# Effects of the Different Mixture Techniques on the Hardened and Durability Properties of Recycled Aggregate Concrete

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# ABSTRACT

Using recycled aggregate in the manufacturing of concrete is a green way to preserve natural resources and lessen pollution in the environment. Various treatment techniques are applied to enhance the appeal of using recycled concrete aggregate (RCA) in concrete; however, these techniques increase the cost of the product.

This study examined how different mixing techniques impact the mechanical and durability properties of concrete with untreated RCA. For this purpose, eighteen different mixtures were made using two different RCA obtained from ready-mix concrete plant waste and old demolished building waste, three different mixing techniques (Normal mixing approach, two-stage mixing approach and sand envelope mixing approach) and three replacement levels (20%,30%,50%). In the study, it was determined that the two-stage mixing technique reduced the water requirement of concrete and improved the compressive strength by 3.3%, splitting tensile strength by 14.2%, modulus of elasticity by 4.2% and impermeability in RCAn series concretes. Moreover, it was determined that the concrete produced with natural aggregate obtained from old building waste had 21% higher compressive strength and 7.2% higher modulus of elasticity than the concrete with normal aggregate at 20% and 30% replacement levels, respectively.

**Keywords:** concrete, recycling, aggregate, mixing, environment.

# ÖZ

Geri dönüştürülmüş agregaların beton üretiminde kullanımı, doğal kaynakların korunması ve çevre kirliliğini azaltılması için çevre dostu bir çözümdür. Geri dönüştürülmüş beton agregalarının beton üretiminde kullanılmasının çekiciliğini artırmak için çeşitli iyileştirme yöntemleri uygulanmakta, ancak bu yöntemler geri dönüştürülmüş beton agregalarının maliyetini artırmaktadır.

Bu çalışmada, çeşitli karıştırma tekniklerinin, herhangi bir iyileştirme yapılmamış geri dönüştürülmüş beton agregası kullanılarak hazırlanan betonun mekanik ve dayanıklılık özellikleri üzerindeki etkileri incelenmiştir. Bu amaçla, hazır beton santrali atığından ve eski yıkılmış bina atıklarından elde edilen iki farklı geridönüştürtülmüş beton agregası, üç farklı karıştırma tekniği (Normal karıştırma yaklaşımı, iki aşamalı karıştırma yaklaşımı ve kum zarf karıştırma yaklaşımı) ve üç değiştirme oranı (%20, %30, %50) kullanılarak on sekiz farklı karışım yapılmıştır. Çalışma sonucunda, iki aşamalı karıştırma tekniğinin betonun su ihtiyacını azalttığı ve RCAn serisi betonlarda basınç dayanımını %3,3, yarmada çekme dayanımını %14,2, elastisite modülünü %4,2 ve geçirimsizliği iyileştirdiği belirlenmiştir. Ayrıca, doğal agrega ile üretilen betondan elde edilen geridönüştürülmüş beton agregalarının, normal agrega ile üretilen betona göre sırasıyla %20 ve %30 ikame seviyelerinde %21 daha yüksek basınç dayanımına ve %7,2 daha yüksek elastisite modülüne sahip olduğu belirlenmiştir.

**Anahtar kelimeler:** beton, geridönüşüm, agrega, karışım, çevre.

# DEDICATION

**"Theory will only take us so far"**

**J. Robert Oppenheimer**

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| | |
|---|---|
| DM | Double Mixing Method |
| $E_c$ | Modulus of Elasticity |
| $f_c$ | Compressive Strength |
| $f_{ct}$ | Splitting Tensile Strength |
| FM | Fineness Modulus |
| ITZ | Interfacial Transition Zone |
| LA | Los Angeles Coefficient |
| MMA | Mortar Mixing Approach |
| NMA | Normal Mixing Approach |
| R | Rebound Value |
| RA | Recycled Aggregate |
| RAC | Recycled Aggregate Concrete |
| RCA | Recycled Concrete Aggregate |
| SEMA | Sand Enveloped Mixing Approach |
| SP | Superplasticizer |
| TSMA | Two-Stage Mixing Approach |
| w/c | Water-Cement Ratio |
| WA | Water Absorption |
| UPV | Ultrasonic Pulse Velocity |

# Chapter 1

# INTRODUCTION

## 1.1 General

According to the UN Brundtland Report, sustainable development is growth that satisfies current needs without endangering the capacity of future generations to satisfy their own (UN,1987). According to the United Nations General Assembly's decision on September 25, 2015, 17 sustainability goals were established to create a better world by 2030, with 169 member countries committing to work towards these targets. To align with these objectives, individuals were encouraged to reduce their environmental impact and implement effective waste management practices, making cities safer, more inclusive, and more resilient (UN, 2015). Evaluating the waste produced by construction operations is a crucial issue for ensuring a better world for future generations and promoting a sustainable environment.

Around 5 tons of waste per person were generated in the EU in 2022 by all households and business activities combined, and only 40.8% of waste was recycled. The construction sector accounts for the largest part of this waste, 38% (Eurostat,2024). Brick and concrete were the two main components of the waste from construction and demolition, with concrete accounting for one-third of the total waste (Özverel & Akanyeti, 2024). Recycling concrete waste and obtaining recycled concrete aggregate (RCA) becomes attractive in terms of sustainability due to the overall volume of waste generated during building and demolition, as well as the percentage of concrete in this debris.

After World War II, waste concrete was first used as a concrete aggregate in Europe. More, RCA began to be used in the USA as base-course material in the 1970s, and in the years that followed, it began to be used in the manufacturing of concrete (Bucks, 1976). In recent years, many countries have established national standards outlining the requirements for using recycled concrete waste in concrete production and are implementing policies to promote the use of RCA. The Swiss government required that all public buildings use at least 25% RCA after this pilot project was completed successfully (Wang et al., 2021). Moreover, between 10% and 15% of aggregates in France are produced from construction and demolition waste (Djerbi Tegguer, 2012) .

Despite appearing to be a sustainable solution, RCA have worse mechanical and physical properties than normal aggregates, which contributes to disadvantages, such as high-water absorption, low specific gravity, and the capacity for fragmentation. Moreover, the attached mortar on RCA adversely impacts the rheological behavior and hardened characteristics of the concrete (Verian et al., 2018). In several studies, the properties of recycled aggregate (RA) and concrete that contain it have been enhanced by removing and strengthening previously adhered mortar (Al-Kheetan et al., 2024; Gong et al., 2022; Merino-Maldonado et al., 2024; Xuyong et al., 2025) . On the other hand, some studies have shown improvement by changing mixing techniques or by supplementing fibers (Bui et al., 2017; Liang et al., 2015; Zhang et al., 2024).

## 1.2 Significance of the Study

Construction and demolition activities regularly generate significant amounts of waste materials, and this waste is dumped on unoccupied land or utilized as backfill material. Since such practices contribute to environmental pollution, recycling construction and demolition waste materials has been a key focus of governmental environmental policies. The use of construction waste is appealing due to its potential to reduce pollution and conserve natural resources. Recycled materials from construction and demolition waste are most frequently used in civil engineering earthworks. However, they are also used as RCA for concrete production. The use of RCA in concrete production is not yet widely used due to the cost of recycling and the costly and time-consuming treatment techniques applied to improve their physical properties. The significance of this research is to investigate the effects of different mixing techniques on the mechanical and durability properties of concrete by using two different RCA obtained from local (North Cyprus) concrete debris sources. Thus, awareness could be created by the government regarding the possible use of concrete waste in concrete production, and the environmental problems caused by these wastes could be reduced.

## 1.3 Objective of the Study

Previous studies indicate that RCA can negatively affect concrete performance due to their high-water absorption capacity and the attached mortar that remains from the parent concrete. These factors lead to a decline in the durability and mechanical properties of concrete. Researchers have developed various treatment methods to improve the quality of RCA, but nearly all of these methods increase costs. This research aims to investigate the efficiency of existing mixing techniques and optimise the replacement level of RCA to improve the fresh and hardened properties of concrete. It was planned to evaluate and compare the engineering properties of two different types of RCA with a constant slump and RAC. For this purpose, eighteen mixes are prepared by using two distinct RA with three different replacement percentages (20%, 30% and 50%) and three different mixing techniques (normal mixing approach, two-stage mixing approach, and sand envelope mixing approach), and one control mix without RCA.

To estimate the impact of the replacement level and mixing technique on the characteristics of concrete, fresh tests and mechanical tests are carried out on prepared samples. Also, some non-destructive tests have been done to compare the results.

## 1.4 Structure of the Study

The following chapters constitute the structure of this study: While the purpose and importance of the work are given in the first chapter, the literature review on the properties of RCA and the physical and mechanical properties of concrete produced from RA is included in the second chapter.
The experimental work, mix design, test procedures, and selecting materials are explained in chapter three. Analysis of the results and a critical discussion of the data are presented in chapter four. Lastly, chapter five concludes with recommendations and final remarks.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Recycled Concrete Aggregate

Aggregates occupy 75-80 % of the concrete volume. Although they are not related to the strength of the concrete, they have a great effect on the volume stability, durability and structural performance of structural concrete. The petrography, shape and texture of the aggregates are related to the adhesion or bond between the particles and cement gel. Hereby, before concrete production, the aggregate's mechanical, physical, and chemical characteristics are assessed by national and international standards (A.M. Neville & J.J. Brooks, 2004; Sahu et al., 2024).

RCA are manufactured by crushing, screening, and sieving concrete debris from demolished structures, prefabricated element producers, and ready-mix concrete plant operations, as well as from disaster sites. In the 1990s, the reuse of concrete was primarily related to a project's location; however, in modern times, it has become an essential component of waste management (Hansen, 1986.; ACI 55R-01, 2001; Xiao, 2018). Therefore, it is critical to understand the properties and effects of RCA on the concrete matrix.

### 2.1.1 Sources of Normal and Recycled Concrete Aggregates in Cyprus

Since 1990, crushed sand and gravel quarrying activities have gained momentum on the southern slopes of the Girne Beşparmak Mountain. Previously, the required material for the construction and infrastructure industry taken from the Gaziveren-

Kumköy coastline was banned because it damaged underground water resources, and the only alternative was to obtain aggregate from the quarries on the mountain (Alkaravlı, 2005). Using crushed rock aggregates in concrete is becoming more popular as a result of environmental laws and regulations related to natural aggregates (Eren and Marar, 2009). According to the data of the Department of Geology and Mining, while 4 million cubic meters of aggregate were produced annually with 15 quarries in 2005, annual production jumped to 5.7 million cubic meters and the number of quarries increased to 17 in 2024.

The Hilarion Formation of Girne Beşparmak Mountain consists of medium-bedded to massive limestones that contain many quarries (Zahedi & Akpınar, 2022; Alkaravlı, 2005). Because of its high abrasion resistance, low water absorption capacity, limestone is an extremely suitable aggregate type for the production of concrete. In 1990, Çelik et al. compared sea gravel (natural aggregate) with crushed gravel. They stated that the most durable aggregate in terms of impact abrasion was natural aggregate. However, concrete made with crushed gravel had a higher compressive strength than concrete made with only natural gravel. In addition, specific gravity, the water absorption, impact and crushing and abrasion test results of aggregate specimens taken from 10 different active quarries located in the Beşparmak Mountains in 2005 were evaluated (Eren et. al, 2005). Accordingly, it was understood that aggregates produced in North Cyprus were suitable for normal and high-strength concrete production.

Although high-quality aggregate and concrete are produced from the limestone obtained from the Beşparmak Mountains, quarrying activities cause various environmental problems. Problems caused by quarries can be listed as psychological and environmental effects on workers and people living in settlements close to quarries due to blasting, accidents caused by large trucks and lorries carrying the produced aggregates, deterioration of the road system caused by heavy loads, change of direction of underground water and deterioration of the geomorphological structure in the region (İlseven&Kaşot, 2020). In the research they conducted, the rock hardness in the Kyrenia Mountain Range was measured, and according to the ISRM (International Society for Rock Mechanics) scale, it was determined that the rocks were rated as hard and quite hard. According to the hardness rating of the limestone, it was determined that the blasting excavation method was inevitable due to the difficulty of excavation and its economics. Blasting excavations cause environmental problems due to ground shaking and air shock (Kahrimar et al., 2005). Considering the total traffic accidents between 2006 and 2016, it is stated that 18% of the accidents were caused by trucks and lorries (İlseven & Kaşot, 2020).

The reuse of RCA is vital for reducing the consumption of natural resources and alleviating the environmental issues caused by construction and demolition waste. Özverel & Akanyeti (2024) reported that the highest amount of waste generated from construction activities in 2023 was 0.74 ton/capita. One third of this waste is concrete, while 31% is masonry. The necessity of renewing the building stock in Northern Cyprus, which is situated in an earthquake zone, also emerges as a significant potential source of demolition waste. At the beginning of 1986–1987, 84 construction sites were inspected to assess concrete manufacturing practices and quality (Çelik, 1990). Various deficiencies in production were observed, and these shortcomings were reflected in the results of the samples taken. In many of the sites, the 28-day compressive strength test results failed to meet the target strength of concrete. In another research, Safkan et al. (2017), from 1974 to 1992, investigated 126 compressive strength experiment results, and according to the results, the average compressive strength is 18 MPa and the standard deviation is 7 MPa. The low-quality materials used in buildings before 1990 and the lack of use of earthquake regulations in structural design show that these buildings are sensitive to earthquake effects and have recycling potential. According to Xiao (2018), the demolition of concrete/masonry structures that have completed their economic life results in concrete waste of 0.32 $m^3/m^2$.

Concrete produced in ready mixed concrete plants and prefabrication plants that do not meet specified design or performance standards often contributes to construction waste due to their disposal. As a result of interviews conducted by phone and face-to-face with ready-mix concrete producers in Northern Cyprus, it was estimated that 11 companies will produce 2.2 million cubic meters of ready-mix concrete annually with 33 different concrete plants in 2023 and 2024. It is calculated that 1.4% of the concrete produced is stored as waste.

### 2.1.2 Production of Recycled Concrete Aggregate

Organisations of various developed countries agree that RCA must include a minimum of 90% mortar and normal aggregate fragmentations by mass (Silva et al., 2014). For this reason, before recycling, the wood, plastic, glass, and other hazardous materials should be removed from the concrete rubble, or these materials should be separated during demolition.

For conventional plant production, large pieces of concrete rubble are made smaller by hydraulic/pneumatic impact breakers/hammers. Then, the material is crushed in a primary crusher with particle sizes between 0-200 mm. Before the first screening, all steel/iron materials are separated by magnetic collectors. After primary crushing, fractions below 40 mm are wasted to eliminate the fine and deleterious substances.

Above 40 mm material is passed through a secondary crusher to reduce all products to a maximum size of 40 mm (Hansen, 1986).

The type of crusher used in aggregate production affects the physical and mechanical characteristics of the aggregate. Jaw, cone or gyratory, impact and roll crushers are major types of crushers that are used in both aggregate and RCA production. Jaw is the most suitable crusher type to obtain a proper particle size distribution for concrete production. On the other hand, impact crushers not only break concrete particles but also break aggregates (Hansen, 1986.; S.W. Nunnally, 2007.; ACI 555 R-01, 2001).

Various production methods can be utilized based on the maximum particle size and the desired quality of the final product. Quattrone et al. (2014) examined the efficiency of different production processes, including mechanical and mechanical/microwave treatments. In this study, various type of crushers (eccentric rotor, screw crusher and modified jaw crusher) used for mechanic grinding and combined with microwave heating. As a result, the amount of attached mortar of the final product was reduced, and the aggregate's water absorption decreased to 1%.

### 2.1.3 Standards for Recycled Concrete Aggregate

Despite numerous studies, the widespread adoption of RCA in concrete has not yet occurred. International standards typically restrict the incorporation of RA into structural concrete or permit its use in small percentages, subject to strength limitations. The concrete strength grade and the characteristics of the RA, including composition, dry density, water absorption, and impurity content, determine the amount of RA that can be used in concrete. Specifications for the requirements of the RCA for the different countries are tabulated in Table 1 (RILEM TC121-DRG, 1994, WBTC 12/2002, 2002, DIN 4226-101, 2017, BS 8500-2, 2016, TS EN 206, 2017).

In Germany, RAC with a concrete class up to C25/30 and C30/37 can be made by substituting RA for 35% and 25% of virgin coarse aggregates, respectively. There isn't any restriction on water absorption and density in England, and RCA is applicable in a greater variety of exposure scenarios and up to strength class C40/50. RILEM has published recommendations on the utilisation of RA in concrete. According to this document, RCA are permitted in structural concrete up to class C50/60. TS EN 206 is a Turkish standard that is legally valid in Turkey and includes the rules for the use of RCA. While the replacement level of RCA with normal coarse aggregate is 50% for concretes that will not be exposed to external environmental factors, this rate is limited to 30% for concretes exposed to corrosion caused by carbonation, freezing and thawing, and chloride-induced corrosion. Specification Works Bureau Technical Circular No.12/2002 describes the use of RA in concrete production in Hong Kong. The use of 100% recycled coarse aggregate in concrete is restricted to nonstructural purposes, where the strength class does not exceed 20 MPa. On the other hand, the design of concrete for general structural applications, except in water-retaining structures, can be feasible when normal coarse aggregates are replaced with 20% RCA and a strength grade of 25-35 MPa.

### 2.1.4 Mechanical and Physical Properties of Recycled Concrete Aggregate

Physical properties (shape and size, bulk density, porosity, water absorption, moisture content, unsoundness, and specific gravity) of aggregate are related to the behavior of aggregate in the concrete matrix and its effect on the properties of concrete (A.M. Neville & J.J. Brooks, 2004). The attached mortar content, water absorption, and specific gravity are the main physical properties that have differences between RCA and normal aggregates (Verian et al., 2018).

