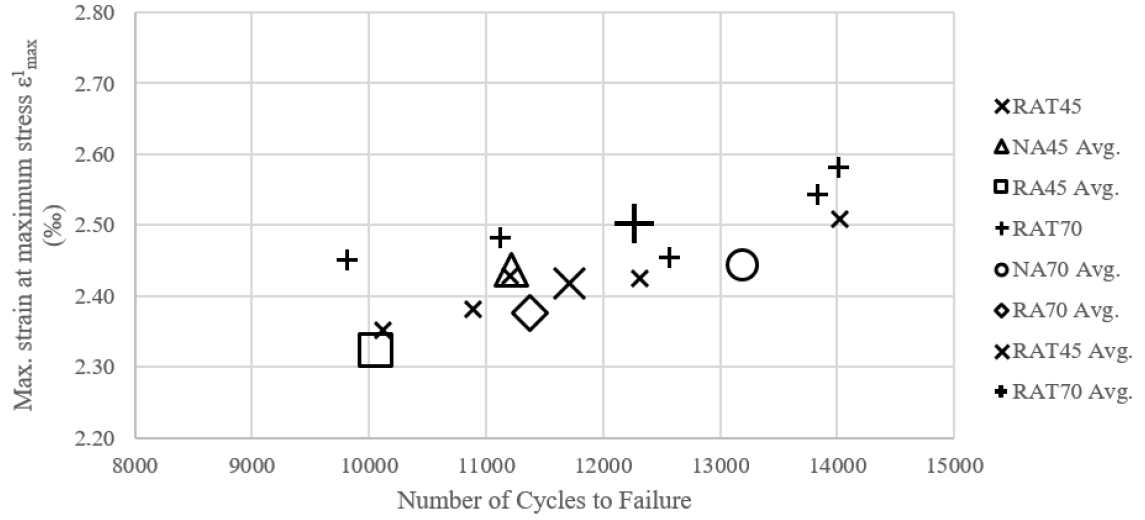


Figure 4.56. Maximum strain at maximum stress of $S_{\max}=0.75$.

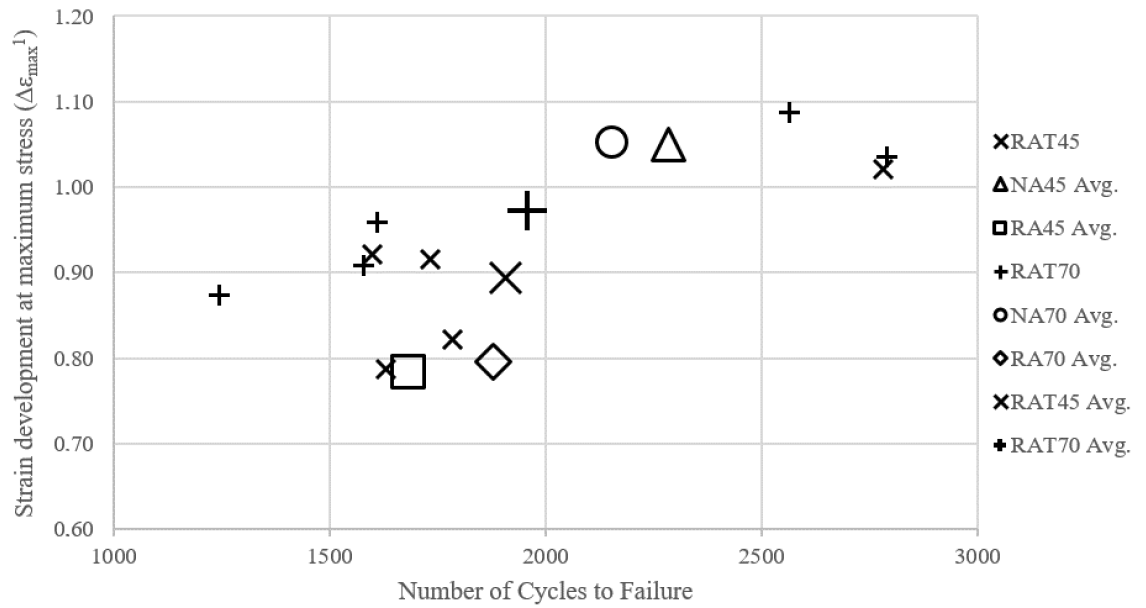


Figure 4.57. Maximum strain at maximum stress of $S_{\max}=0.75$.

When Figure 4.57 is viewed, it is seen that there was higher strain development for treated specimens with respect to untreated specimens. RAT45 specimens had 14% higher strain development than RA45 specimens whereas RAT70 specimens had 22% higher strain development with respect to untreated version RA70 specimens. However, NA45 specimens performed 18% higher strain development than RAT45 and NA70 specimens exhibited 11% higher strain development with respect to RAT70. Here 11% difference is highly practical when full replacement of recycled aggregates was considered. When individual results are inspected, no relation between number of cycles to failure and strain development at maximum stress was observed for both series. Results were not found to be much deviated.

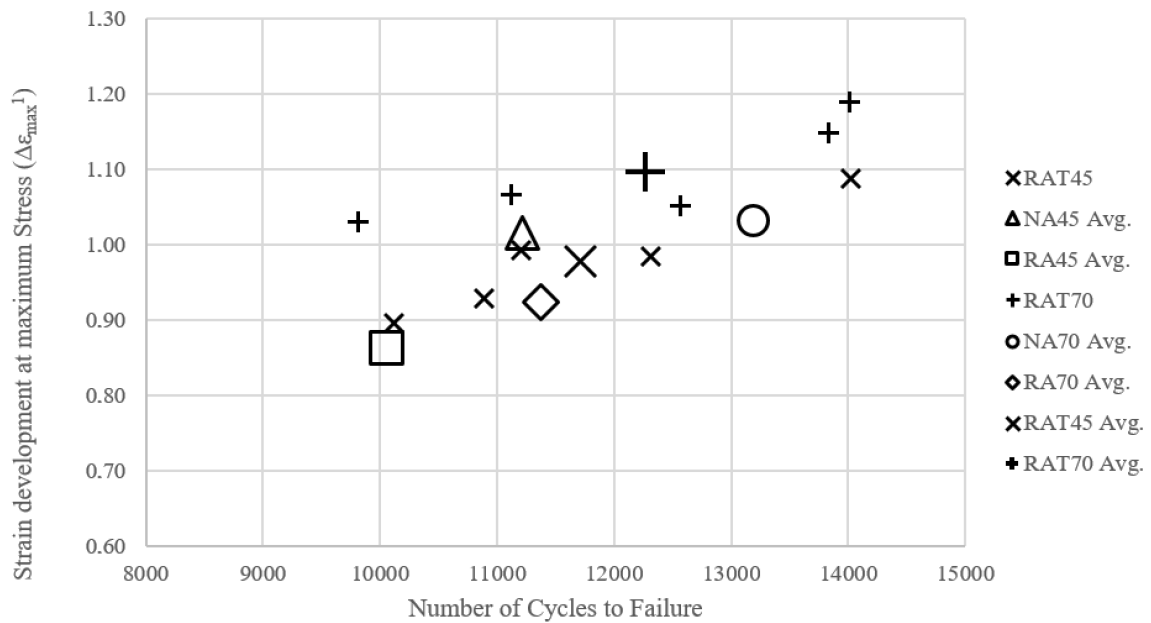


Figure 4.58. Maximum strain at maximum stress of $S_{max}=0.75$.

Treated specimens were found to have more strain development at maximum stress than untreated specimens for stress level of 0.75 similar to 0.85 stress level as seen in Figure 4.58. As was given in previous sections, all specimen series had experienced closer values of strain development for lower level of maximum stress. Surprisingly, RAT70 specimens had the highest development especially more than both natural concrete series. Also RAT45 specimens performed better than recycled aggregate concrete

and very close to natural concrete specimens. Treated specimens had denser interfacial transition zone after the slurry treatment and this enhanced the mechanical properties of the resulting concrete. Most probably inner cracks already within the specimens affect the overall fatigue performance of untreated specimens.

RAT70 specimens all performed higher than 0.001 and also deviation in the results were low. Also there seemed to be an increase with the increase of the number of cycle to failure (N_f) also similar relation was observed for RAT45 specimens.

4.6.3.3. Loss of stiffness. Loss of stiffness for treated specimens were also calculated from the secant modulus of the unloading branch and results are given in Figure 4.59.

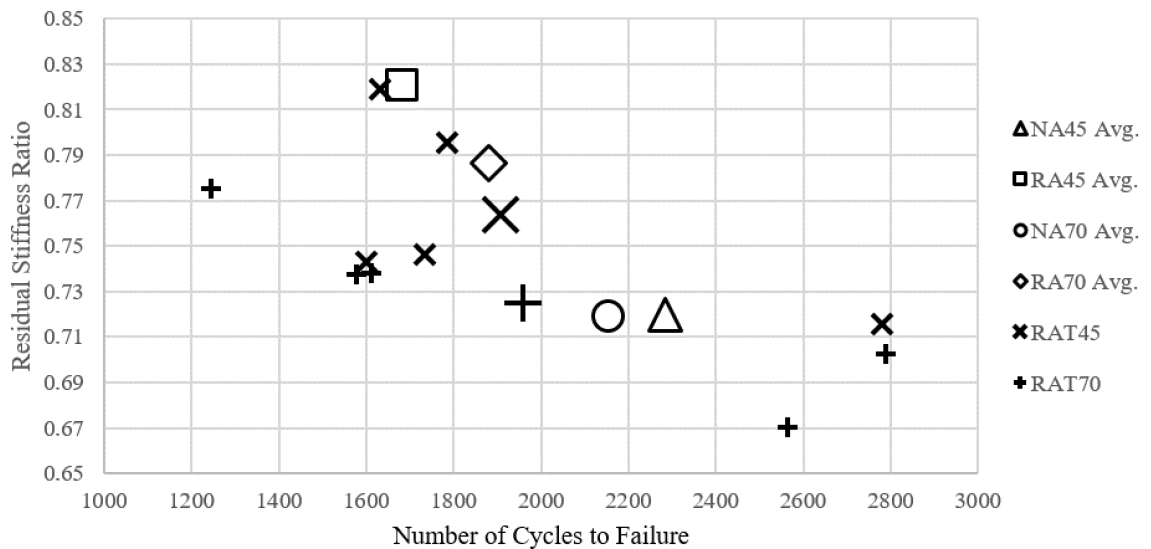


Figure 4.59. Residual stiffness ratio of specimens under $S_{max} = 0.85$

When stiffness evaluation results are observed, it is seen that treated specimens performed better than recycled aggregates but did not perform as good as natural concrete specimens. Treated specimens were able to withstand against repetitive loads better than untreated specimens with denser interfacial transition formation and less inner cracks due to inner bleeding. RA45 specimens had the worst average results and crushed at their 82% of the stiffness acquired from the first cycle, however RAT45 specimens were able to endure cyclic loads till the stiffness decreased to 76% which

seems quite a good improvement. RA70 specimens had performed better than RA45 specimens in this aspect as was given in previous sections. Also RAT70 specimens had improved performance and were able to withstand cyclic loads till 72% which is very close to natural concrete samples. Individual results were deviated since RA70 specimens had one specimens that have 67% result and the worst one had performed till stiffness fell to 77%. RAT45 results were less deviated with respect to RAT70 results.