Table 1: Specifications in different countries for the utilization of RCA

| Country/ Standard | Classification | Minimum Concrete Content (%) | Minimum Density ($kg/m^3$) | Maximum Water Absorption (%) | Maximum replacement level for virgin coarse aggregate (%) | Max. Allowable Strength Class | Field Application |
|---|---|---|---|---|---|---|---|
| Germany DIN 4226-100 | Type 1<br>Type 2 | >90<br>>70 | >2000<br>>2000 | <10<br><15 | 20-35<br>20-35 | C30/37 for 20% replacement C25/30 for 35% replacement | Structural concrete with X0*, XC1 to XC4, XF1 to XF3, XA1 exposure conditions (pre-stressed concrete not allowed) |
| England BS EN 206 BS 8500-2 | RCA | >95 | - | - | 20 | C40/50 | Structural concrete with X0, XC1 XC4, XF1 exposure conditions |
| RILEM TC-121DRG | Type II | <100 (obtained from concrete rubble) | >2000 | <10 | 100 | C50/60 | Structural concrete |
| Turkey TS EN 206 | Type A | >90 | >2100 | - | 50 | C30/37 | Structural concrete with X0, XC1-4, XF1, XA1, XD1 exposure conditions |
| Hong Kong WB TC 12/2002 | RCA | <100 | >2000 | <10 | 20<br><br>100 | C25/30<br><br>C16/20 | Structural Concrete Non-structural concrete |

*X0: No risk of corrosion or attack
XC1-4: Corrosion induced by carbonation
XF1-3: Freeze/thaw attack
XA1: Slightly aggressive chemical environment
XD1: Corrosion induced by chlorides other than from sea water (Moderate humidity)

Strength, toughness, and hardness are important mechanical qualities, particularly when the aggregate will be used in road construction or be exposed to high wear (A.M. Neville, 2011).

#### 2.1.4.1 Attached Mortar

The amount of attached mortar has a vital importance for governing the fresh and hardened properties of concrete that includes RCA. The attached mortar on the RA creates two different interfacial transition zones (ITZ). The old ITZ is formed between old concrete aggregate and cement mortar. The new ITZ exists between the RCA surface and the new cement mortar (Verian et al., 2018). During the production of RCA, the crushing process causes microcracks inside the attached mortar, and high concentration of calcium hydroxide crystals, microcracks and extreme porosity are the main reasons for the ITZ's weakness (Chen et al., 2024). Thus, the existence of attached mortar helps in the formation of a second ITZ and also diminishes the physical and mechanical properties of the aggregate due to its porous and weak structure.

The amount of attached mortar varies depending on the size of the RA. According to Hansen (1986), the volume percentage of attached mortar to natural aggregate particles ranged from 25 to 35% for coarse RA measuring 16–32 mm, around 40% for aggregates measuring 8–16 mm, and approximately 60% for aggregates measuring 4–8 mm. Etxeberria et al. (2007) reported that the amount of adhered mortar was approximately 20% for the 10/25 mm aggregate fraction and around 40% for the 4/10 mm fraction in their study. Brand et al. (2015) estimated the attached mortar content by using sodium sulfate solution. The original aggregates were subjected to freezing and thawing cycles to facilitate the removal of attached mortar. Mortar content was measured at about 26% for the particles between 4-25 mm, whereas the amount of attached mortar was 13% for the diameter larger than 25 mm.

#### 2.1.4.2 Water Absorption

Aggregate's water absorption and porosity affect the cement paste-aggregate bond and directly affect resilience to freezing and thawing, abrasion resistance, chemical stability and specific gravity. Water absorption is measured by the mass difference between the saturated-surface dry mass and oven-dry mass of aggregates. The general assumption is that the aggregates are in a saturated surface-dry state when the concrete begins to harden and gain strength. However, total water absorption is calculated after 24 hours. For that reason, when the aggregates are included to the dry mixture, the total water amount of the mixture should be adjusted according to the effective water/cement ratio (A.M. Neville & J.J. Brooks, 2004; Teychenne et al., 1997) .

Ordinary virgin aggregates are less porous than the leftover mortar that is adhered to the RA's surface. As a result of this circumstance, RCA are more likely than typical aggregates to absorb water.

To obtain highly accurate results of the water absorption of RA, Tam et al. (2008) developed a new method. In this method, dry aggregate is put into a pycnometer, and water is added to the pycnometer by observing the decrease in the water level at certain intervals without being exposed to external weather factors. In this method, deviations caused by the stick-adhered mortar during the drying-wetting cycle are prevented, and water absorption amounts at different time intervals are calculated. Furthermore, Djerbi Tegguer (2012) generated a new approach to measure the water absorption of RA by using the hydrostatic weighing technique. The results verify that water absorption measurements for RA cannot be performed using the standard methods. The saturation of the RA continues up to 85-110 hours, and at the end of 24 hours, 60-70% of the total water absorption is completed.

Zaetang et al. (2016) stated that the water absorption of RCA from low-strength concrete blocks was %5,3. Ismail & Ramli (2013); Muñoz Pérez et al. (2024) ; Siletani et al. (2024) studied the RCA that were crushed by waste concrete test samples obtained from laboratories. The water absorptions obtained from the experiments are 6.45%, 1.48%, and 5.6%, respectively. In their study, Brand et al. (2015) found that the recycled aggregate, derived from high-quality airport pavement concrete, had a water absorption value of 5.51%. Moreover, some researchers prefer to study aggregates recycled from the demolition of end-of-life buildings. While the water absorption in the study conducted by Akpinar & Al Attar (2021) in North Cyprus was found to be 4.6% (13-19 mm) and 6.1% (5-12 mm), it was 6.2% in the aggregates obtained from the demolished building in New York (Yildirim et al., 2015). In a study investigating the effect of particle size distribution on concrete, aggregates obtained from the demolition waste of a juvenile jail built in the Netherlands in 1998 and water absorption rate of 6.73% were used. It is clear that the quality of the parent concrete has a direct impact on the amount of water absorption (Zong et al., 2025).

#### 2.1.4.3 Specific Gravity

The specific gravity of aggregate is another important parameter that depends on its porosity. Specific gravity, as defined by ASTM C127-24, is the ratio of the mass of a unit volume of material to the mass of an equivalent volume of water. The bulk specific gravity based on saturated and surface-dry condition is necessary for the mix design calculations and governs the yield of concrete (A.M. Neville & J.J. Brooks, 2004).

The apparent specific gravity of most natural aggregate’s ranges from 2.4 to 3, and this reflects the amount of the pores of the aggregate particle (A.M. Neville, 2011). Verian et al. (2018) collected data from the literature between 1994 and 2017 and analysed the specific gravity of RCA. According to the results, the apparent specific gravity of recycled concrete is lower than normal aggregates and ranges between 1.9

to 2.7, based on the quantity of attached mortar and petrography of the parent rock. Also, a lower specific gravity value is correlated with higher water absorption.

#### 2.1.4.4 Abrasion Resistance

The Los Angeles test, as specified in ASTM C131/C131M-20, is used to assess the abrasion resistance of the aggregate, and this test is a simulation of the abrasion and attrition behaviour of the material. Abrasion resistance is concerned with the hardness of concrete and is an important criterion for the acceptability of aggregates for use in concrete applications (A.M. Neville & J.J. Brooks, 2004) . According to the Verian et al. (2018) the loss of mass values at the end of the Los Angeles test for different RA varies between 20% and 51.5%.

## 2.2 Recycled Aggregate Concrete

RAC is described in the RILEM report (Hansen, 1986): "Concrete is produced using RA or combinations of RA and other aggregates. " Silva et al. (2014) classified the aggregates achieved from construction and demolition waste into 4 groups according to their ingredients. RCA include mortar and concrete masonry units at least 90% by mass. Recycled masonry aggregate contains lightweight concrete blocks, ceramic bricks, blast-furnace slag and sand-lime bricks and blocks inside 90%. Mixed RA composed of concrete and masonry rubble and construction and demolition RA are classified into this category since they are contaminated with other substances (asphalt, glass, plastics, wood) relatively high.

The characteristics of concrete manufactured with RA are different due to the variety of ingredients in the aggregates and especially the adhered mortar found in RCA. Researchers primarily focus on changes in concrete properties such as slump loss, reductions in compressive and splitting tensile strengths, decreases in modulus of elasticity, and increases in drying shrinkage. (Fonseca et al., 2011; Katrancı & Çakır, 2025; Limbachiya et al., 2000; Ozbakkaloglu et al., 2017; Sobuz et al., 2024).

### 2.2.1 Rheologic Properties

Water content, fineness and amount of cement, as well as the type of mineral admixture, aggregate type and grading, aggregate-to-cement ratio, mixing duration, and temperature, are the factors that affect workability (A.M. Neville & J.J. Brooks, 2004) .

The total quantity of water for obtaining desired workability is the combination of water inside the aggregate pores and effective free water that reacts with cement particles. When using typical concrete mix design techniques, the water content refers to the free water, and as the aggregates are saturated when they are added, the additional water required for absorption properties is already included. Despite the high-water absorption, the effective surface area of RA remains lower than that of conventional aggregate. This results in a loss of strength in concrete made with aggregates that require high water, even when the effective water-cement ratio is the same (Folino & Xargay, 2014; Montero & Laserna, 2017; Zong et al., 2025).

Sobuz et al. (2024) examined the fresh properties of concrete with different sizes (5/12 mm and 12/20 mm) and concentrations using various testing methods. The results show that concrete mixtures with aggregate sizes of 12–20 mm have higher slump, compacting factor, K-slump, slump and ball penetration value than those included with aggregates of 5–12 mm. According to the test results, the slump loss was measured as 5.7% for 12/20 mm and 6.4% for 5/12 mm, respectively.

The effects of initial moisture and mixing techniques were investigated in the study using high-quality RCA. After the aggregates were prepared as saturated surface-dry oven-dry and partially saturated, concrete mixtures were made using the normal mixing technique defined in the ASTM C192/C192M-24 and the two-stage mixing technique developed by Tam. While it was reported that the saturation rate of aggregates did not affect the viscosity of concrete, the initial slump of concretes prepared with the two-stage mixing approach technique was higher (Brand et al., 2015).

In her 2021 study, Akpınar used RCA obtained from the demolition of an old public school in Northern Cyprus. Aggregates are recycled from concrete manufactured using natural aggregates used in Cyprus. The required water was increased 5.7% and 13.2% for 25% and 50% replacement levels (Akpinar & Al Attar, 2021).

In North Cyprus, where concrete is typically produced at central ready-mix plants and transported to construction sites using truck mixers. Therefore, superplasticizers are commonly used in concrete production. According to the study conducted with 4 different RCA containing different amounts of concrete, brick, glass, and bitumeneous, polycarboxylic-based superplasticizers gave satisfactory results (Bravo et al., 2017).

The density of fresh concrete is essential for determining the concrete yield per batch, and it is significantly influenced by the physical properties of the aggregates (A.M. Neville & J.J. Brooks, 2004). In the study, different pozzolanic slurries were applied to the surfaces of the aggregates. The RAC mixture with non-treated aggregates exhibits lower density. The specific gravity of the aggregates to which micro silica slurry treatment was applied increased from 3.52 to 3.82 (Siletani et al., 2024). Turanlı

(1993) investigated the effect of different water/cement ratios on the fresh unit weight of RAC. While the fresh unit weight of RAC was 2229 kg/$m^3$ for a 0.5 water-cement ratio, this ratio decreased to 2214 kg/$m^3$ for 0.7. In the study where the RA replacement level was gradually increased from 15% to 60%, a decrease in the fresh unit weight of concrete, from 2380 kg/$m^3$ to 2350 kg/$m^3$, was reported (Ismail & Ramli, 2013). In another study, the amount of fresh unit weight loss for a 15% replacement level was approximately 4%, while this figure increased to 9% for a 45% of aggregate replacement (Sobuz et al., 2024).

In summary, RAC tends to lose consistency due to surface roughness, high water absorption, attrition of aggregates with prolonged mixing time and the existence of deleterious substances. To minimize consistency loss, it has been suggested to use saturated aggregates, different mixing techniques and increase the amount of superplasticizer (Bui et al., 2017; Chadha et al., 2024; Lin et al., 2024).

### 2.2.2 Hardened Properties

#### 2.2.2.1 Compressive Strength

In addition to its impermeability, resistance to environmental exposure conditions and structure that prevents corrosion of metals embedded within it, the main features that make concrete a popular building material is its incredible behavior under pressure. Porosity is a primary factor governing the concrete’s compressive strength. Therefore, water/cement ratio, degree of compaction, and aggregate/cement ratio are the factors that influence the strength of concrete. On the other hand, the aggregate physical properties and quality are related to the bond between aggregate and cement gel and this bond is closely related to the compressive strength of concrete (A.M. Neville & J.J. Brooks, 2004).

The replacement level of RCA in concrete is one of the key factors influencing its compressive strength. Akpinar & Al Attar (2021) reported the 28-day compressive strength loss as 5.3%, 23.7%, 21.5% and 30.7% for the 25-50-75-100% replacement levels, respectively. For the 90-day compressive strengths, these amounts are 7.7%, 17.2%, 21.4% and 32.9%. In another study conducted in Peru, 28-day concrete cylinder compressive strengths were presented as 25.3, 25.1, 24.8, 23 and 21.7 MPa. The RCA replaced between 10% and 40% of the volume of normal coarse aggregates (Muñoz Pérez et al., 2024).

In the study where high-quality RCA and normal aggregate (granitic crushed stone) were used, the 28-day cylinder compressive strengths of the samples taken from the concrete mixtures were measured as 33.6, 30.4 and 29.1 MPa for 30, 60 and 100% replacement levels, respectively. In the control samples, the 28-day cylinder compressive strength was presented as 36.5 MPa (Folino & Xargay, 2014). In the study investigating the effect of RCA on the long-term compressive strength of concrete, the 28-day compressive strength of cylinder samples for the control mixture was 35.5 MPa, while the 6-month compressive strength increased by 19% to 42 MPa. The concrete compressive strength at the end of 6 months remained the same as the control mixture for the mixtures using 25% RA, while 13% was reported for the 50% change rate. In the concrete mixture where all the coarse aggregates in the mixture were replaced with RCA, the variation between the 28-day concrete compressive strength and the 6-month compressive strength was reported to be only 1% (Etxeberria et al., 2007).

In addition to studies showing that the compressive strength of concrete decreases with the increase in the amount of RA, in the literature, it is also reported that it does not affect the strength up to a certain rate. Research on the use of RCA in high strength concrete revealed that replacing up to 30% of the concrete with RCA did not affect the concrete's compressive strength (Limbachiya et al., 2000). Moreover, in the study conducted by Xuyong et al. (2025) in which they investigated the effect of RCA on the properties of self-compacting concrete, aggregates obtained from local construction plants were used instead of normal aggregates at 15, 30 and 50% by mass. The 7, 8 and 90-day compressive strengths of samples taken from mixtures made with fly ash, portland cement and blast furnace slag were measured. Accordingly, the compressive strengths at a 30% change rate were measured as 42.62 and 69 MPa, respectively. These values are 1.2 and 4 MPa greater than the compressive strength values measured in the control samples. In the study conducted to enhance the quality of concrete made with poorly graded aggregates, 2 different RA were used. The RA used were prepared separately from poor old pavement plates (compressive strength 15-20 MPa) and high-quality concrete samples (compressive strength 35-50 MPa). According to the research results, an improvement in compressive strength was achieved up to a 30% change rate, while the compressive strength gradually decreased after a 30% change rate (Kubissa et al., 2015). In another study where treatment was applied to aggregates, it was stated that the optimum change rate was 45% (Ismail & Ramli, 2013).

In many studies conducted on RAC, it has been indicated that the mechanical properties of the concrete decrease as the amount of RA increases, and the main reason for this is that the old mortar adhered to the aggregate weakens the interfacial transition zone between new cement gel and RA. The rough surface and rich in moisture on the aggregate surface can help to create the large crystal layers and improve the interfacial transition zone (Chen et al., 2024). In the study examining the behavior of water-saturated RCA as internal curing material, the compressive strength increased by 14% for w/c=0.7, 11% for w/c=0.6 and 3% for w/c=0.5 at 50% replacement. On the other hand, concrete incorporating oven-dry RA at the same replacement ratio exhibited a 10% decrease in compressive strength at a water-cement ratio of 0.5 (Yildirim et al., 2015).

Different mixing techniques were developed to improve the interfacial transition zone between the new mortar layer and the RA. Two-stage mixing approach (TSMA) (Tam et al., 2005), double mixing method (DM) (Ryu, 2002) , sand-envelop mixing approach (SEMA) and mortar mixing approach (MMA) (Liang et al., 2015) are some of the developed mixture techniques. In the study comparing TSMA with the normal mixing technique, 3, 7 and 28-day compressive strengths were found to be higher for mixtures using TSMA (Brand et al., 2015). A comparable study carried out in Australia confirmed that the use of the TSMA mixing method contributes to increased compressive strength (Ozbakkaloglu et al., 2017). In the study, the mechanical and physical properties of aggregates were improved using various treatment techniques. According to the findings, RAC exhibits greater compressive strength when produced by the sand-enveloped mixing method compared to the mortar mixing and two-stage mixing methods (Liang et al., 2015).

#### 2.2.2.2 Splitting Tensile Strength

Although concrete is a brittle material and its dominant feature is compressive strength, the tensile strength of concrete becomes important in some engineering purposes. Since it is very difficult to apply tensile force on concrete, the tensile strength of concrete is measured using indirect methods such as the flexure test and splitting test. While the rupture modulus is measured on a beam sample in the bending test, a high horizontal compressive force is applied to the concrete cylinder/cube sample by a narrow line to ensure its splitting (A.M. Neville & J.J. Brooks, 2004). In contrast to uniaxial compression, the concrete experiences a biaxial tensile-compressive stress state during the tensile splitting test. Under this stress distribution, damage occurs by inducing cracks between aggregates and cement gel. The cracks developed rapidly and caused failure along the concrete section. Consequently, the estimation of the splitting tensile test depends critically on the weak interfacial transition zone (Zong et al., 2025).

According to Yildirim et al. (2015), the tensile strength of concrete decreases as the RCA content increases. In the research where 3 different water/cement ratios and recycled coarse aggregate were used, it was determined that the water/cement ratio and tensile strength were inversely proportional. In the mixtures where RA was used, the tensile strength decreased from 4.6, 3.8 and 3 MPa to 4.2, 3.7 and 2.9 MPa, respectively (Turanlı,1993). In the research conducted in Bangladesh, RCA were replaced with normal aggregate at 15, 30 and 45% replacement levels. According to the results, the 28-day splitting tensile strength of the control samples was measured as 4.58 MPa. However, this value decreased to 3.77 MPa after the RA ratio increased (Sobuz et al., 2024). Substituting only the large sized aggregates at varying replacement proportions, the study seeks to ascertain how RA affect the mechanical characteristics of concrete. Tensile strength was found to drop by 3, 10, and 18 per cent in mixtures containing 30, 50, and 70% RA. (Bui et al., 2017) .

In the study conducted on the effect of particle size distribution, the tensile strengths of concretes containing RCA prepared according to the optimum, lower and upper limit values of the particle size distribution curve given for coarse aggregates in the

European standard were measured. The splitting tensile strength of the concrete was measured as 5.5 MPa for the upper limit of the particle size distribution, while it was recorded as 5.3 MPa for the lower limit. As can be seen, finer particles provide greater adhesion with the cement paste (Zong et al., 2025).

In the study comparing different mixing techniques, it was concluded that the tensile strengths of concrete samples prepared using TSMA changed by 20% and 7% (Brand et al., 2015).

**2.2.2.3 Modulus of Elasticity**

The modulus of elasticity is a critical input parameter in the design and structural assessment of reinforced or pre-stressed concrete structures. As commonly understood, the modulus of elasticity of concrete corresponds to the slope of the stress-strain curve. The descending part of the stress–strain curve is related to the ductility of material, and the peak of the ascending part is related to the brittleness. The stress-strain behaviors of the two main materials of the concrete (aggregate and cement paste) are given in Figure 1. Concrete behaves differently under load than its individual components due to the development of bond cracks at the interface between aggregate and cement paste. As the applied stress attains roughly 70 percent of the ultimate strength, cracks in the mortar start to form, causing the stress-strain curve to bend at an increasing rate. After that, the formation of a continuous network of load carrying paths decreases and reaches to the maximum strength (A.M. Neville & J.J. Brooks, 2004; A.M. Neville ,2011).

As can be understood from the stress-strain behavior of concrete, the modulus of elasticity is directly correlated to the concrete strength, the type of aggregate and the bond between the aggregate and cement paste. In the information given so far, it has been stated that RAC has a weak ITZ and this negatively affects the mechanical properties of the concrete. Thus, the modulus of elasticity of recycled concrete is lower than normal concrete.

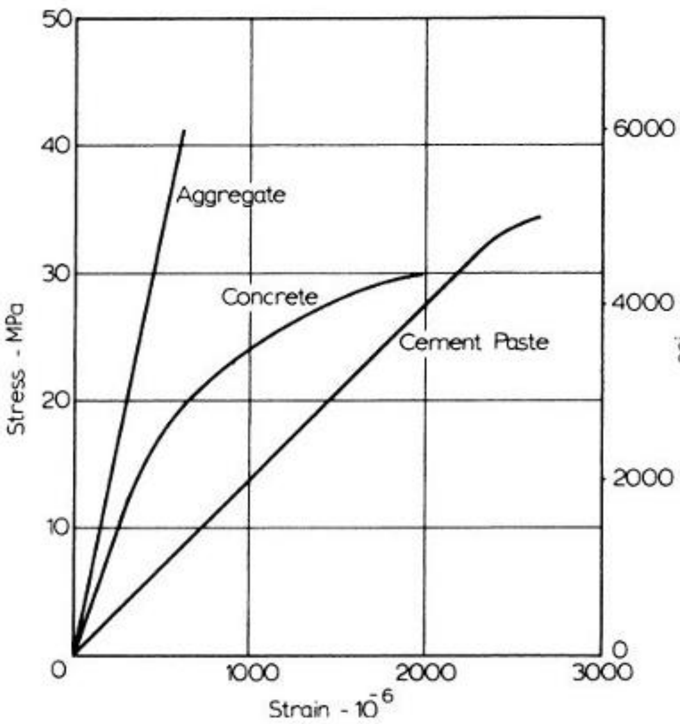



Figure 1: Stress–strain relationship for concrete and main ingredients (cement paste and aggregate) (A.M. Neville,2011)

Several researchers have reported that the modulus of elasticity of concrete decreases with higher replacement levels of RCA in place of natural aggregate. Concrete samples without RCA exhibited a 28-day modulus of elasticity of 23.19 GPa, while samples with 10%, 20%, 30%, and 40% RCA replacement showed moduli of 23.01, 22.60, 21.91, and 21.51 GPa, respectively. In a study conducted in Argentina examining the failure behavior of RAC, when 30% of the normal aggregate was replaced with RCA, the modulus of elasticity decreased by 9.6%. Additionally, at 60% and 100% replacement levels, it dropped by 22.5% and 34.4%, respectively (Folino & Xargay, 2014). In another study where the gradation range of RA was 12-20 mm, concrete samples with 15%, 30%, and 45% replacement levels showed decreases in the modulus of elasticity of approximately 7.42%, 12.94%, and 17.52%, respectively (Sobuz et al., 2024).

Curing conditions and moisture of the sample are also important parameters in determining the modulus of elasticity. In the study, 20, 50 and 100% of the coarse aggregates were replaced with RA, the elastic modulus decreased from 36 GPa to 30.5 GPa in the scenario where the samples were kept in the laboratory environment (low relative humidity and room temperature). On the other hand, in samples cured in water and under temperature control, the modulus of elasticity diminished from 43 to 33.5 GPa (Fonseca et al., 2011).

Ozbakkaloglu et al. (2017) stated that "the modulus of elasticity of the RAC manufactured using two two-stage mixing approach is slightly higher than that of the RAC manufactured using normal mixing"

The aggregate volumetric proportion affects the elasticity modulus of concrete (A.M. Neville & J.J. Brooks, 2004) . The study concluded that partially replacing coarse aggregates (5.6, 6.73-, and 7.93-mm sieve mesh) with RA increased the modulus of elasticity by 10-12% and 8-11%, respectively, as the amount of normal aggregates decreased from 70% to 50% and 50% to 30%  (Bui et al., 2017).

### 2.2.3 Durability

#### 2.2.3.1 Permeability

The durability of concrete is mostly related to its permeability. Permeability is defined as the ease with which liquids or gases can travel through concrete. Pores inside the concrete play an important role in its durability.  As the cement paste begins to harden and the bond between the aggregate and the cement paste becomes stronger, the void system within the concrete decreases. Aggregates also contain pores; however, these are discontinuous.  Pores must be continuous if permeability occurs. If the porosity is high, that means pores are connected, transport the harmful gases and liquids inside the concrete and deterioration of concrete occurs (A.M. Neville & J.J. Brooks, 2004).

There is various test methods related to the structure of the pore system in concrete. The volume of pore space in concrete is measured by an absorption test according to ASTM C642-21. Moreover, different test methods were developed to estimate the sorptivity and surface absorption of concrete. Water permeability is another important parameter to evaluate the durability of concrete and is mostly related to the water/cement ratio of concrete. Although aggregates have a minimal effect on permeability due to being coated with cement paste, their impermeability contributes to water resistance by increasing the tortuosity of the water flow path (A.M. Neville, 2011).

Water penetration depths were measured in a study conducted with two different cement types (CEM I 32.5 and CEM II/B-V 32.5) and high and low-quality RCA. For the concrete that is produced by low-quality RCA, a great impact has been observed on the depth of water penetration. While the water penetration depth was measured as 39 mm in the control samples, it was determined to be 69 mm for 10% replacement and 135 mm for 50% replacement by normal coarse aggregate. However, water penetration depth under pressure did not increase radically in concrete samples produced with high-quality RCA and CEM II/B-V type cement (Kubissa et al., 2015).

#### 2.2.3.1 Drying Shrinkage

Drying shrinkage refers to the reduction in concrete volume that occurs due to the loss of moisture from the drying concrete (A.M. Neville & J.J. Brooks, 2004) . Drying shrinkage occurs when water is withdrawn from concrete in an ambient humidity that is lower than 100%. When adsorbed water in the capillary pores starts to remove the concrete, the volume of the hydrated cement paste decreases due to the hydrostatic tension force inside the pores. Consequently, the porosity of the concrete can significantly influence shrinkage (A.M. Neville, 2011).

The elasticity modulus of the aggregate affects drying shrinkage. In particular, lightweight aggregates exhibits greater shrinkage behavior than normal-weight aggregates. Troxell et al. (1958) investigated the long-term creep and shrinkage of concrete that produced with different aggregates having fixed mix proportions in an ideal environment (air temperature 21 °C and relative humidity 50 per cent). It was determined from the study that concrete incorporating sandstone aggregates experienced higher drying shrinkage in both the short term (28 and 90 days) and long term (up to 25 years) relative to concretes with quartz, limestone, granite, and basalt aggregates (A.M. Neville & J.J. Brooks, 2004).

In the drying shrinkage test performed on 15x15x75 cm beam samples, the samples were stored in water for 1 week, and then the drying shrinkage up to 90 days was measured. The drying shrinkage at the end of 90 days was determined to be between 38-84% for different water-cement ratios in 100% RAC compared to normal concrete. The highest drying shrinkage was measured in the concrete sample with the highest water/cement ratio (Turanlı, 1993).

Yildirim et al. (2015) examined the drying shrinkage up to 112 days for three different water-cement ratios (0.5, 0.6 and 0.7) and two replacement levels (50 and 100%). w/c =0.5 Control was found to exceed all RAC containing groups and exhibit half the final shrinkage in w/c=0.5 and 0.6 after 112 days.

In the study investigating the effects of two-stage mixing approach on the properties of RAC, shrinkage strains were lower for the two-stage mixing approach compared to normal mixing procedure mixes, although the difference was often below 10% at later ages. According to the results, RAC experienced drying shrinkage between 560 and 630 micro strain after 90 days (Brand et al., 2015).

In another study utilizing a two-stage mixing approach, it was noted that the percentage change in RCA was directly proportional to drying shrinkage up to 70 days. Results also suggest that there were only slight variations found between the drying shrinkages of companion mixes made with two-stage mixing and normal mixing approaches. Moreover, the effect of water absorption of aggregates in equivalent mixtures on drying shrinkage was also investigated. It has been revealed that concrete prepared with aggregates with lower water absorption shrinks less (Ozbakkaloglu et al., 2017).

# Chapter 3

# METHODOLOGY-EXPERIMENTAL STUDY

## 3.1 Introduction

This chapter details the materials utilised in this research and comprehensively outlines the experimental procedures. Additionally, it includes an explanation of mix preparation, casting, curing, and testing techniques.

## 3.2 Materials

The following section outlines the materials utilized in this experimental study**:**

### 3.2.1 Cement

According to ASTM C 150-07, this study used Type I cement obtained from a local cement plant, BEM (Boğaz Endüstri Madencilik Ltd.). The chemical composition and physical properties of the cement are tabulated in Table 2.

Table 2: Chemical and physical properties of cement

<table>
<tr><th>Chemical Property</th><th>Insoluble Residue</th><th>Loss of Ignition</th><th>$SO_3$</th><th>$SiO_2$</th><th>CaO</th><th>CaO (free)</th><th>MgO</th><th>$Al_2O_3$</th><th>$Fe_2O_3$</th><th>Cl</th></tr>
<tr><td>Percentage (%)</td><td>0.91</td><td>3.71</td><td>2.86</td><td>19.74</td><td>63.30</td><td>1.16</td><td>1.67</td><td>4.37</td><td>3.93</td><td>0.02</td></tr>
<tr><td colspan="3">Potential Phase Composition</td><td colspan="2">$C_3S$</td><td colspan="2">$C_2S$</td><td colspan="2">$C_3A$</td><td colspan="2">$C_4AF$</td></tr>
<tr><td colspan="3">Percentage (%)</td><td colspan="2">60</td><td colspan="2">12</td><td colspan="2">6</td><td colspan="2">12</td></tr>
<tr><td colspan="3">Physical Property</td><td colspan="2">Specific Gravity ($g/cm^3$)</td><td colspan="2">Blaine Fineness ($m^2/kg$)</td><td colspan="2">Time of setting (minutes)</td><td colspan="2">Expansion (mm)</td></tr>
<tr><td colspan="3"></td><td colspan="2">3.11</td><td colspan="2">347.4</td><td colspan="2">135</td><td colspan="2">1</td></tr>
</table>

### 3.2.2 Water

Tap water of acceptable quality, free from impurities such as oils, alkalis, acids, and organic content, was used in the preparation and curing of all concrete samples.

### 3.2.3 Chemical Admixture

According to ASTM C494/C494M-24 Type F, which pertains to high-range water-reducing / superplasticizing concrete admixtures, BASF MasterGlenium® 27 was utilised as a chemical admixture. This polycarboxylic ether-based, new-generation superplasticizer, unlike traditional superplasticizers, allows for significantly longer workability without delaying the setting time and achieves a high reduction in the amount of mixing water. The main properties of the admixture used are detailed in Table 3.

Table 3: Properties of chemical admixture

| **Specification** | **Product Data** |
|---|---|
| Appearance | Brown liquid |
| Specific gravity | 1.05 ± 0.02 g/cm³ at 20°C |
| pH | 7.0 ± 1 |
| Alkali content (%) | ≤ 2.50 by mass |
| Chloride content (%) | ≤ 0.10 by mass |

### 3.2.4 Fine Aggregate

Well-graded crushed limestone (0-5 mm) from the Beşparmak Mountains in Cyprus was utilised as a fine aggregate in this study. The specific gravity, water absorption, and bulk density of the fine aggregate were specified according to ASTM C128-22 and

ASTM C29/C29M-23, respectively. The results were obtained from laboratory tests conducted on the aggregates, as presented in Table 4. Sieve analysis was performed on the fine aggregates following ASTM C136/C136M-19, and the results were classified according to ASTM C33/C33M-18. The particle size distribution of the fine aggregate is presented in Figure 2.

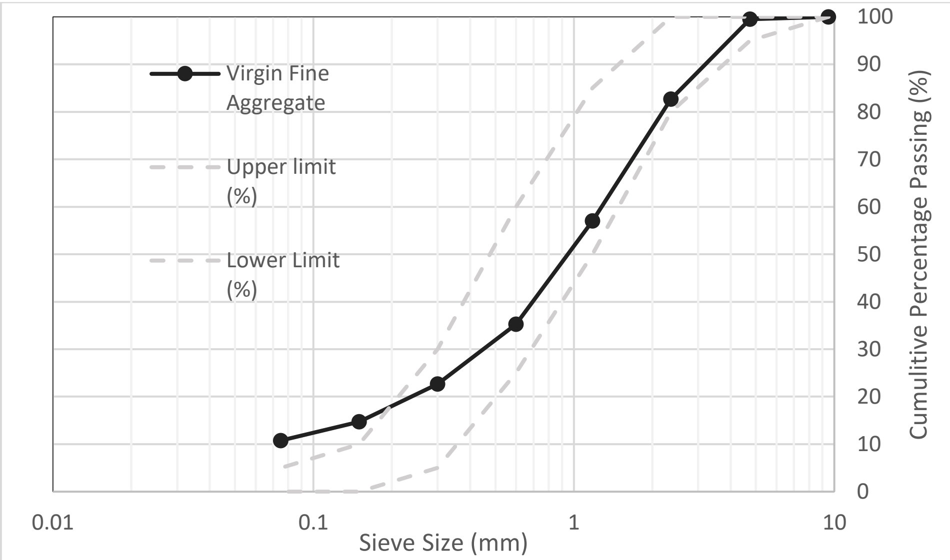



Figure 2: Gradation curve of fine aggregate

### 3.2.5 Coarse Aggregate

Aggregates with three different gradations (2.36/9.5 mm, 4.75/19 mm, and 9.5/25 mm), produced in the same quarry as fine aggregate, were utilised as coarse aggregate. Geometric, physical, and mechanical properties were evaluated according to ASTM C127-24, ASTM C29/C29M-23, ASTM C136/C136M-19, and ASTM C131/C131M-20, with results provided in Table 4 and Figure 3.

### 3.2.6 Recycled Concrete Aggregate

#### 3.2.6.1 Sources of Concrete Wastes

RCA used in this study was obtained from two different waste sources. RCAn (RCA new) was recycled from waste concrete by a ready-mix concrete production plant near

Famagusta. This waste consists of concrete that cannot be used due to returned orders or inaccurate production. It also includes waste left over from cleaning the production plant and trucks during concrete production. The other RCA (RCAo) is derived from concrete waste generated from the demolition of an old structure. This structure was built in the 1940s-1950s and is located in Famagusta. It was demolished in 2018, and the waste was stockpiled. The structure was constructed to serve as an industrial building, including of a steel and reinforced concrete structural system and concrete block walls.