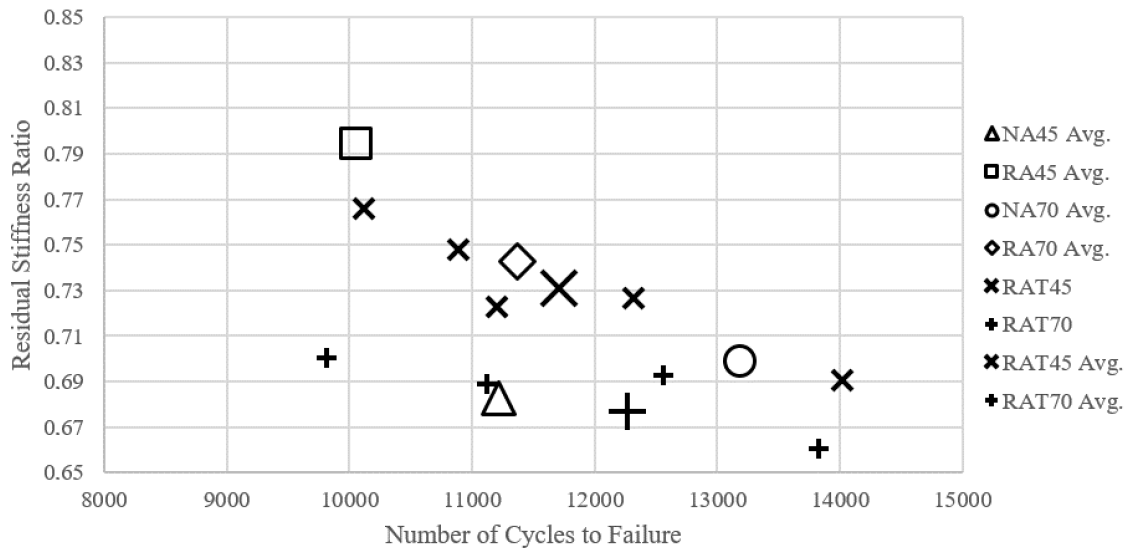


Figure 4.60. Residual stiffness ratio of specimens under $S_{max} = 0.75$

In Figure 4.60, residual stiffness results of specimens were given. RAT70 specimens performed better than all specimens including natural concrete. RAT70 performed best for lower level stress. Also RAT45 specimens performed better with respect to higher level of loading and they were intact till residual stiffness ratio decreased to 73%.

Also under lower stress level residual stiffness ratios of all specimens were lower. But specimens incorporating recycled aggregates whether treated or not had higher progress which may be concluded that recycled aggregate concrete performance is much better under 75% maximum stress level. This may be related to their initial condition

that has extra interfacial transition zone formation that contains cracks which is not present in natural concrete specimens. This conclusion may be helpful in design phases of structural applications.

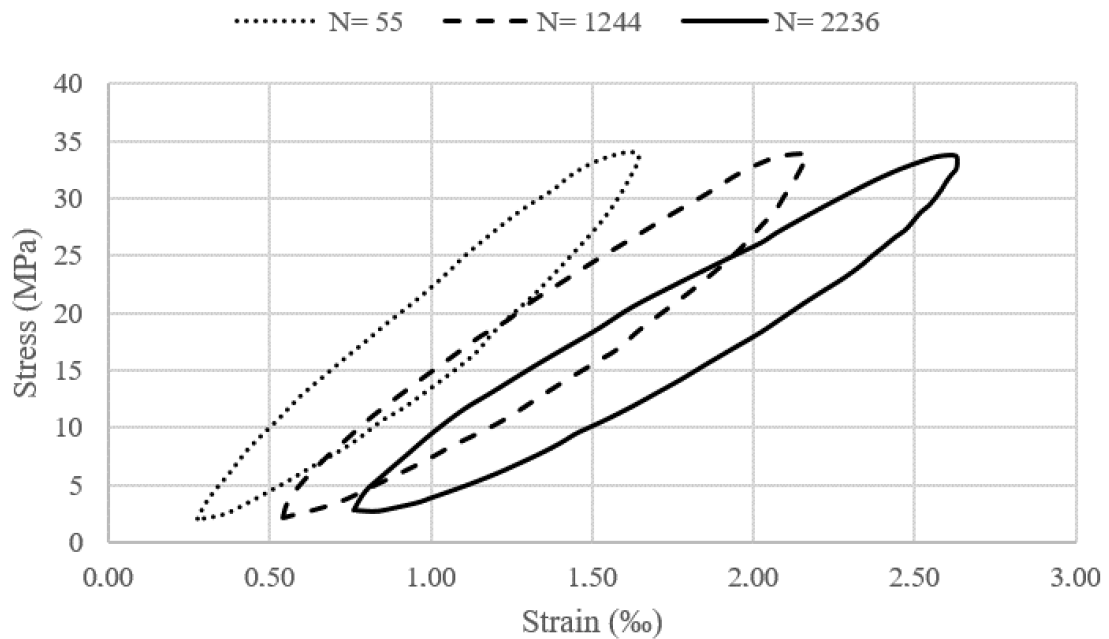


Figure 4.61. Fatigue stress strain relation of NA45 specimen under $S_{max} = 0.85$

4.6.3.4. Fatigue stress strain relation. When Figures 4.61, 4.62, 4.63 and 4.64 are viewed, stress strain relations of four different specimens are given. In each figure, stress strain relations in three different cycles are given. All specimens had higher strains with increasing cycle numbers although stress was not increasing any more than as it was for the first cycle which resembles the strain due to fatigue loading. Also as can be viewed from all four figures, with the increase of the number of cycles strain difference between the strains at the maximum stress and strains at the minimum stress increase which results in decrease in stiffnesses.