The primary distinctions between RCAn and RCAo are related to the aggregate type and the age of the source concrete. RCAn includes crushed limestone aggregate and was produced in the last year. RCAo contains natural uncrushed aggregates. The characteristic compressive strength of parent concrete is unknown. RCA used in the study are shown in Figure 4.

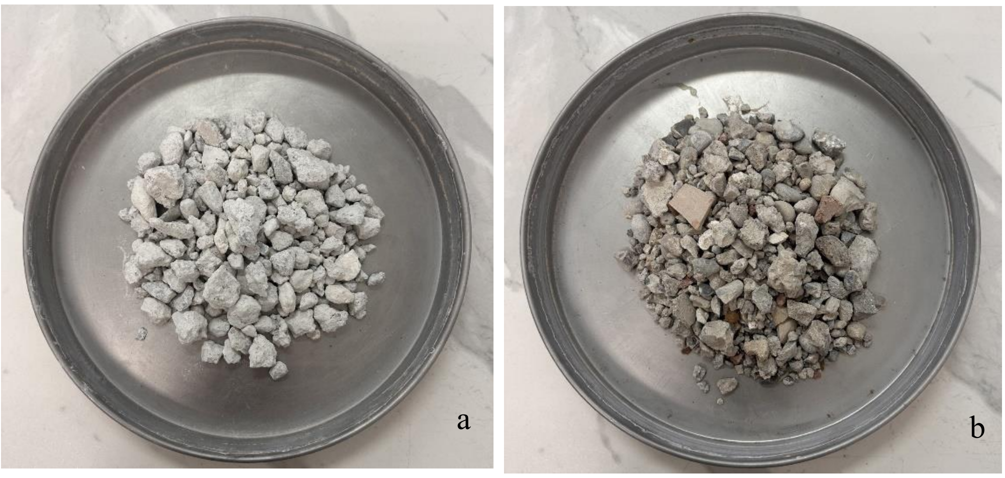


Figure 4: RCA (a) RCAn (b) RCAo

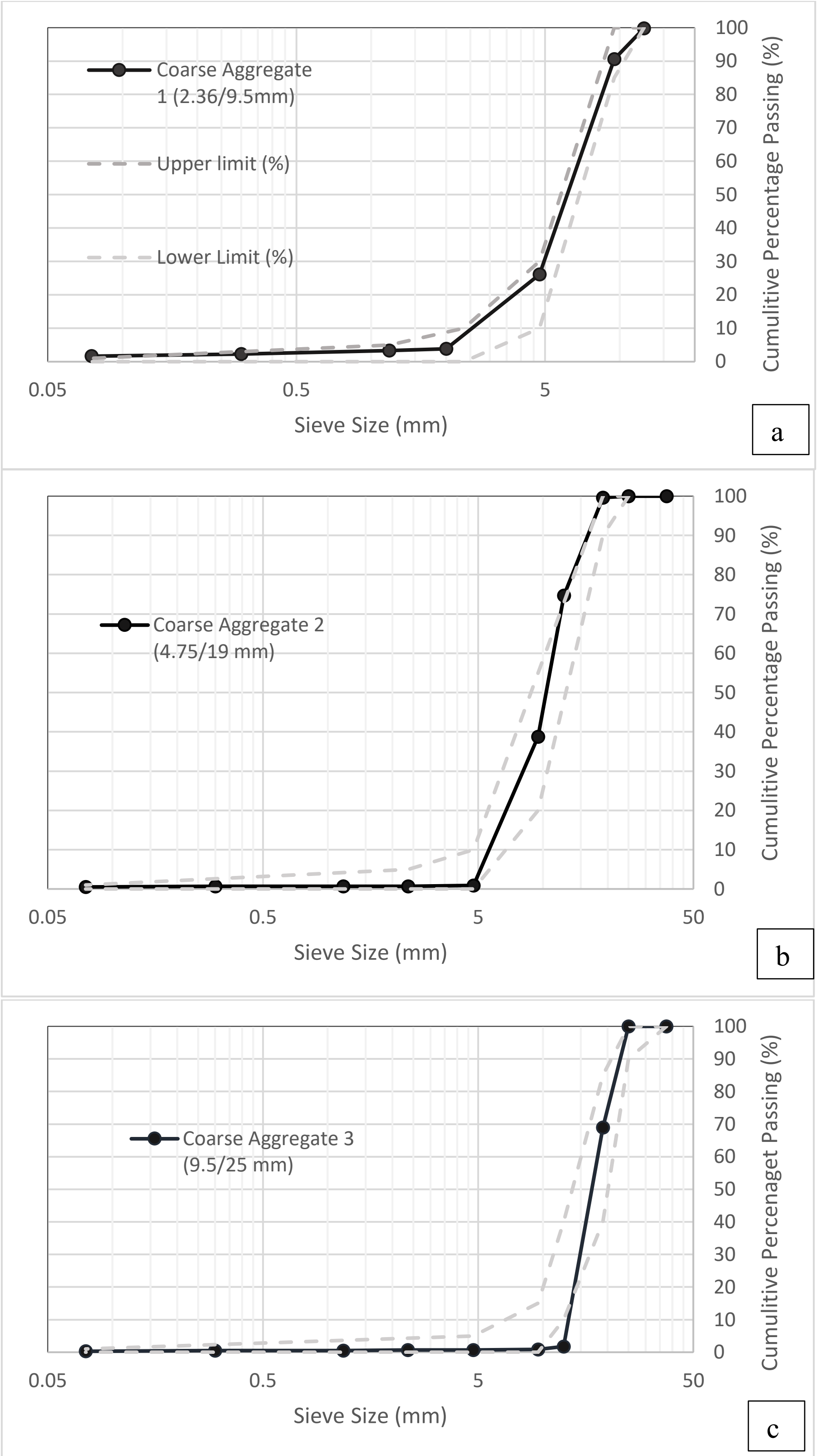



Figure 3: Gradation curves for normal coarse aggregate (a) coarse Aggregate 1 (2.36/9.5 mm), (b) coarse Aggregate 2 (4.75/19mm), (c) coarse Aggregate 3 (9.5/25mm)

#### 3.2.6.2 Recycling and Sample Preparation

The impact breaker type crusher machine (METSO LT 12/13) is used as a primary crushing machine in recycling processes to reduce the fragment size of concrete blocks. It comprises a series of rotating hammers that strike the stone and throw it against the breaker bars, forming the outer casting of the machine. This process is repeated several times as the stone rebounds. The conveyor transports the crushed material to the scalping screen. This belt is often beneath a magnet to remove pieces of drill steel or other tramp iron.

After the crushing process, recycled materials achieved from old structure and new concrete wastes were collected and grouped by using sieves (5 mm and 25 mm). The RA (RCAn) were washed using a 5 mm sieve to remove excessive fine particles from the aggregates. At the end of the process, RCA were obtained. The preparation procedure of the RCA from new concrete waste is illustrated in Figure 4.

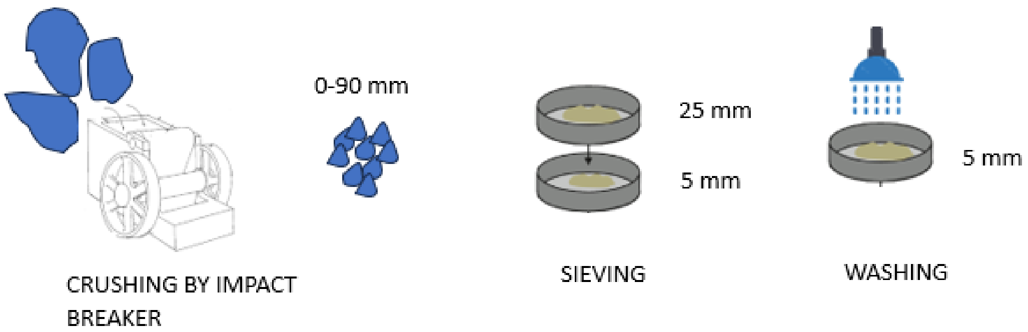



Figure 4: Sample preparation process for RCAn

### 3.2.6.3 Laboratory Tests for Recycled Concrete Aggregate

RA components were categorized following the TS EN 933-11:2010 standard. According to the standard, floating materials were extracted from the aggregates and other ingredients were classified based on type. Each RCA's component classification is displayed in Table 5.

Table 5: Ratio of each material in the RA (% mass)

| **Constituent** | **Glass** | **Wood** | **Plaster** | **Brick** | **Unbounded Aggregate** | **Concrete** |
|---|---|---|---|---|---|---|
| **RCAn** | **-** | **-** | **-** | **-** | 28.8 | 71.2 |
| **RCAo** | 0.02 | 0.2 | 1.9 | 1.7 | 10.6 | 85.6 |

Specific gravity and water absorption test, sieve analysis, bulk density and abrasion resistance test (Los Angeles test) were carried out on RCA according to related ASTM standards and results are given in Table 4. Sieve analysis results of RCA are presented in Figure 5.

The attached mortar content is calculated by the equation (1) (Xiao, 2018) given below:

$$x = \frac{\rho_{RCA} - \rho_{NCA}}{\rho_M - \rho_{NCA}} \quad (1)$$

where:

$\rho_M$ : apparent density of mortar

$\rho_{NCA}$: apparent density of normal coarse aggregate in parent concrete

$\rho_{RCA}$ : apparent density of RCA

X: content of adhered mortar by volume

The apparent density of aggregate was determined according to the ASTM C29/C29M-23 by using the aggregates obtained after the Los Angeles experiment, and the apparent density of mortar was assumed to be 1.7 g/cm$^3$.

Table 4: Mechanical and physical properties of aggregates

| Aggregate Type | Grading Rate (mm) | FM (%) | $S_D$ (g/cm$^3$) | $S_{SSD}$ (g/cm$^3$) | $S_A$ (g/cm$^3$) | WA (%) | Bulk Density-SSD (kg/m$^3$) | Void Content (%) | LA | Attached Mortar (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Coarse 1** | 2.36/9.5 | 3.73 | 2.67 | 2.71 | 2.78 | 1.48 | 1 598 | 40.9 | - | - |
| **Coarse 2** | 4.75/19 | 4.59 | 2.71 | 2.72 | 2.74 | 0.46 | 1 555 | 42.8 | 23.7 | - |
| **Coarse 3** | 9.5/25 | 5.28 | 2.69 | 2.70 | 2.72 | 0.39 | 1 514 | 42.3 | 23.4 | - |
| **Fine** | 0/5 | 2.88 | 2.62 | 2.68 | 2.78 | 2.19 | - | - | - | - |
| **RCAn** | 4.75/19 | 4.29 | 2.04 | 2.27 | 2.64 | 11.19 | 1 459 | 35.6 | 39.5 | 39.5 |
| **RCAo** | 4.75/19 | 4.63 | 2.22 | 2.36 | 2.58 | 6.4 | 1 504 | 39.9 | 29.3 | 29.3 |

FM: Fineness modulus,$S_{D:}$ Specific gravity (relative density) on oven-dry, $S_{SSD:}$ Specific gravity (relative density) on SSD condition, $S_{A:}$ Apparent Specific gravity (relative density), WA: Water absorption of aggregates after 24 hours, LA: Loss of weight in percentage after fragmentation

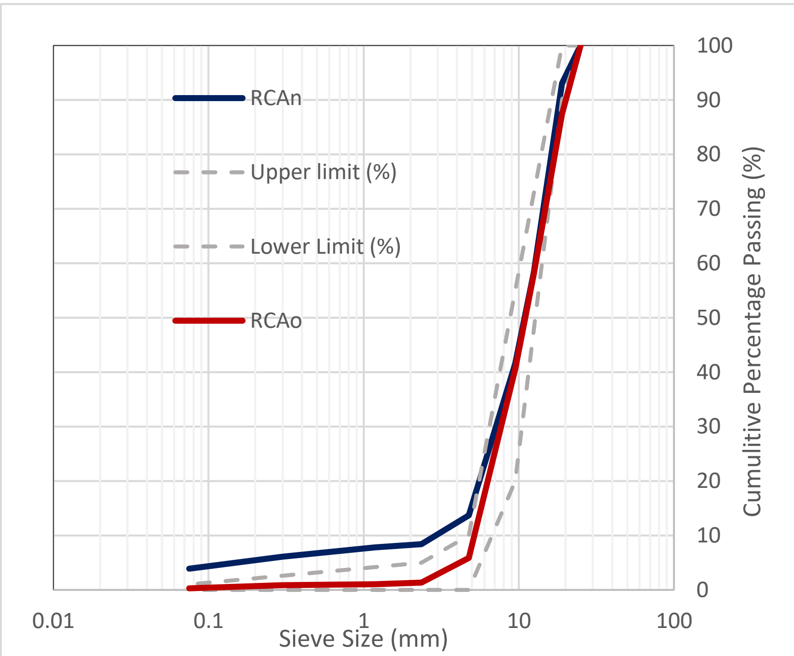


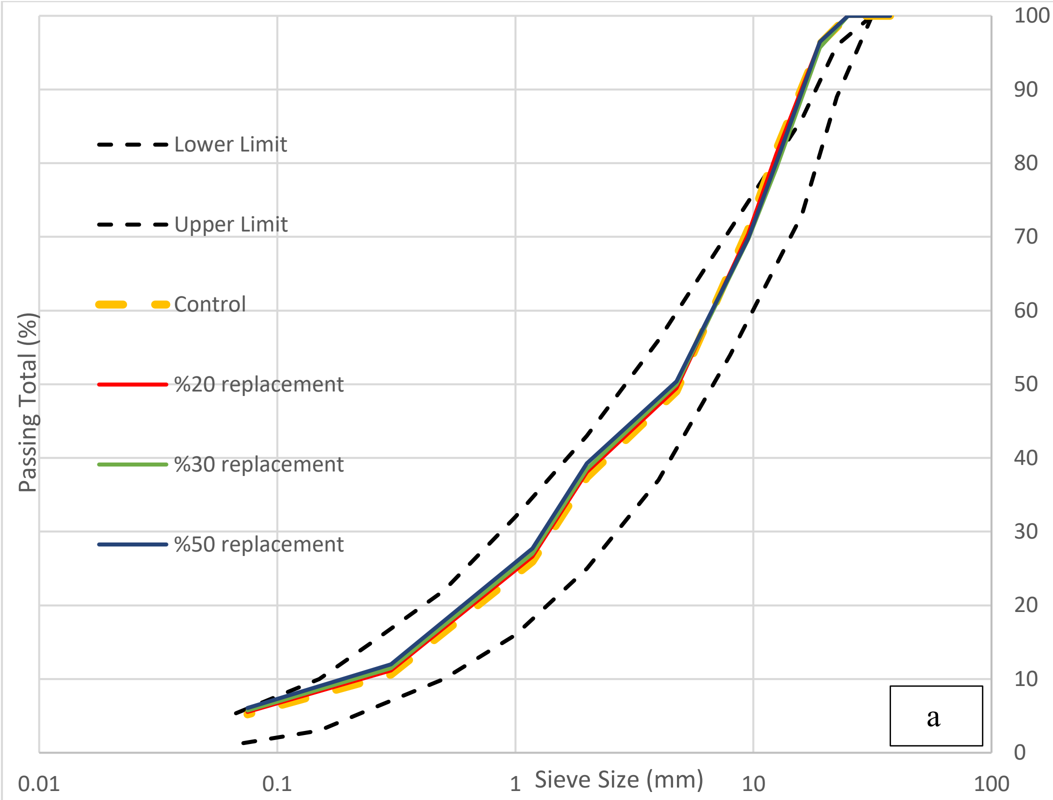
Figure 5: Gradation curves for RCAn and RCAo

## 3.3 Mix Design Calculations

The amount of required materials for each mixture was calculated according to the ACI 211.1-91. The target compressive strength class at 28 days was designated as C30/37, and the slump value was 200±20 mm. The absolute volume approach was employed to determine the proportions of aggregates in the concrete. Moreover, TS 802:2016 limits were used to obtain the desired particle size distribution curve for pumpable concrete. The proportions of fine and coarse aggregate to enter the mixture are adjusted to remain within the limits in this curve. The mixture grading curve illustrated in Figure 6 was used to determine the amount of RCA used at different replacement levels. To estimate the required water and optimum cement content, five different trial mixtures were prepared using control mixture calculations and chemical admixture ratios. Based on the results of the trial mixtures, it was determined that 322 $kg/m^3$ of cement was necessary for the targeted 28-day compressive strength. To achieve a water/cement ratio of 0.54, 0.5% superplasticiser was added, and the amount of water required was reduced by 10%.

## 3.4 Mix Proportioning

The slump value remained constant during the laboratory research, and three different mixture techniques were employed for the various replacement levels of coarse aggregate (20%, 30%, and 50%) utilising two types of RCA (RCAn and RCAo). To evaluate the effectiveness of the mixing technique, a total of nineteen mixes were prepared. Within each series, the quantities of cement, fine aggregate, and superplasticiser remained constant, while the volume of RCA was varied in relation to the natural coarse aggregate The amounts of ingredients in each mixture are presented in Table 6.