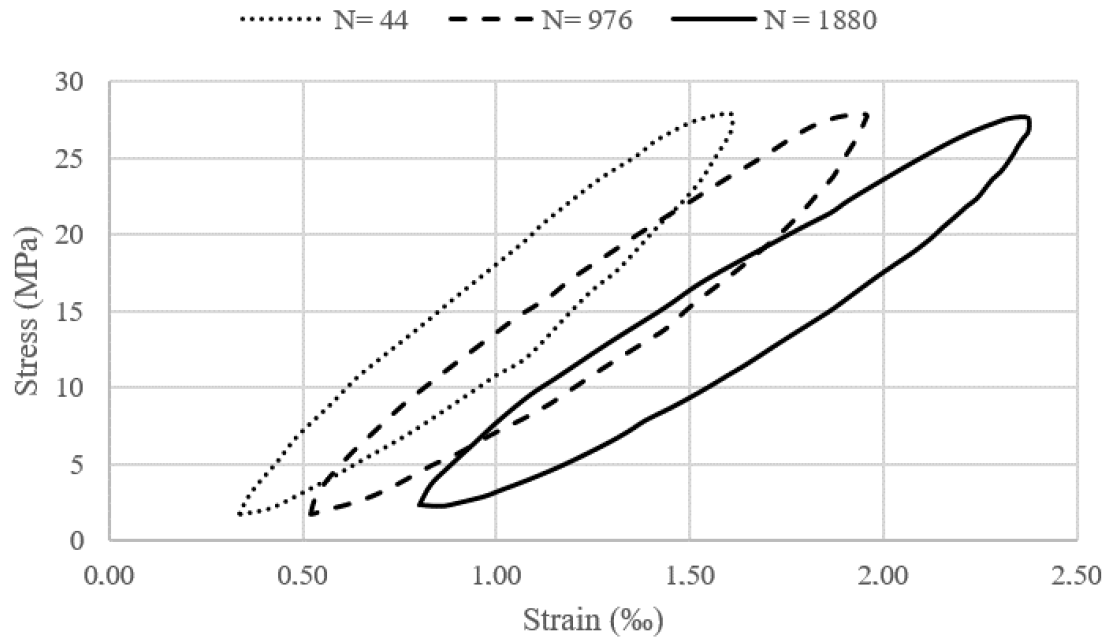


Figure 4.62. Fatigue stress strain relation of RA45 specimen under $S_{max} = 0.85$.

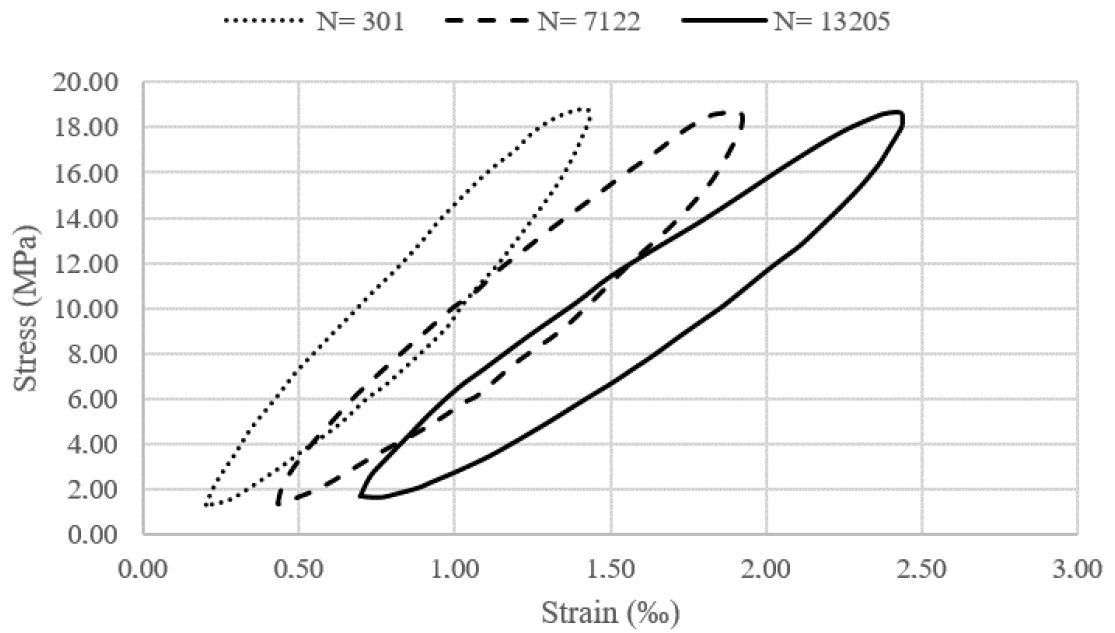


Figure 4.63. Fatigue stress strain relation of NA70 specimen under $S_{max} = 0.75$.

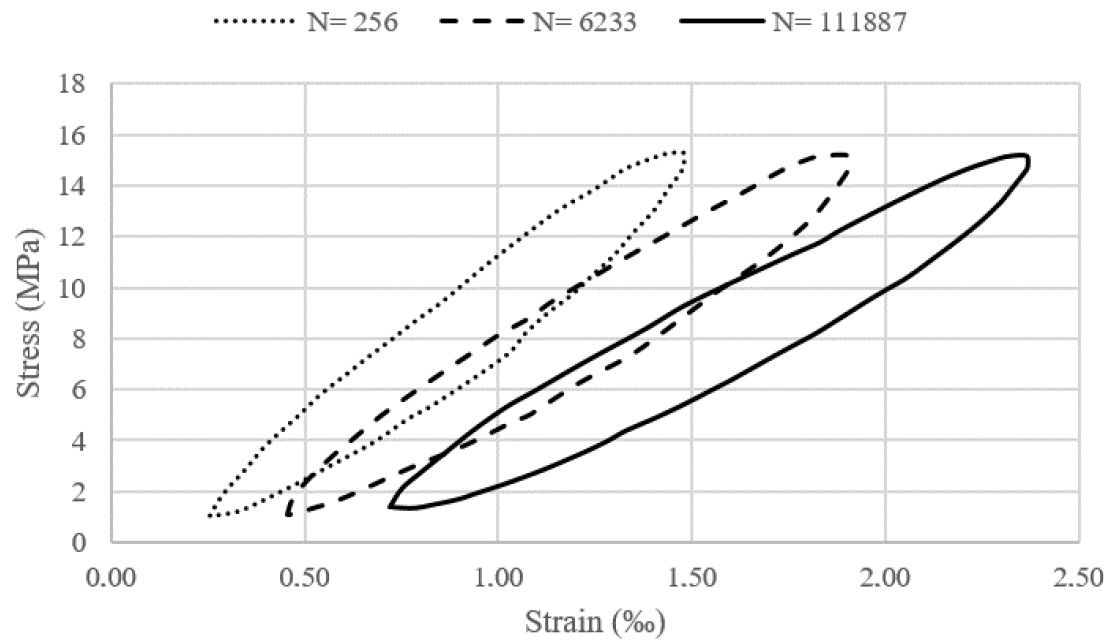


Figure 4.64. Fatigue stress strain relation of RA70 specimen under $S_{max} = 0.75$.

5. CONCLUSION

5.1. Conclusion

Density of recycled aggregates were found to be lower than natural aggregates since they contain microcracks and have porous structure. Water absorption of recycled aggregates were assessed as four times bigger than natural aggregates. Water absorption of recycled aggregates increased with decreasing diameter size. Aggregates impact and crushing values were found to be higher than natural aggregates as expected however, proper production of recycled aggregates attributed to relatively good aggregate strength results. Flakiness index was also found to be reasonable. For all aggregate tests, recycled aggregate test results were found to deviate from natural aggregate results. Unit weight of fresh concrete was found to be lower than that of natural concrete specimens. Air content of fresh concrete was found to increase with increasing slope with the increasing replacement level. Workability was found to be adversely affected with the increasing replacement level and lower water-to-cement ratio specimens were found to be more affected with the increasing replacement level. Fresh concrete unit weight was also found to decrease with the increase in the replacement level as expected but no significant effect of water-to-cement ratio was seen in this decrease. Fresh concrete air measurement results also proved the higher adverse effect of increasing replacement level when lower water-to-cement ratio is considered. Compressive strength was found to decrease with the increasing replacement level and decrease for lower water-to-cement ratio specimens were found to be higher than that of higher water-to-cement ratio specimens. For high water-to-cement ratio specimens, early (2 and 7 days) compressive strength was found to be less affected with respect to natural concrete however, 28 and 90-day specimens were significantly affected and had decreases up to 18% than natural concrete compressive strength. For lower water-to-cement ratio specimens all compressive strength results were significantly affected with the increasing replacement level. 28 and 90-day results were most affected and had decreases of 22% and 25% respectively. Decreases in modulus of elasticity with increasing replacement level were found to be higher than that in compressive strength. 28-day

modulus of elasticity decreases were 24% and 29% for high and low water-to-cement ratios respectively. Early strength results were less affected for both water-to-cement ratios, however for compressive strength results lower water-to-cement ratio specimens were significantly affected. Decreases in splitting tensile test results were found to be less with respect to compression test results. 28 day splitting tensile strength values were 14% and %19 less for high and low water-to-cement ratio. And also early strength results were significantly affected especially for low water-to-cement ratio specimens. Decreases in flexural strength were found to be higher than splitting tensile test results and similar to compressive strength results. Lower water-to-cement ratio specimens were slightly more affected from increasing replacement level with respect to higher water-to-cement ratio specimens. In Figure 5.1, compressive and flexural strengths of concrete containing different amounts of recycled aggregates with different concrete qualities are given.

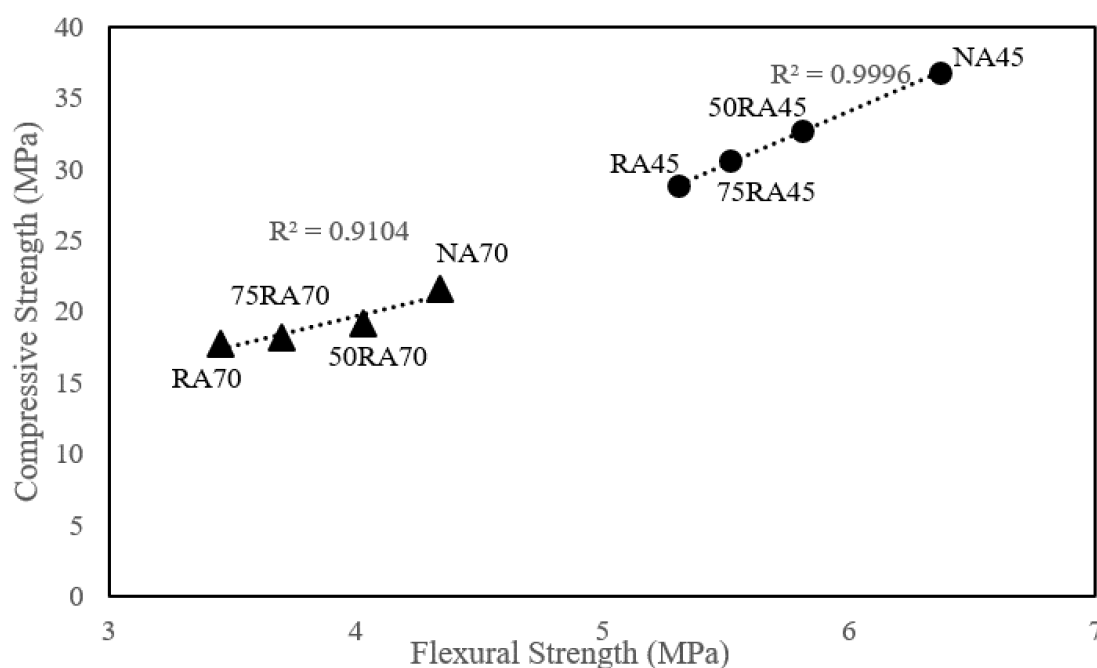


Figure 5.1. Compressive and flexural strength comparison of specimens.