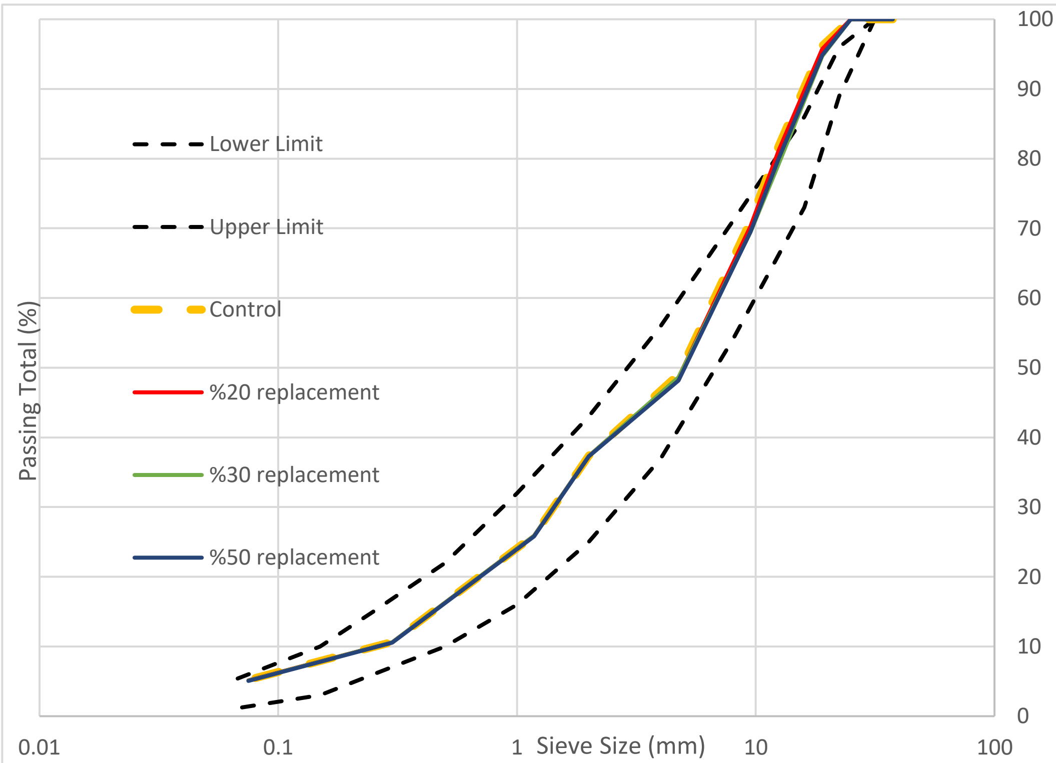




Figure 6: Mixing grading curves (a) for RCAn series, (b) for RCAo series

Table 6: Mix proportions

| Mix Type | Cement (kg/m$^3$) | Total Water (kg/m$^3$) | Effective Water (kg/m$^3$) | SP* (kg/m$^3$) | Fine (kg/m$^3$) | Coarse Agg. 1 (kg/m$^3$) | Coarse Agg. 2 (kg/m$^3$) | Coarse Agg. 3 (kg/m$^3$) | RCA (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| Control | 322 | 201 | 174 | 1.6 | 826 | 359 | 478 | 229 | - |
| RCAn20NMA | 322 | 222 | 174 | 1.6 | 809 | 278 | 393 | 169 | 184 |
| RCAn30NMA | 322 | 232 | 174 | 1.6 | 800 | 256 | 281 | 185 | 277 |
| RCAn50NMA | 322 | 252 | 174 | 1.6 | 784 | 179 | 236 | 91 | 453 |
| RCAn20TSMA | 322 | 189 | 169 | 1.6 | 809 | 278 | 393 | 169 | 184 |
| RCAn30TSMA | 322 | 208 | 154 | 1.6 | 800 | 256 | 281 | 185 | 277 |
| RCAn50TSMA | 322 | 220 | 152 | 1.6 | 784 | 179 | 236 | 91 | 453 |
| RCAn20SEMA | 322 | 222 | 174 | 1.6 | 809 | 278 | 393 | 169 | 184 |
| RCAn30SEMA | 322 | 207 | 149 | 1.6 | 800 | 256 | 281 | 185 | 277 |
| RCAn50SEMA | 322 | 216 | 138 | 1.6 | 784 | 179 | 236 | 91 | 453 |
| RCAo20NMA | 322 | 187 | 174 | 1.6 | 831 | 283 | 397 | 170 | 195 |
| RCAo30NMA | 322 | 194 | 174 | 1.6 | 824 | 262 | 285 | 187 | 295 |
| RCAo50NMA | 322 | 206 | 174 | 1.6 | 811 | 184 | 240 | 92 | 484 |
| RCAo20TSMA | 322 | 167 | 154 | 1.6 | 831 | 283 | 397 | 170 | 195 |
| RCAo30TSMA | 322 | 174 | 154 | 1.6 | 824 | 262 | 285 | 187 | 295 |
| RCAo50TSMA | 322 | 199 | 167 | 1.6 | 811 | 184 | 240 | 92 | 484 |
| RCAo20SEMA | 322 | 177 | 164 | 1.6 | 831 | 283 | 397 | 170 | 195 |
| RCAo30SEMA | 322 | 193 | 173 | 1.6 | 824 | 262 | 285 | 187 | 295 |
| RCAo50SEMA | 322 | 206 | 174 | 1.6 | 811 | 184 | 240 | 92 | 484 |

*SP: Superplasticizer

The control mix corresponds to a conventional concrete mixture. The letter "RCAn" stands for RCA obtained from new concrete waste, and "RCAo" represent RCA obtained from old structure demolition waste. The numbers (20, 30 and 50) represent the percentage of RCA replacement in each mixture. Finally, the last letters were symbolised by the applied mixture technique.

## 3.5 Concrete Mixing Procedure

The different mixing techniques, such as two-stage mixing approach (TSMA) ,normal mixing approach (NMA) and sand enveloped mixing approach (SEMA), were used in this study. The mixing processes for each mixing approach are presented in Figure 7.

In the normal mixing method, all aggregates were placed into the pan mixer and blended until a uniform mixture was achieved. Subsequently, cement was added and mixed for one minute. A portion of the mixing water was set aside and combined with the superplasticiser. To prevent the aggregates and cement from absorbing the chemical admixture, the mixing water was added first, followed by the water–additive mixture, which was then mixed for an additional two minutes.

In the TSMA procedure, both normal and recycled aggregates were placed into the pan mixer and mixed until a uniform consistency was reached. Half of the mixing water was then added, and mixing continued for one minute to allow the aggregates to become saturated. After 30 seconds, cement was introduced into the mixture, followed by the addition of the remaining water and superplasticiser. The entire mixture was then blended for an additional two minutes.

The SEMA mixing technique was carried out as follows: fine aggregate and 75% of the mixing water were combined in the pan mixer and mixed for 30 seconds. Cement was then added to the wet aggregate mixture and mixed for 45 seconds to form a mortar. Afterward, RA, normal aggregates, the remaining mixing water, and superplasticiser were added sequentially and mixed for 90 seconds.

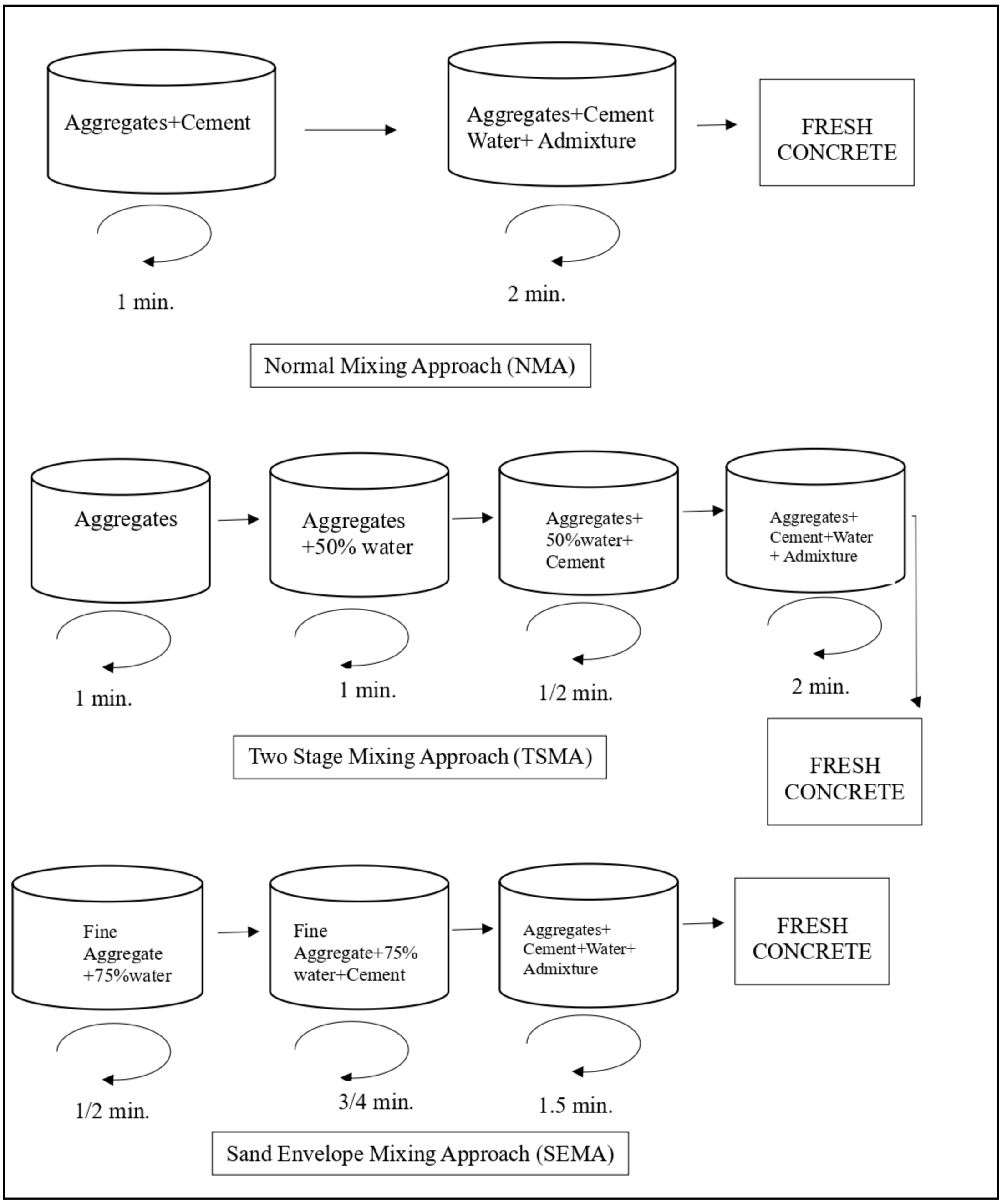



Figure 7: Mixing techniques

The mixtures were made at room temperature. The relative humidity of the mixing environment was approximately 50±10%. A 200-Lt. capacity laboratory-type pan mixer was used to mix concrete. Before each mixture, the mixer and the experiment tools were washed with tap water to ensure that they were clean and moist.

## 3.6 Casting and Curing

From each mixture, 475 specimens were prepared, comprising 19 cubes (150×150×150 mm), 3 cylinders (150×300 mm), and 3 beams (100×100×500 mm) to assess hardened concrete properties and durability performance. Before each casting, the moulds were cleaned, and mould oil was applied to facilitate the demolding of samples. After casting, samples were kept in the curing room with their moulds at a room temperature of 23ºC and relative humidity of 98% for 24 hours to protect them from vibration and temperature change. After that, the samples were removed from their moulds and stored in water at 20±2ºC until the time of testing.

## 3.7 Determination of Fresh Properties of Concrete

### 3.7.1 Slump Test

According to ASTM C143/C143M-20, the slump test was performed to assess whether each mixture met the desired consistency. The slump test is a widely used test method to check whether concrete has the same consistency rather than its rheological properties. In the experiment, the extent to which the concrete, which is placed in a standard-sized funnel by compacting it in 3 layers, collapses within a certain time after the funnel is withdrawn is measured by a steel ruler.

### 3.7.2 Fresh Unit Weight

The density (unit weight) of freshly mixed concrete and yield value were determined based on the ASTM C138/C138M-24a. The principle of the experiment is to measure the mass of fresh concrete placed in a 7-lt capacity measure by consolidating it in three stages using the rodding method. The capacity of measure and the consolidation method should be selected according to the maximum diameter of aggregate and the consistency of the concrete.

## 3.8 Determination of Hardened Properties of Concrete

### 3.8.1 Compressive Strength Test

For each mix, twelve cube samples were prepared with 150 mm edges to measure the compressive strength of concrete. The effect of replacement level, aggregate type and mixture technique at 3, 7, 28 and 90 days was investigated according to TS EN 12390-3:2019 standard. In the experiment, a 3000 kN capacity Toni Technik Model 2010 servo hydraulic concrete testing press machine was used to load the sample at a speed of 0.6 MPa/s without any impact. The mean of the three values at varying ages was computed and reported. Cured specimens were tested as soon as possible in a saturated surface dry condition. Moreover, 150x10x150 mm cube samples were used to obtain the dry unit weight of the concrete mixtures

### 3.8.2 Splitting Tensile Strength Test

Cube specimens measuring 150 × 150 × 150 mm were prepared to perform the splitting tensile test following a 28-day curing period in a controlled laboratory environment, under TS EN 12390-6:2024 Annex A. In the experiment, the load was applied to the sample at a speed of 0.05 MPa/s by using the bearing bar and plywood strips as shown in Figure 8. The tensile splitting strength was calculated using Equation (2).

$$f_{ct} = \frac{2xF}{\pi xLxd} \quad (2)$$

where:

$f_{ct}$: splitting tensile strength (MPa)

F: maximum applied force (N)

L: length of the sample (mm)

d: height of the sample (mm)

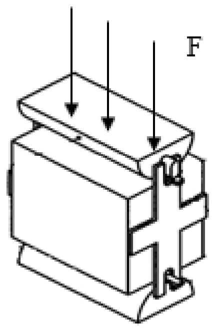



Figure 8: Schematic representation of the splitting tensile strength test

### 3.8.3 Ultrasonic Pulse Velocity Test

The test was performed according to ASTM C597-22 on the 28-day compressive strength test samples. This examination encompasses the computation of the velocity of the pulse wave traversing the cube concrete specimen. The duration required for the pulse to travel between the two transducers positioned at opposing ends of the specimen is recorded. To minimise variations due to sample saturation, specimens were dried with a cloth upon removal from water before conducting measurements. CONTROLS Model 58-E4800 ultrasonic pulse velocity apparatus was used during this research.

### 3.8.4 Rebound Hammer Test

This test was performed according to ASTM C805/C805M-18. The cube samples used for the determination of concrete compressive strength were subjected to a 100 kN preload using a concrete test press, and their surface hardness was measured using a rebound hammer (compressing metal plunger).

### 3.8.5 Modulus of Elasticity Test

28-day elastic modulus of 150x300 mm cylindrical concrete samples was determined according to the ASTM C469/C469M-22. The test setup is presented in Figure 9. Firstly, the ultimate stress of the identical cylinder sample was measured by ASTM C39/C39M-24. Subsequently, two additional samples were loaded to 40% of their ultimate load. Measurements were taken of the longitudinal strain at this load level and the stress associated with a longitudinal strain of 0.00005. The calculation of the modulus of elasticity was carried out based on Equation (3).

$$E = (S_2 - S_1)/(\varepsilon_2 - 0.000050) \quad (3)$$

where:

E: chord modulus of elasticity, MPa

$S_1$: stress associated with a longitudinal strain, $\varepsilon_1$, of 50 millionths, MPa

$S_2$: stress associated with 40% of the ultimate load, MPa

$\varepsilon_2$: longitudinal strain produced by stress $S_2$

To provide plane surfaces on the ends of the cylinder surface, sulfur capping was applied according to the ASTM C617/C617M-23.

### 3.8.6 Water Penetration Depth Test

150x150x150 mm cube samples were used to determine the water penetration depth under pressure in accordance with TS EN 12390-8:2019. After maintaining pressure on the samples for 72 hours, the depth of water ingress was determined on the split specimen surfaces using a steel ruler.

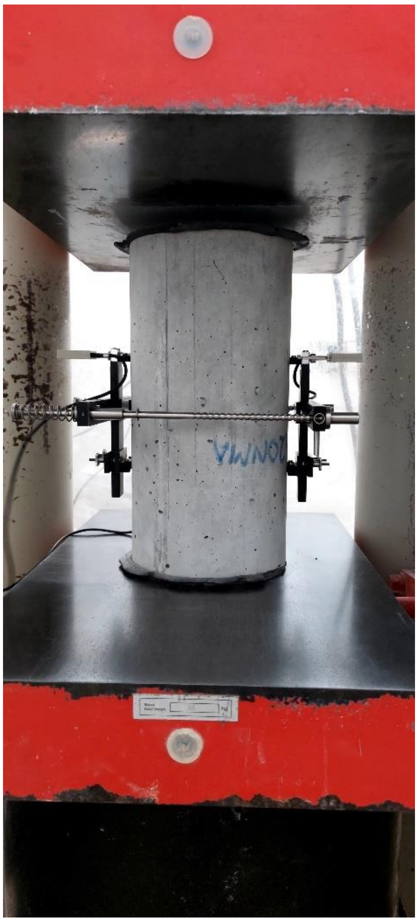


Figure 9: Modulus of elasticity test setup for RCAn20NMA

### 3.8.7 Drying Shrinkage Test

Length changes of hardened concrete were measured according to ASTM C157/C157M-24e1. In this experiment, prism samples with dimensions of 100x100x500 mm were used. The samples were cured in water for 28 days, then kept at room temperature, and the length changes on days 4-7-14-28-56-112, and 140 were measured with a mechanical strain gauge (MAYES/DEMEC4999) using studs mounted on their surfaces shown in Figure 10. In this way, the volumetric contraction or expansion behaviour of the concrete sample was evaluated without the effect of temperature change and applied force during drying process.