Slurry treatment method was found to be effective when fresh concrete properties were to be assessed. Decrease in the superplasticizer amount to have similar slump values were found to be promising. For full replacement level of recycled aggregates,

superplasticizer amount decreased 20% and 15% for high and low water-to-cement ratio specimens respectively. Effect of slurry treatment on compressive strength was highly apparent when 28 day results were examined. 16% and 10% increases in compressive strength were monitored for low and high water-to-cement ratio specimens respectively. Flexural strength results were also enhanced and for 28-day results 11% and 9% increase were seen for low and high water-to-cement ratio specimens respectively. Splitting tensile strength results were also found to be enhanced with the effect of treatment. 9% and 2% increases were recorded for low and high water-to-cement ratio specimens respectively. In Figure 5.2, compressive and flexural strengths of slurry treated specimens containing different amounts of recycled aggregates with different concrete qualities are given.

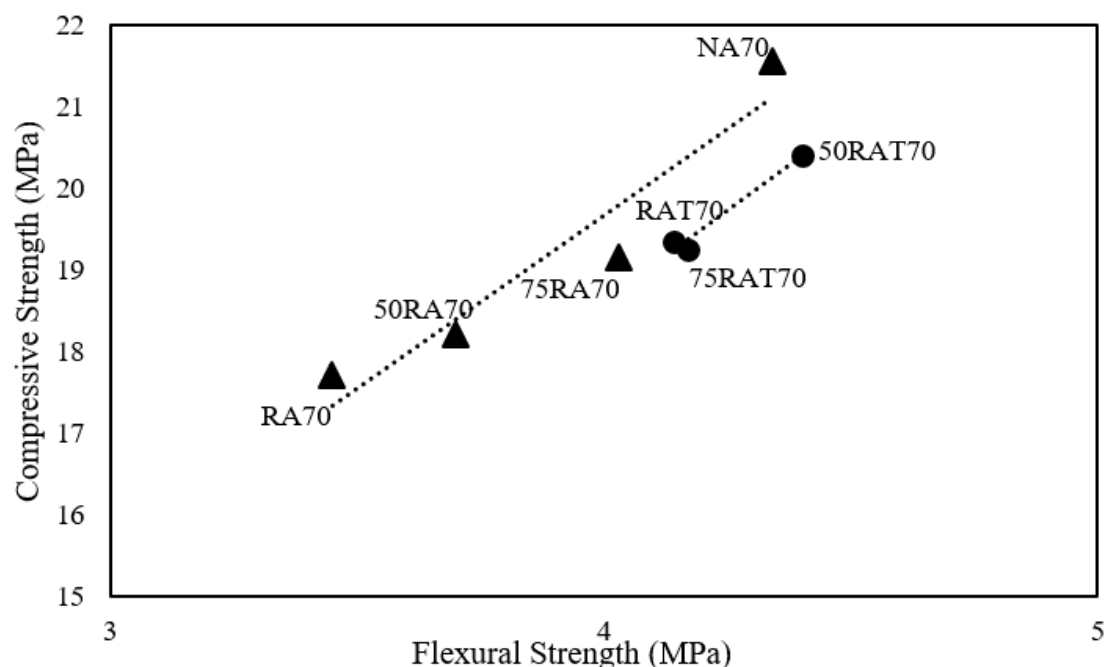


Figure 5.2. Compressive and flexural strengths comparison of slurry treated and untreated specimens ($w/c = 0.70$).

Biodeposition treatment on recycled aggregates were found to be effective when water absorption results were examined. Since high water absorption capacity of the recycled aggregates is highly prominent on the resulting concrete, enhancement on water absorption will contribute to overall integrity of the concrete mix. Water ab-

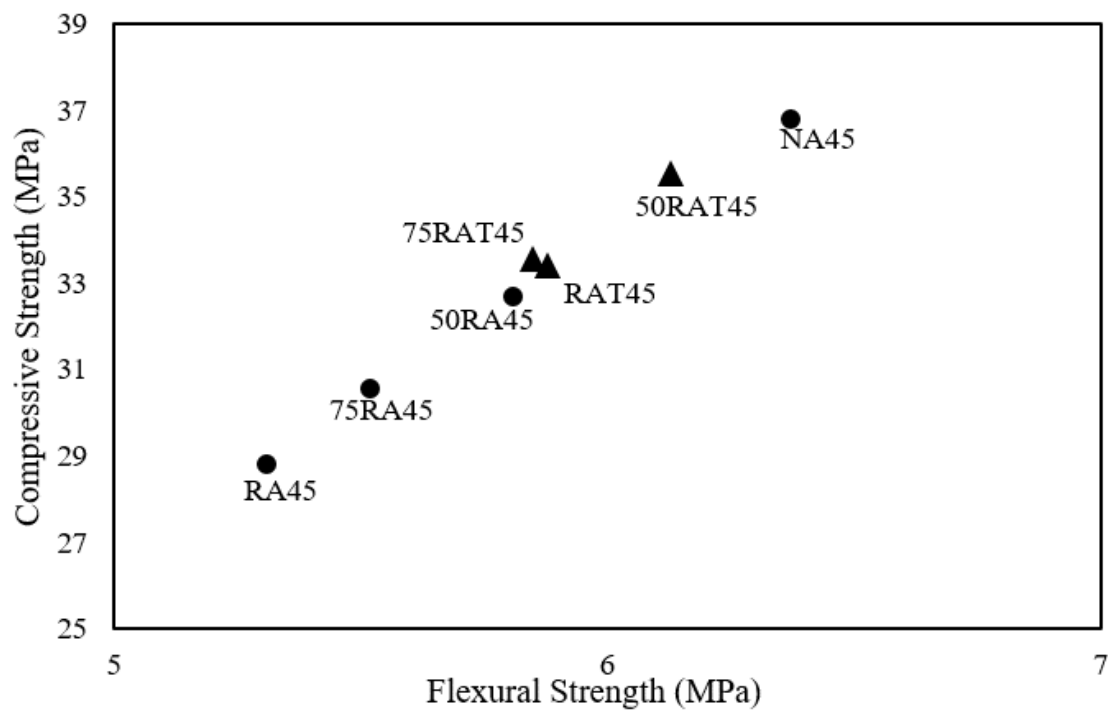


Figure 5.3. Compressive and flexural strengths comparison of slurry treated and untreated specimens ($w/c = 0.45$).

sorption capacities of same aggregate batches were measured before and after biodeposition application. After treatment, decreases of likely 30% were obtained for both batches which seem to be a promising result for concrete mix with recycled aggregates. However, resulting bacteria treated specimens were not as good as natural aggregates against water absorption.

Due to SEM analysis on bacteria treated recycled aggregate specimens, high amount of calcium carbonate was detected on the surface of the aggregates and visuals of huge amounts of cubic calcium carbonate particles were recorded. Also bacterial imprints with likely $2.7\ \mu\text{m}$ were detected in many parts of those calcium carbonate particles. Besides cubic particles, spherical formations were observed which were classified as vaterite particles which were produced by the very same bacterial units. 28 days compressive strength results of concrete containing bacteria treated aggregates were also found to be better than untreated concrete specimens. However, when 7 day results were inspected, positive effect of bacteria treatment was not seen. This may be related to low quality of the new interfacial transition zone in the early days and that may result in easier failure of the specimens whether treated or not. In later days, due to lower water absorption of treated specimens higher amount of unhydrated cement particles may have been hydrated contributing the overall compressive strength of the specimens.

Concrete mixes containing recycled aggregates were found to be highly affected when exposed to freeze-thaw cycles. Slurry treated specimens showed high performance under freeze-thaw conditions with respect to untreated versions. Cycles to failure were enhanced, dynamic modulus measurements were better and also visual investigations approved the effect of the slurry treatment. Also residual flexural strength tests were conducted and treated specimens had highly better flexural strength than untreated versions for specimens in the same number of cycles. In Figures 5.4 and 5.5, number of cycles freeze-thaw failure results are given versus number of cycles to fatigue failure results for both maximum fatigue loading rates.

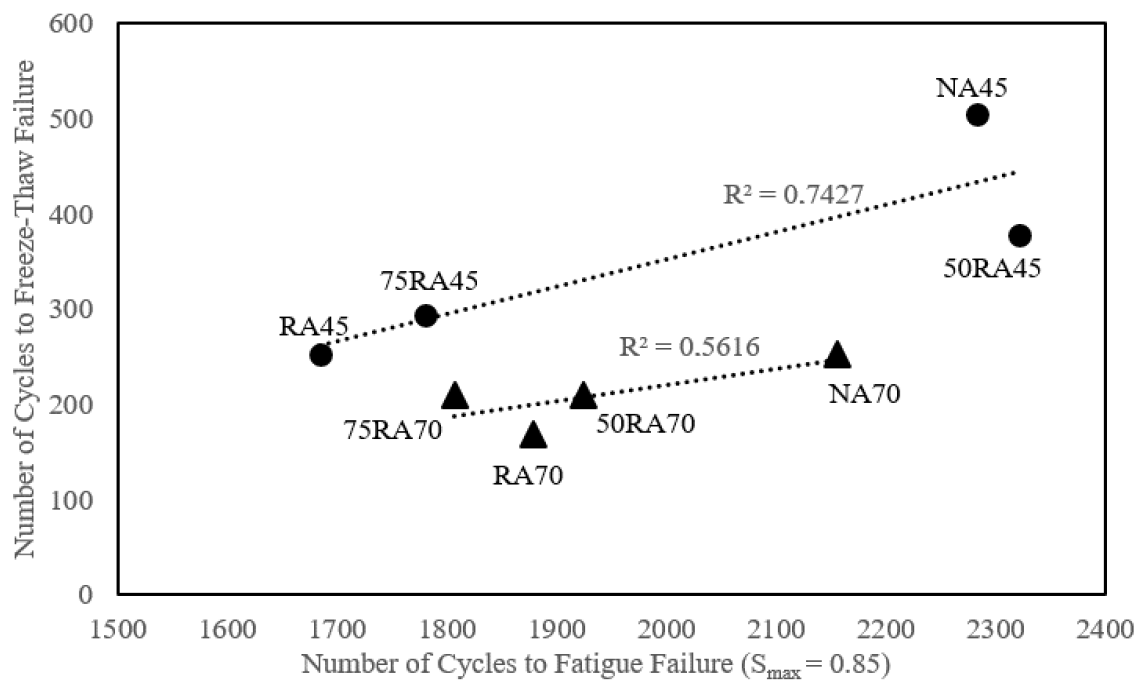


Figure 5.4. Number of cycles freeze-thaw failure vs. fatigue failure $S_{max} = 0.85$.