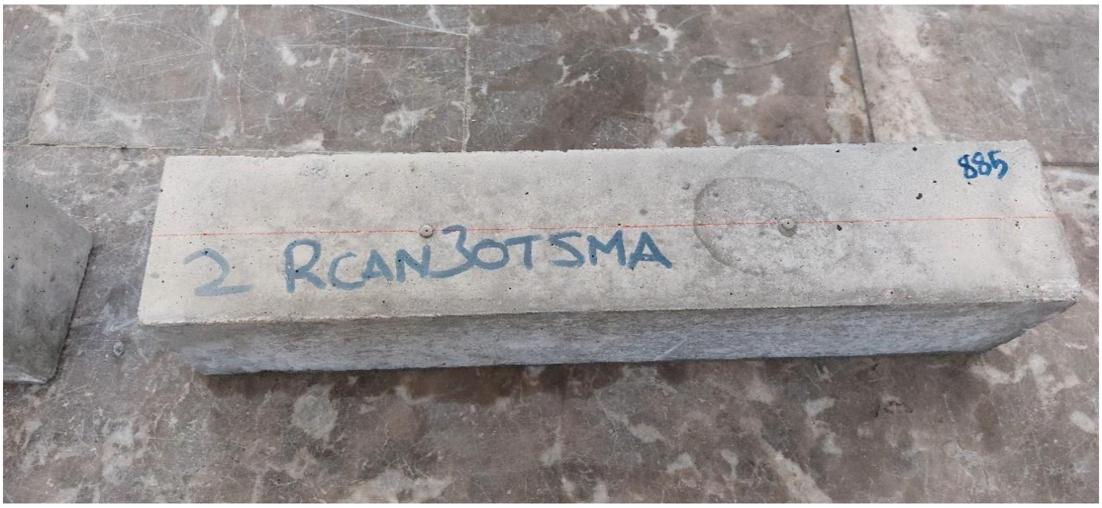



Figure 10: Length change measurement for determination of drying shrinkage of concrete

# Chapter 4

# RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter presents the results of an experimental study involving eighteen different concrete mixes to investigate the impact of mixing techniques and aggregate types on recycled aggregate concrete (RAC). The discussion covers tests conducted on fresh concrete, including the slump test and the fresh unit weight, as well as tests on hardened concrete, such as compressive and tensile strength, modulus of elasticity, drying shrinkage, and permeability. Additionally, non-destructive tests— the rebound hammer and ultrasonic pulse velocity tests—are examined. Following data analysis using Microsoft Excel 2016, the results were organised into tables and illustrated through graphs.

## 4.2 Water Demand of Mixture

Mixing water is a critical factor in attaining the required workability of concrete. Part of the mixing water is absorbed by the aggregates, facilitating their saturation, while the residual free water is vital for the hydration of cement and the proper coating and bonding of fine aggregates, thereby enabling the formation of a cohesive cement paste. Free water between the cement gel and coarse aggregates is necessary during the transportation and placement of concrete. During the compaction process, some of the free water is trapped in the concrete and used for the hydration of the cement and the development of strength, while the excess water is expelled through bleeding. The volume of water remaining in the concrete is filled with compounds formed as a result of hydration. As can be inferred from this process, the quantity of water incorporated in the mix is a critical determinant of the workability characteristics of fresh concrete and profoundly impacts the mechanical performance and durability of hardened concrete by modulating the porosity within the concrete matrix.

Table 7: Amounts of required water for the mixtures

| Mix Type | Cement ($kg/m^3$) | Total Water ($kg/m^3$) | Difference of Total Water ($kg/m^3$) | Effective Water ($kg/m^3$) | Saved Amount of Effective Water ($kg/m^3$) | Total w/c | Effective w/c | Slump (mm) |
|---|---|---|---|---|---|---|---|---|
| Control | 322 | 201 | - | 174 | - | 0.62 | 0.54 | 180 |
| RCAn20NMA | 322 | 222 | + 21 | 174 | - | 0.69 | 0.54 | 190 |
| RCAn30NMA | 322 | 232 | + 31 | 174 | - | 0.72 | 0.54 | 180 |
| RCAn50NMA | 322 | 252 | + 51 | 174 | - | 0.78 | 0.54 | 200 |
| RCAn20TSMA | 322 | 189 | -12 | 169 | 5 | 0.59 | 0.52 | 200 |
| RCAn30TSMA | 322 | 208 | +7 | 154 | 20 | 0.65 | 0.48 | 200 |
| RCAn50TSMA | 322 | 220 | +19 | 152 | 22 | 0.68 | 0.47 | 200 |
| RCAn20SEMA | 322 | 222 | +21 | 174 | - | 0.69 | 0.54 | 200 |
| RCAn30SEMA | 322 | 207 | +6 | 149 | 25 | 0.64 | 0.46 | 220 |
| RCAn50SEMA | 322 | 216 | +15 | 138 | 36 | 0.67 | 0.43 | 200 |
| RCAo20NMA | 322 | 187 | -14 | 174 | - | 0.58 | 0.54 | 190 |
| RCAo30NMA | 322 | 194 | -7 | 174 | - | 0.60 | 0.54 | 200 |
| RCAo50NMA | 322 | 206 | +5 | 174 | - | 0.64 | 0.54 | 210 |
| RCAo20TSMA | 322 | 167 | -34 | 154 | 20 | 0.52 | 0.48 | 190 |
| RCAo30TSMA | 322 | 174 | -27 | 154 | 20 | 0.54 | 0.48 | 190 |
| RCAo50TSMA | 322 | 199 | -2 | 167 | 7 | 0.62 | 0.52 | 190 |
| RCAo20SEMA | 322 | 177 | -24 | 164 | 10 | 0.55 | 0.51 | 190 |
| RCAo30SEMA | 322 | 193 | -8 | 173 | 1 | 0.60 | 0.54 | 180 |
| RCAo50SEMA | 322 | 206 | +5 | 174 | - | 0.64 | 0.54 | 200 |

The quantities of total and free water, along with the corresponding w/c and effective w/c ratios, as well as the slump values for each mixture, are provided in Table 7. According to the results, as the amount of RA increases, the amount of water required by concrete rises. It means that workability decreases. The decrease in workability, or, in other words, the increase in mixing water, is consistent with other research results in the literature (Sobuz et al., 2024; Ismail & Ramli, 2013; Akpinar & Al Attar, 2021).The increase in required water is due to the high-water absorption of RCA and the increase in surface roughness of the attached mortar.

It is understood that when TSMA and SEMA mixing techniques are used in RCAn series mixtures, it causes a decrease in the effective water amount. While 5 kg/m$^3$ of water decreases at 20% replacement level, 22 kg/m$^3$ at 50% replacement level for the TSMA mixing method. This saving causes a decrease in the effective water-cement ratio. There is a similar situation in concrete mixtures in the RCAo series. The effective w/c ratios of mixtures prepared with the TSMA mixing method are lower than those prepared with NMA mixing method.

It has been reported that the TSMA mixing technique decreases the amount of water necessary to achieve the same concrete consistency (Brand et al., 2015). In this mixing technique (TSMA), adding 75% of the water entering the mixture with the aggregates at the beginning causes the aggregates to be saturated with water when in contact with the cement. The bonding of the water-saturated aggregate with the cement paste is more effective and also improves its workability properties (Montero & Laserna, 2017). The reduction in water content observed in the SEMA technique can be attributed to the fact that when the aggregate comes into contact with the cement mortar, the mortar coats the aggregate surface, thereby inhibiting the absorption of water required for saturation. While this leads to a decrease in the overall water demand, it also results in a weaker bond between the cement gel and the aggregate.

## 4.3 Fresh Unit Weight

The density of freshly mixed concrete is largely determined by the relative amounts and specific gravities of its component materials, such as cement, aggregates, and water. The specific gravity of the RCA under SSD conditions was measured to be 2.27 and 2.36 g/cm$^3$ for RCAn and RCAo, respectively. The average specific gravity of the normal aggregate under SSD conditions was measured to be 2.70 g/cm$^3$. Therefore, as the proportion of RCA in the mix increases, the unit weight of fresh concrete will decrease.

Figure 11 illustrates that the addition of RCA with different replacement levels reduces the fresh unit weight of the mixture. While the unit weight of concrete mixture produced with normal aggregate is 2 439 kg/m$^3$, the corresponding values for mixtures using RCAn are 2 394 kg/m$^3$, 2 368 kg/m$^3$, and 2 308 kg/m$^3$ on average for the 20, 30, and 50% replacement levels, respectively. Furthermore, in the mixtures with RCAo replacement at 20%, 30%, and 50%, the unit weight declined by 16 kg/m$^3$, 46 kg/m$^3$, and 77 kg/m$^3$, respectively. The results show that the specific gravity of the RCA is lower for values close to the normal aggregate used in the mixture. Siletani et al. (2024) reported similar results for RCAo series mixtures. The study reported weight loss of 50 kg/m$^3$ for a 40% replacement of RCA.

It is also understood from Figure 11 that the mixing technique impresses the unit weight of fresh concrete. While the unit weights of the mixtures using NMA decrease by 6% for the RCAn series at a 50% change ratio, the reductions are 5.7% and 4.3% for the TSMA and SEMA techniques, respectively.

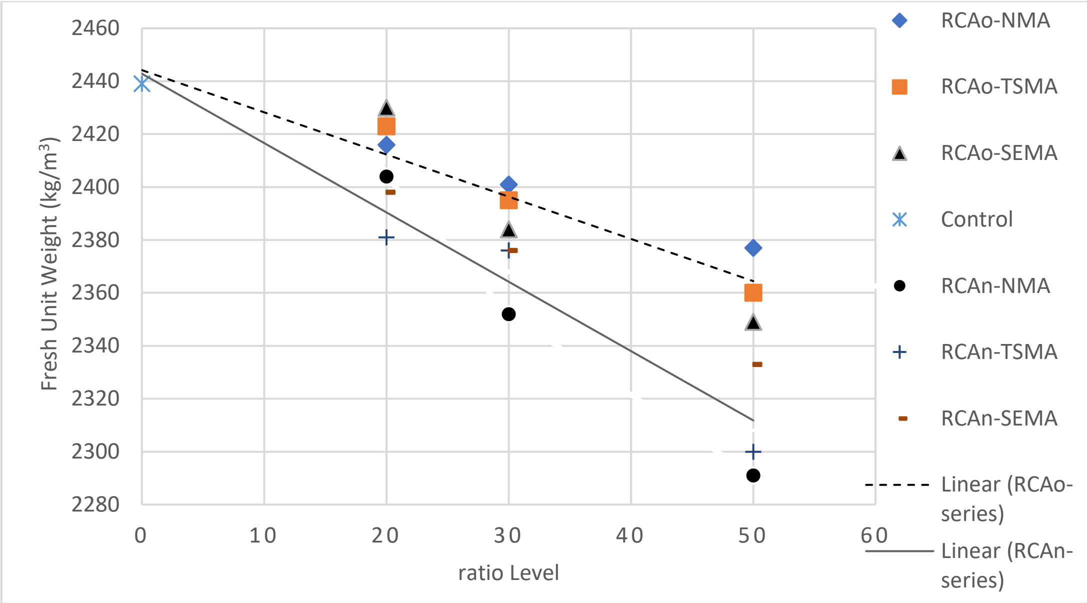



Figure 11: Influences of the replacement level, type of RCA, and mixture technique on the fresh unit weight of concrete

The unit weight reductions of the concrete mixtures in the RCAo series at a 50% change rate are 2.5%, 3.2%, and 3.7% for NMA, TSMA, and SEMA, respectively. The effect of the mixing technique on the unit weight relates to the decrease in the mixture's water demand. The increased unit weight causes the concrete to have a denser structure and reduces the voids inside. For this reason, the TSMA and SEMA techniques yield better unit weight results than the NMA technique.

## 4.4 Hardened Density (Unit Weight)

Figure 12 illustrates the hardened density of concrete samples under saturated and surface-dry conditions at 28 days. The unit weight of hardened concrete containing recycled concrete aggregate (RCA) decreased with increasing replacement levels. The greatest reduction of 4.6% and the smallest reduction of 0.5% were observed in the RCAn50NMA and RCAn20NMA samples, respectively, relative to the control mixture. The results obtained were consistent with the literature (Ozbakkaloglu et al., 2017).

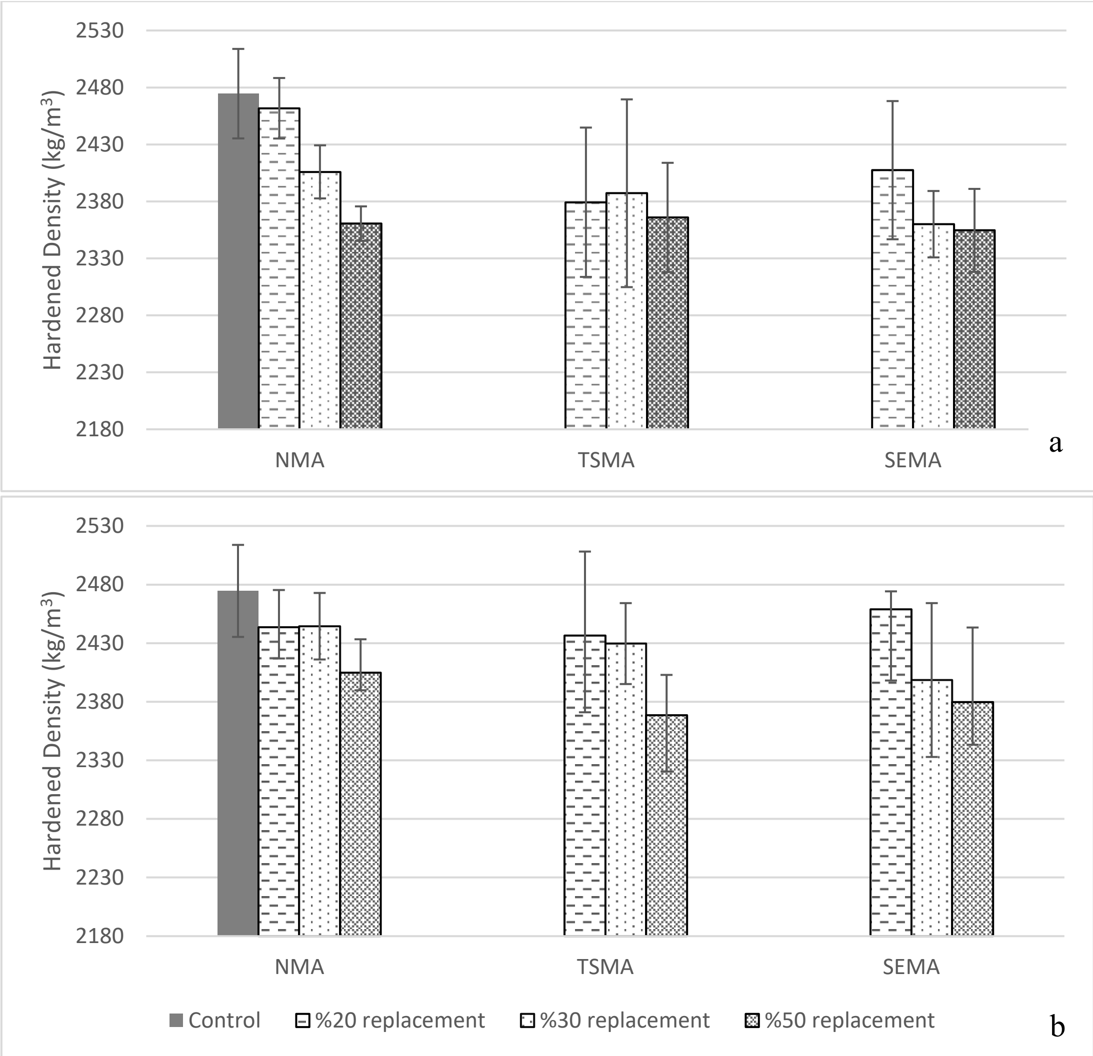



Figure 12: Hardened density of concrete samples for different replacement levels and mixing techniques (a) RCAn (b) RCAo

## 4.5 Compressive Strength

Among the key parameters affecting concrete strength development are the water-cement ratio, cement type, and aggregate characteristics, as demonstrated by the compressive strength results presented in Figure 13. The replacement of the RCA causes a decline in the early and long-term compressive strength of concrete. Almost all researchers reported the same findings (Akpinar & Al Attar, 2021; Etxeberria et al., 2007; Folino & Xargay, 2014; Muñoz Pérez et al., 2024).