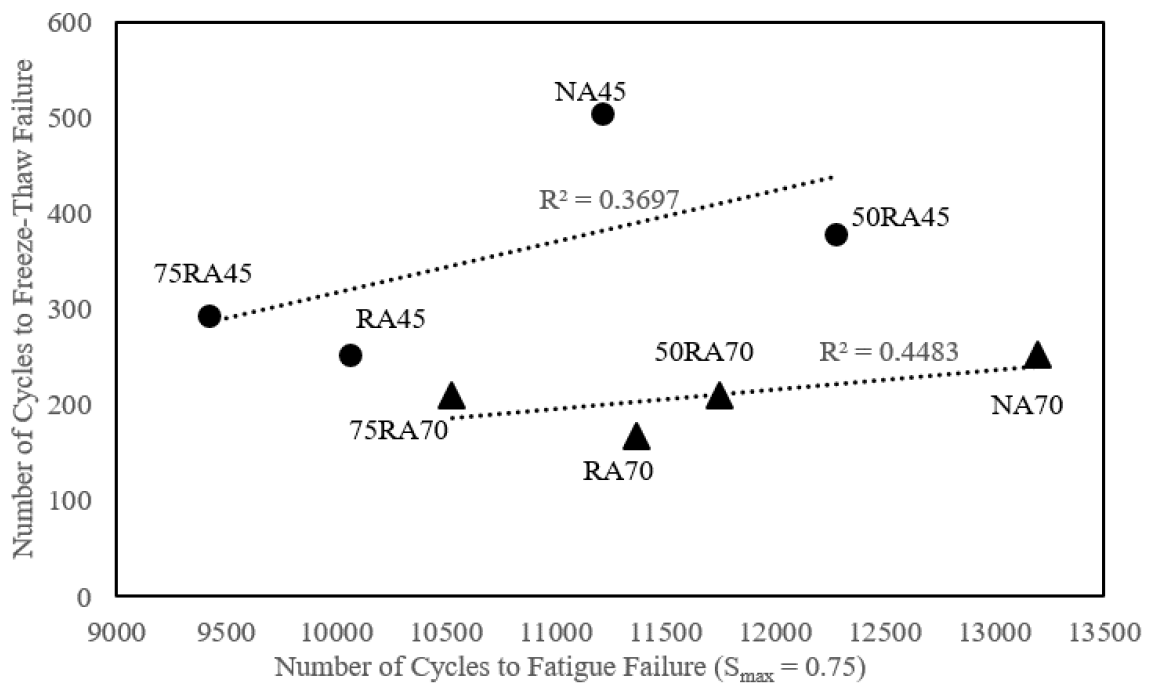


Figure 5.5. Number of cycles freeze-thaw failure vs. fatigue failure $S_{max} = 0.75$.

Fatigue tests were conducted and number of cycles to failure were investigated. For high water-to-cement ratio, when effect of replacement level was assessed, it may be said that replacement level had no major effect on number of cycles to failure especially for 85% maximum stress level. When 75% maximum stress level is considered, for full replacement level, mean of the number of cycles were found to be slightly lower than other replacement levels. Significance of the effect of the replacement level due to number of cycles to failure increased when lower water-to-cement ratio specimens were tested. When longitudinal strain and stiffness developments under compression fatigue loading were investigated, replacement level of recycled aggregates were found to be of high significance contradictory to one of the few studies on fatigue of recycled aggregates on concrete [10].

When strain values at maximum stress is inspected, maximum strain values before failure was higher for natural concrete specimens for 85% maximum stress level whereas, the difference between natural and recycled concrete specimens were less when 75% maximum stress is inspected.

When strain at first cycle values were assessed, it is seen that recycled aggregate concrete specimens had higher average results than natural concrete specimens for maximum stress level of 85% whereas recycled aggregate specimens had slightly higher strain values when maximum stress level was 75%. This may be attributed to higher plastic deformation left in recycled aggregate specimen when higher amount of stress levels is reached.

Strain development due to fatigue loading was found to be higher for normal concrete specimens especially at higher maximum stress level. Strain development values were 33% and 29% higher for high and low water-to-cement ratio specimens respectively. Strain development values at low maximum stress level was found to be 14% and 17% for high and low water-to-cement ratio specimens respectively. This shows under repetitive compressive forces concrete containing recycled aggregates goes to failure without developing strain as much as normal concrete specimens can. This may be related to less deformation capacity because of the cracks already present

in recycled aggregates due to adhered mortar and inner cracks formed due to inner bleeding occurred because of the high water absorption of recycled aggregates.

All specimens when exposed to compression fatigue loading, experienced losses of stiffness. With the strain data recorded, losses of all specimens are obtained from the secant modulus that are calculated from the unloading branch of each fatigue cycle. It was seen that recycled aggregate specimens failed relatively earlier without losing much of their stiffness and normal concrete specimens were able to withstand more deformation and accordingly they were able to have more loss of stiffness prior to failure. Surely these results are of major importance since recycled aggregates are clearly not able to perform under fatigue compression like natural concrete specimens.

Effect of slurry treatment on aggregates were found to be minimal under fatigue loading. Number of cycles to failure was found to be slightly higher. Treated specimens were able to perform higher strain of only 4%. Strain development of treated specimens under higher maximum stress level was higher especially for higher water-to-cement ratios. When stress level is lower, they were able to have higher amount of strain development.

Effect of slurry treatment was found on loss of stiffness values. Treated specimens were able to resist failure till stiffness fell to 76% ($w/c=0.45$) and 73% ($w/c=0.70$) of the stiffness value in the first cycle whereas untreated specimens resisted fatigue loads till 82% ($w/c=0.45$) and 78% ($w/c=0.70$). Also it is found that final stiffness values were very similar for both water-to-cement ratios when natural aggregates were used however, same observation was not valid for concrete containing recycled aggregates. Effect of slurry treatment was found to be more apparent for lower stress level fatigue loading.

As a general conclusion of this study, use of recycled aggregates in structural concrete should be encouraged. Several countries added use of recycled aggregates in structural concrete in construction manuals (USA %10, UK 20%, Australia %30) whereas some countries such as Japan and Hong Kong who have been using these

aggregates are increasing the replacement level [63]. With the findings of this study, when static mechanical, freeze-thaw and fatigue performance are considered together, use of recycled coarse aggregates in structural concrete may be considered up to a replacement level of 50 %.

5.2. Future work

Current research exhibited performance of recycled aggregates and surface treatments applied. With these findings on the performance of treatment methods, there are still unanswered questions on actual mechanisms affecting the properties of interfacial transition zone. Further investigation has to be done to evaluate the possible use of recycled aggregate concrete in the field. Suggestions for future work are provided below:

- (i) Analyzing recycled aggregate matrix interface is planned to have better understanding especially for the treated specimens.
- (ii) Effect of treatment should also be analyzed under microscopic observations to interpret the effect of the treating sequence on recycled aggregates.
- (iii) Since recycled aggregates have more than one interfacial transition zone structure, multiple visual analyses should be done on each recycled aggregate specimens.

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