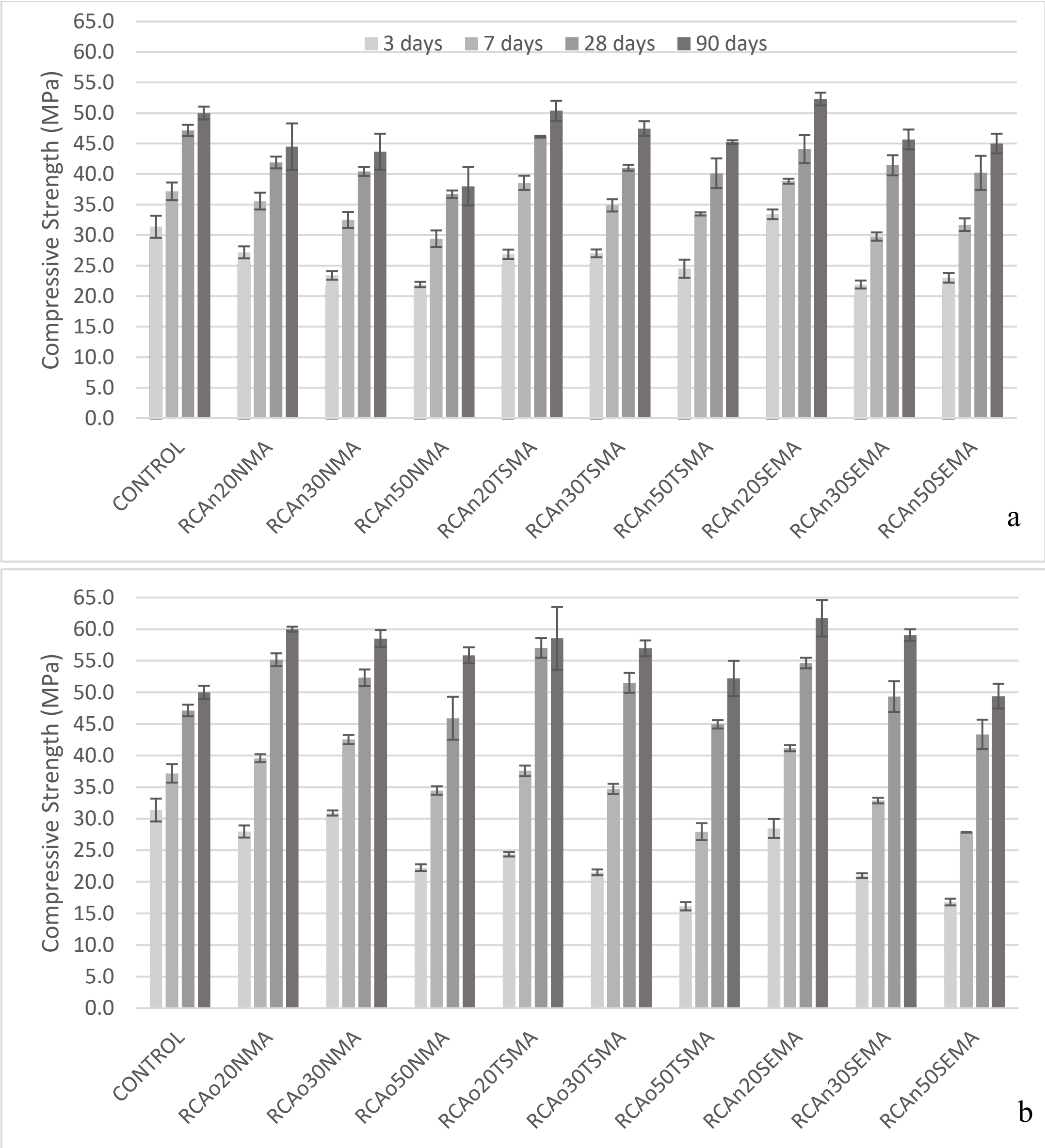



Figure 13: Effects of the RCA replacement and mixture techniques on the compressive strength of concrete (a) RCAn (b) RCAo

In concretes where RCA (RCAn) was replaced with normal aggregate at a rate of 20%, 3-day compressive strengths decreased by 13.4% and 14.3% for NMA and TSMA, respectively. The strength decrease at 30% replacement rate was 25.8, 14 and 30.2% for NMA, TSMA and SEMA, respectively. In concretes where half of the coarse aggregates in the mixture were RCAn, 3-day compressive strengths decreased by 30.2, 14 and 24.8% for NMA, TSMA and SEMA, respectively. The 3-day compressive strength of concrete samples prepared with RCAo tends to decrease due to the replacement level increases. The reason why the strength loss rate is higher than the samples prepared with RCAn is that the unhydrated cement particles that are likely to be present in the mortars adhered to RCAn contribute to the early strength of the concrete (Fonseca et al., 2011).

It was determined that the 7-day compressive strength results of RCAn20SEMA and RCAn20TSMA concretes were higher than the control samples. The lowest strength loss on the 7-day compressive strength at 30% and 50% change rates was 6.1% and 9.9%, respectively in the TSMA mixing method. For concretes containing RCAo, compressive strength was obtained 6% higher than the control sample for 20% replacement level. TSMA and SEMA mixing methods improve early strength development according to the 7-day compressive strength results of concrete because of the reduction of mixing water.

According to the 28-day concrete compressive test results, the most effective mixing technique for 20% and 30% replacement levels is TSMA, consistent with other research findings in the literature (Brand et al., 2015; Ozbakkaloglu et al., 2017; Tam et al., 2005). The 28-day compressive strength loss for RCAn20TSMA, RCAn30TSMA, and RCAn50TSMA is 2%, 13%, and 14.8%, respectively. The TSMA method reduces the w/c ratio and ensures that the RA are saturated before contacting the cement, thus improving the bond between the aggregates and the cement paste. The improvement of the ITZ between aggregate and cement paste exhibits a greater compressive strength of concrete.

For concretes in the RCAo series, the 28-day compressive strengths exceed those of the control samples across all mixing techniques for 20% and 30% replacement levels.

The reductions in 28-day compressive strength for RCAo50NMA, RCAo50TSMA, and RCAo50SEMA are 2.7%, 4.9%, and 8.5%, respectively. The difference between the 28-day compressive strengths of two different RA shows the effect of the aggregate type on the compressive strength of concrete. RCAo aggregates obtained from concrete produced using natural aggregates have a denser structure in terms of formation. Since it has a round surface, it improves its negative feature in bonding by breaking it during the mortar and recycling that is attached on it, thus contributing to the concrete compressive strength. Shahria Alam et al. (2013) mentioned that, if the mechanical property of the RCA is better than normal aggregates, it can increase the compressive strength of concrete.

For the RCAn series, 90-day compressive strengths are approximately 10% greater than 28-day strengths. For concretes in the RCAo series, this ratio is 13% . Moreover, the 90-day compressive strengths of all concretes in the RCAo series are higher than the reference concrete. When the behavior of concrete under pressure is considered, when the ultimate load is approached, a crack is formed between the aggregate and the cement paste and this crack progresses and causes the strain to increase. One of the obstacles on this crack line is the coarse aggregate grains. In cases where the strength of coarse aggregates is greater than the cement paste, coarse aggregates prevent the progress of the crack and contribute positively to the strength of the concrete. This explains why the 90-day strength increase of RCAo series concretes is higher than that of RCAn series concretes.

## 4.6 Splitting Tensile Strength

The splitting tensile strengths obtained as a result of different mixing techniques and RCA replacements in RCAn and RCAo series are shown in Figure 14. As can be understood, the increase in the amount of RCA in the mixture causes a decrease in the splitting tensile strength of concrete. These results are consistent with the results of other researchers (Sobuz et al., 2024; Yildirim et al., 2015; Turanlı, 1993). The amount of decrease in tensile strength varies between 3% and 25% as in previous studies (Brand et al., 2015; Bui et al., 2017).

The highest splitting tensile strength was obtained from RCAn20SEMA samples, which gave almost the same results as the control samples. In the mixtures prepared with the NMA method using RCAn obtained from concrete wastes from ready-mixed concrete plants, the decline in splitting tensile strength was 8, 22 and 30.5% for the 20, 30 and 50% replacement levels, respectively. On the other hand, these amounts increased by half (2.8%, 11% and 16%) in the samples prepared with the SEMA mixing technique.

In the mixtures made with RCAo, the splitting tensile strength obtained from SEMA and TSMA techniques for 20% replacement level was almost equal to the control sample, while it was 3% higher than the control sample for the NMA mixing technique.

Similar to the RCAn series, the splitting tensile strengths obtained from the RCAo30TSMA samples were higher than the other samples prepared using the same mixing technique. The lowest strength in this series was obtained from RCAo30SEMA samples.

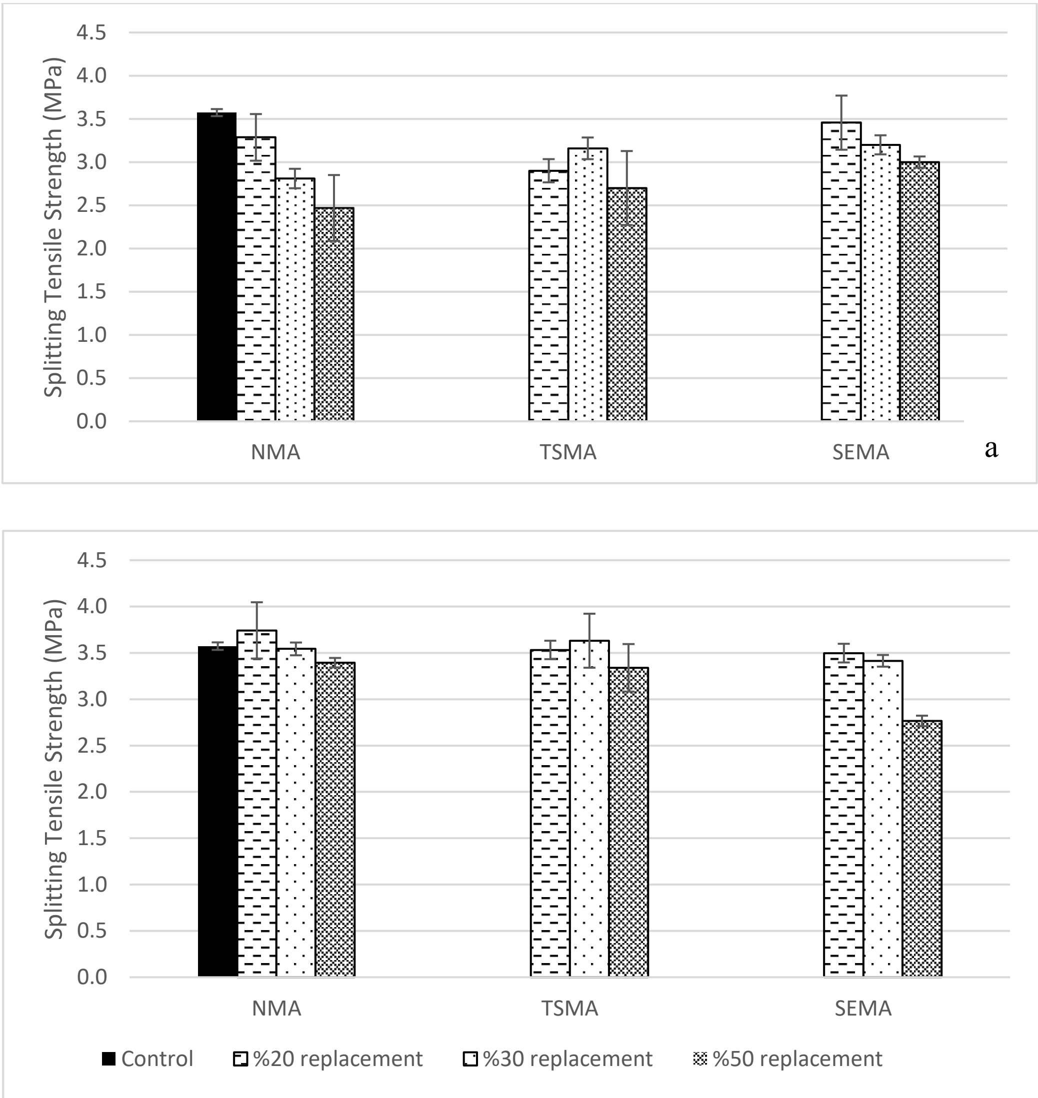



Figure 14: Splitting tensile strength test results (a) for series RCAn, (b) for series RCAo

In the splitting tensile strength test, the load is applied on a narrow strip on the sample and the tensile behavior of the plane is provided. The adhesion of the coarse aggregates and the cement paste along this plane plays a dominant role in the tensile strength of the concrete sample (A.M. Neville & J.J. Brooks, 2004; Zong et al., 2025). However, the presence of gaps in the fracture plane is as important as adhesion. The reduction in tensile strength observed in the RCAn series can be attributed to the highly porous nature of the aggregates used. On the other hand, SEMA and TSMA mixing techniques reduce the amount of water, which helps improve the ITZ zone (Chen et al., 2024) and increases the tensile strength in mixtures where the RA replacement ratio is 30% and 50%.

The fact that the tensile strengths in the RCAo series are equal to or higher than the control sample for 20% and 30% replacement rates can be explained by the aggregate used. The RA used in this series is obtained from concrete produced with natural aggregates and it is known that natural aggregates have a harder structure than limestone due to their formation process. For this reason, while the force applied in the splitting tensile test progresses through the crack on the sample, the natural aggregates prevent the progress of this crack due to their durable structure. At 50% replacement level, aggregate cement paste bond is the superior parameter rather than aggregate structure.

While TSMA and SEMA mixing techniques positively contribute to the tensile strength of RCAn aggregates, they do not significantly affect RCAo. At a 30% replacement level, the TSMA technique produced the best splitting tensile strength results for both RCAn and RCAo.

## 4.7 Correlation between Compressive and Splitting Tensile Strength

According to the results of the splitting tensile strength and compressive strength tests, a relationship was established between the two parameters' average values, as illustrated in Figure 15. The ratio of splitting tensile strength to compressive strength changes from 0.061 to 0.079 for all mixes. It has been reported that the ratio of splitting tensile strength to compressive strength ranges from 0.049 to 0.069 within the same compressive strength interval. As illustrated in the figure below, this ratio for concrete samples containing RCAn is approximately 7.3%, while in the RCAo series, it is about

6.7%. The splitting tensile strength tends to decrease as the compressive strength increases, which is attributed to the increasing brittleness of the concrete. This behavior can be further explained by the fact that the RCAo series exhibits higher compressive strength compared to the RCAn series.

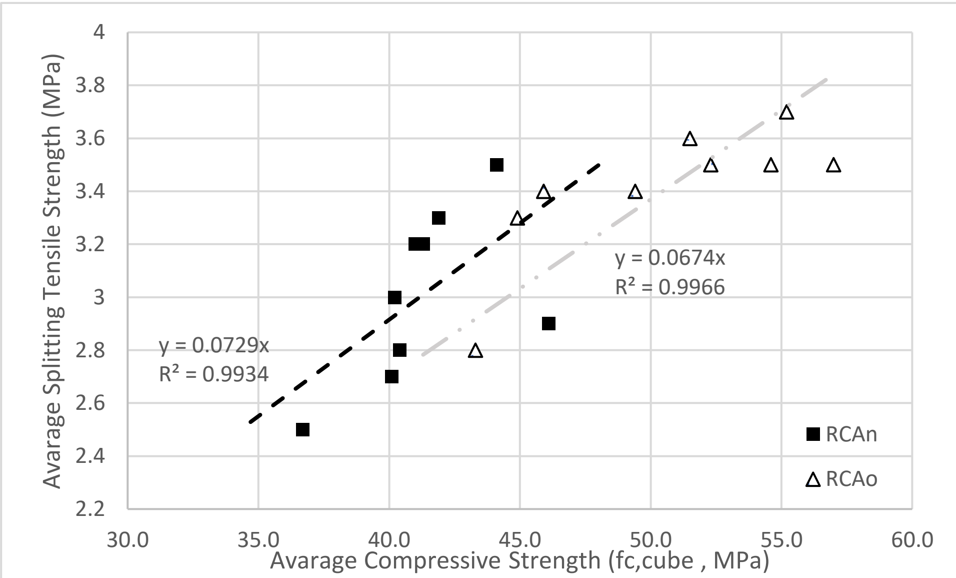



Figure 15: Correlation between compressive strength and splitting tensile strength for RAC

Some empirical formulas have been suggested to relate to splitting tensile strength. According to the relationship in Eurocode 2 (EN 1992-1-1:2004) and FIB Model Code (2010), the ratio of tensile splitting strength to compressive strength for structural concrete with normal compressive strength ($f_{ck, cylinder}$: 20- 50 MPa) varies between 0.096 and 0.076. It is understood that the splitting tensile strength to compressive strength ratios in this study are lower when compared to standard values. This indicates that the use of formulas related to certain parameters of the concrete should be revised when designing structures in which concrete produced with RA will be used.

## 4.8 Non-Destructive Tests

Many indirect methods (Ultrasonic pulse velocity, Schmidt hammer, penetration resistance, pull out, gamma radiography, etc.) have been established to estimate the strength of hardened concrete by non-destructive test methods. Some of these methods establish an empirical connection between the density of the concrete and its hardness and strength.

### 4.8.1 Ultrasonic Pulse Velocity (UPV)

Since the UPV test is the measurement of the speed of the high-energy pulse of vibrations passing through the concrete, it is used to discover voids, cracks or deteriorations in the concrete. It is also an alternative method for estimating the elasticity modulus of the concrete (A.M. Neville, 2011).

Table 8 and Figure 16 gives ultrasonic pulse velocity measurements made on 28-day concrete compressive strength test samples. According to Table 8, as the amount of RA rises, the ultrasonic pulse velocity decreases. In samples using the NMA mixing technique in the RCAn series, UPV decreased by 7.7, 2.7, and 8.7% for 20-30 and 50% replacement levels, respectively. For the TSMA and SEMA techniques, the UPV was reduced by 18.2% and 21.5% at 50% replacement level, respectively. On the other hand, as the amount of RCA increases in samples in the RCAo series, the UPV slows down slightly. The mixing technique has no significant effect on the UPV results for RCAo series.

Table 8: Ultrasonic pulse velocity results of RAC

| Mix ID | Sample No | UPV (m/s) | Mix ID | Sample No | UPV (m/s) |
|---|---|---|---|---|---|
| Control | 1 | 5 520 | | | |
| | 2 | 5 400 | | | |
| | 3 | 5 170 | | | |
| RCAn20NMA | 1 | 5 260 | RCAo20NMA | 1 | 4 350 |
| | 2 | 5 090 | | 2 | 4 290 |
| | 3 | 5 300 | | 3 | 4 340 |
| RCAn30NMA | 1 | 4 890 | RCAo30NMA | 1 | 4 400 |
| | 2 | 4 790 | | 2 | 4 310 |
| | 3 | 4 600 | | 3 | 4 360 |
| RCAn50NMA | 1 | 4 890 | RCAo50NMA | 1 | 4 370 |
| | 2 | 5 030 | | 2 | 4 350 |
| | 3 | 4 730 | | 3 | 4 290 |
| RCAn20TSMA | 1 | 5 140 | RCAo20TSMA | 1 | 4 340 |
| | 2 | 5 170 | | 2 | 4 400 |
| | 3 | 4 620 | | 3 | 4 370 |
| RCAn30TSMA | 1 | 4 450 | RCAo30TSMA | 1 | 4 340 |
| | 2 | 4 490 | | 2 | 4 210 |
| | 3 | 4 300 | | 3 | 4 290 |
| RCAn50TSMA | 1 | 4 270 | RCAo50TSMA | 1 | 4 320 |
| | 2 | 4 370 | | 2 | 4 120 |
| | 3 | 4 510 | | 3 | 4 310 |
| RCAn20SEMA | 1 | 4 320 | RCAo20SEMA | 1 | 4 300 |
| | 2 | 4 370 | | 2 | 4 250 |
| | 3 | 4 520 | | 3 | 4 310 |
| RCAn30SEMA | 1 | 4 350 | RCAo30SEMA | 1 | 4 320 |
| | 2 | 4 320 | | 2 | 4 260 |
| | 3 | 4 323 | | 3 | 4 510 |
| RCAn50SEMA | 1 | 4 190 | RCAo50SEMA | 1 | 4 140 |
| | 2 | 4 190 | | 2 | 4 000 |
| | 3 | 4 250 | | 3 | 4 200 |

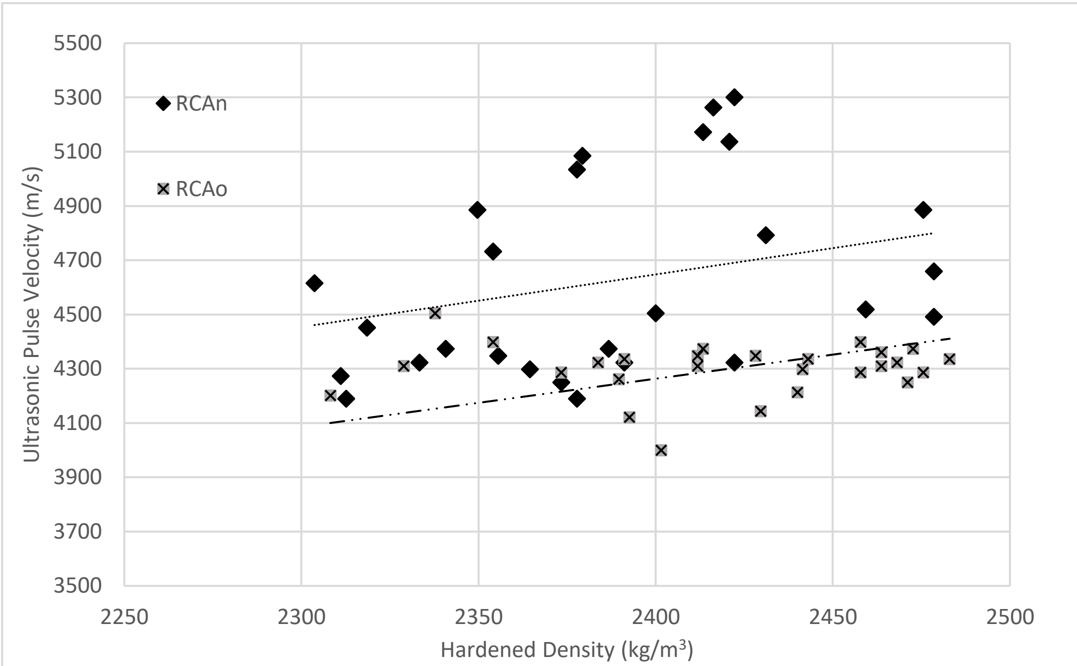


Figure 16: Ultrasonic pulse velocity test results of the 28 days cube samples

According to Figure 16, as the hardened density of concrete increases when the sound transmission speed increases. The rise in hardened density indicates a reduction in voids within the concrete's internal structure, resulting in faster sound transmission. In addition, it is seen that the sound transmission speed of the concrete samples in the RCAn series is faster than that in the RCAo series among the samples with the same specific gravity. The reason for this is that the RA used in the RCAn series concretes creates a filling effect in the voids due to the high quantity of fine particles it contains. In RAC, the UPV method should be compared with the hardened density of the concrete rather than the compressive strength.

Arioz et al. (2018), reported that for the same w/c ratios, slightly higher UPV values were measured for concretes that obtained normal aggregates compared to crushed limestone aggregates. The reason for the opposite results in this study is that the parent rock of the RCA and the normal aggregate are different. Therefore, when measuring the ultrasonic pulse, the normal aggregates in the RCAo block the sound wave and cause it to travel around, resulting in a lower UPV. In addition, ingredients (glass, brick, wood) in RCAo also reduce the sound transmission speed. The type of coarse aggregate utilized in concrete has a significant impact on UPV (Mohammed et al., 2021). As a result, it was determined that the UPV method was not a suitable method for indirect compressive strength measurements in RAC.

**4.8.2 Rebound Hammer (Surface Hardness) of Concrete**

The rebound hammer test was performed at 28 days to assess the quality (homogeneity) and surface hardness of the RAC samples, with the results summarized in Table 9. The findings indicate a linear correlation between concrete compressive strength and surface hardness: as surface hardness decreases, compressive strength correspondingly declines. Consequently, increasing the proportion of RCA in the mix leads to a reduction in the surface hardness of the concrete.

When the results in the RCAn series were examined, the results closest to the control sample were obtained from RCAn20SEMA and RCAn20TSMA samples. Since the surface hardness of the concrete is directly related to the aggregate used, the rebound values (R) of the concrete samples in the RCAo series were determined to be higher than the samples in the RCAn series. According to the rebound values, the most effective mixing technique with a 20% replacement level was SEMA for the RCAo series.

Table 9: Rebound hammer test results of RAC

| Mix ID | Sample No | Comp. Strength $f_{c-28day}$ (MPa) | R | Mix ID | Sample No | Comp. Strength $f_{c-28day}$ (MPa) | R |
|---|---|---|---|---|---|---|---|
| Control | 1 | 46.1 | 32 | | | | |
| | 2 | 47.9 | 35 | | | | |
| | 3 | 47.4 | 31 | | | | |
| RCAn20NMA | 1 | 40.8 | 31 | RCAo20NMA | 1 | 56.1 | 35 |
| | 2 | 42.6 | 31 | | 2 | 54.1 | 38 |
| | 3 | 42.3 | 28 | | 3 | 55.3 | 36 |
| RCAn30NMA | 1 | 39.6 | 26 | RCAo30NMA | 1 | 52.8 | 36 |
| | 2 | 40.9 | 29 | | 2 | 50.8 | 35 |
| | 3 | 40.8 | 30 | | 3 | 53.3 | 33 |
| RCAn50NMA | 1 | 36.1 | 25 | RCAo50NMA | 1 | 49.4 | 33 |
| | 2 | 37.3 | 28 | | 2 | 42.6 | 30 |
| | 3 | 36.8 | 28 | | 3 | 45.7 | 31 |
| RCAn20TSMA | 1 | 46.3 | 34 | RCAo20TSMA | 1 | 58.5 | 35 |
| | 2 | 46.1 | 35 | | 2 | 55.4 | 35 |
| | 3 | 46 | 36 | | 3 | 57.2 | 34 |
| RCAn30TSMA | 1 | 40.7 | 33 | RCAo30TSMA | 1 | 53.2 | 34 |
| | 2 | 41.6 | 29 | | 2 | 50.1 | 36 |
| | 3 | 40.8 | 32 | | 3 | 51.2 | 34 |
| RCAn50TSMA | 1 | 37.5 | 31 | RCAo50TSMA | 1 | 44.6 | 31 |
| | 2 | 42.3 | 30 | | 2 | 44.5 | 33 |
| | 3 | 40.6 | 30 | | 3 | 45.7 | 30 |
| RCAn20SEMA | 1 | 41.8 | 35 | RCAo20SEMA | 1 | 54.2 | 37 |
| | 2 | 46.4 | 32 | | 2 | 55.6 | 37 |
| | 3 | 44 | 34 | | 3 | 54.1 | 35 |
| RCAn30SEMA | 1 | 39.8 | 29 | RCAo30SEMA | 1 | 51.5 | 34 |
| | 2 | 41.4 | 30 | | 2 | 49.8 | 33 |
| | 3 | 43.1 | 28 | | 3 | 46.7 | 32 |
| RCAn50SEMA | 1 | 39.7 | 31 | RCAo50SEMA | 1 | 45.4 | 33 |
| | 2 | 37.7 | 30 | | 2 | 43.8 | 34 |
| | 3 | 43.2 | 30 | | 3 | 40.8 | 35 |

R: Rebound number

## 4.9 Modulus of Elasticity

The effect of RCA (RCAn and RCAo) on the elasticity of concrete is given in Figure 17. It is clearly understood from the results that as the RA substitution increases, the modulus of elasticity of the concrete gradually decreases, as consistent with other results in the literature (Folino & Xargay, 2014; Sobuz et al., 2024; Turanlı, 1993). Moreover, the results show that the quality of RCA is crucial for the modulus of elasticity. The modulus of elasticity results for the RCAo series samples are greater than RCAn series samples.

In RCAn series samples, the elasticity modulus decreased by an average of 8.4%, 15.4% and 23% for 20, 30% and 50% replacement levels, respectively, compared to the control sample. The diminish in modulus of elasticity of concrete produced using RCAn was determined to be 10% more than in other studies (Folino & Xargay, 2014; Sobuz et al., 2024). The main reason is the quality of parent concrete that is used for generating RCA. This causes the new ITZ bond formed between the new cement paste and the RA to weaken. For 30% and 20% replacement levels, the elastic modulus of the concretes obtained using the TSMA mixing method was higher than the samples obtained using the NMA and SEMA mixing methods. In the concrete samples where the RCA was replaced with normal coarse aggregate at a rate of 50%, the SEMA mixing technique gave the best results, followed by TSMA and NMA, respectively. In their study, Ozbakkaloglu et al. (2017) found that using the TSMA mixing technique resulted in concretes with a greater modulus of elasticity than conventional mixes.

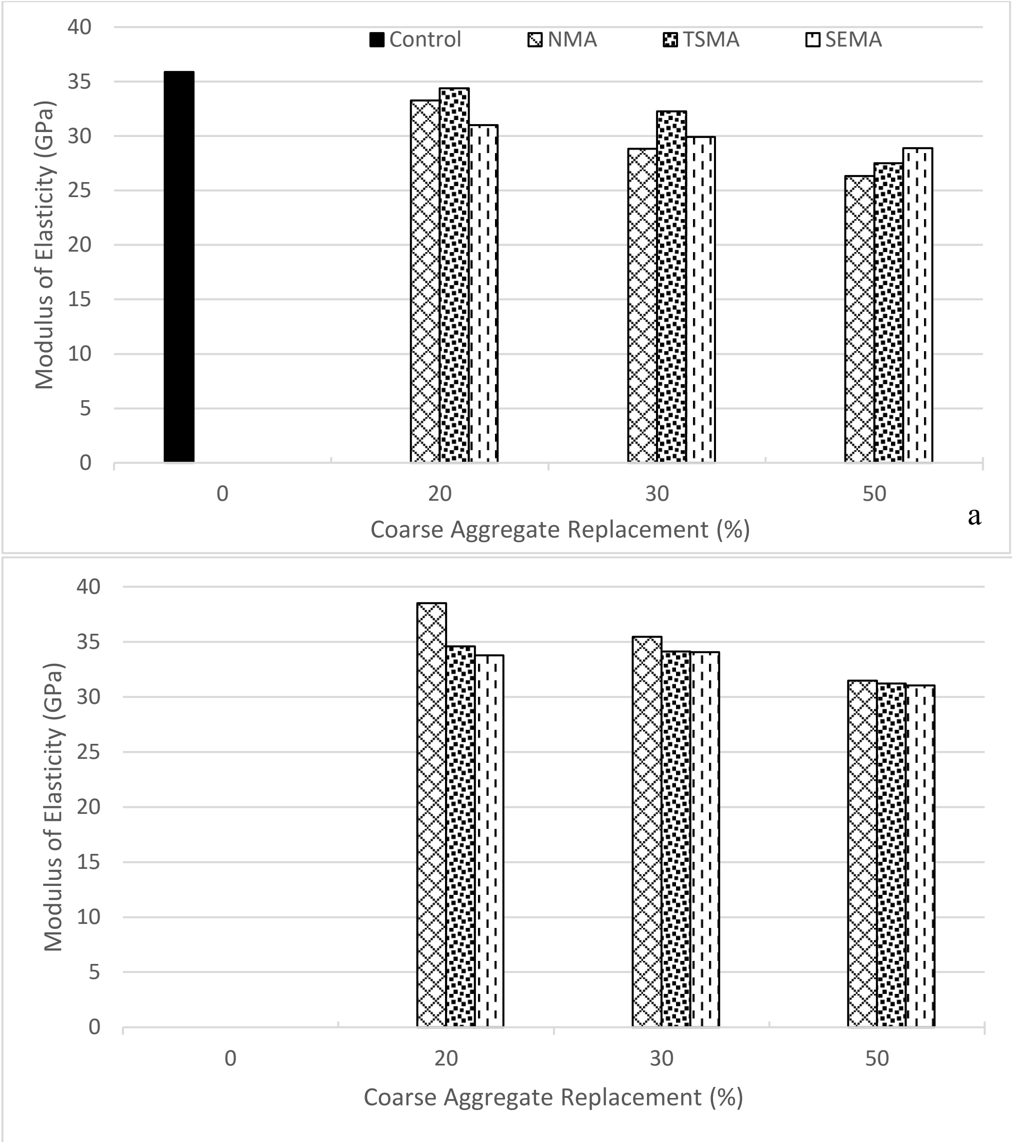



Figure 17: Modulus of elasticity of RAC mixes (a) RCAn (b) RCAo

Although the modulus of elasticity in RCAo20NMA samples exceeded that of the control, RCAo20TSMA and RCAo20SEMA samples showed a minor decline. At a 30% replacement level, the NMA mixing technique had no significant effect on the modulus of elasticity of concrete, whereas the TSMA and SEMA techniques resulted in a 5% reduction. In mixtures where RCAo-type aggregate was replaced by 50%, the modulus of elasticity decreased by 13%. In samples where aggregates recycled from natural aggregate concrete were used, TSMA and SEMA mixing techniques yielded lower elastic modulus results than the NMA technique for 20% and 30% replacement level, while the mixing technique at 50% replacement level had no effect on the results.

When the TSMA technique is used, the aggregates are saturated with water before the cement contact with water, so the cement paste adheres more effectively to the aggregate and causes the ITZ bond to be stronger. This explains why the TSMA method yields higher modulus of elasticity values compared to NMA. At a 50% replacement level, the aggregate type plays a more significant role than the interfacial transition zone (ITZ) bond, as recycled aggregate (RA) exhibits insufficient strength. At elevated replacement levels (50%), the quality of the aggregate becomes the dominant factor influencing the elastic modulus, rather than the bond between the cement paste and the aggregate. As shown in Figure 17(b), at this replacement level, the elastic modulus of the RCAo series samples exceeds that of the RCAn series.

The results indicate that the petrographic characteristics of the aggregate from which the RA is derived influence the modulus of elasticity of RAC. In samples prepared with RA from the same petrographic origin (limestone) as the normal aggregate used in concrete, changing the mixing method results in an improvement of the ITZ bond and thus an increase in the modulus of elasticity. In RCA containing natural aggregate, it was determined that the mixing technique had no effect, since the volumetric stability of the aggregate rather than the ITZ bond was dominant in determining the modulus of elasticity.

## 4.10 Permeability

Water penetration depths of concrete samples after 3 days are shown in Figure 18 and the water penetration for the RCAo20NMA sample is shown in Figure 19. In the series where RCA of RCAo and RCAn are used, the replacement level and water penetration depth change in direct proportion. In this study, where the water penetration depth of the control samples was determined as 37 mm, the water penetration depths of the samples other than RCAn20NMA were measured below the control sample at 20% and 30% replacement levels for the RCAn series. However, water penetration depths in RCAn50NMA, RCAn50SEMA and RCAn50TSMA samples were determined above the control sample. In the samples in the RCAo series, the water penetration depths of all samples except RCAo50SEMA were measured lower than the control sample.

Except for the RCAn series samples with 50% RA replacement, the lowest water penetration depths were observed in specimens prepared using the TSMA mixing technique, according to the results. In the water penetration test, which assesses concrete permeability, pressurised water is applied to the concrete surface. A strong bond between the aggregate and the cement paste effectively inhibits the ingress of water (A.M. Neville, 2011). Apart from the cement paste, the aggregates occupying the concrete base must also be impermeable. RCAn aggregates are more porous than RCAo aggregates, which results in higher water penetration depth measurements. The reason for the water penetration depths of the concrete samples in the RCAo series being lower than those in the RCAn series is the higher porosity of the RCA.

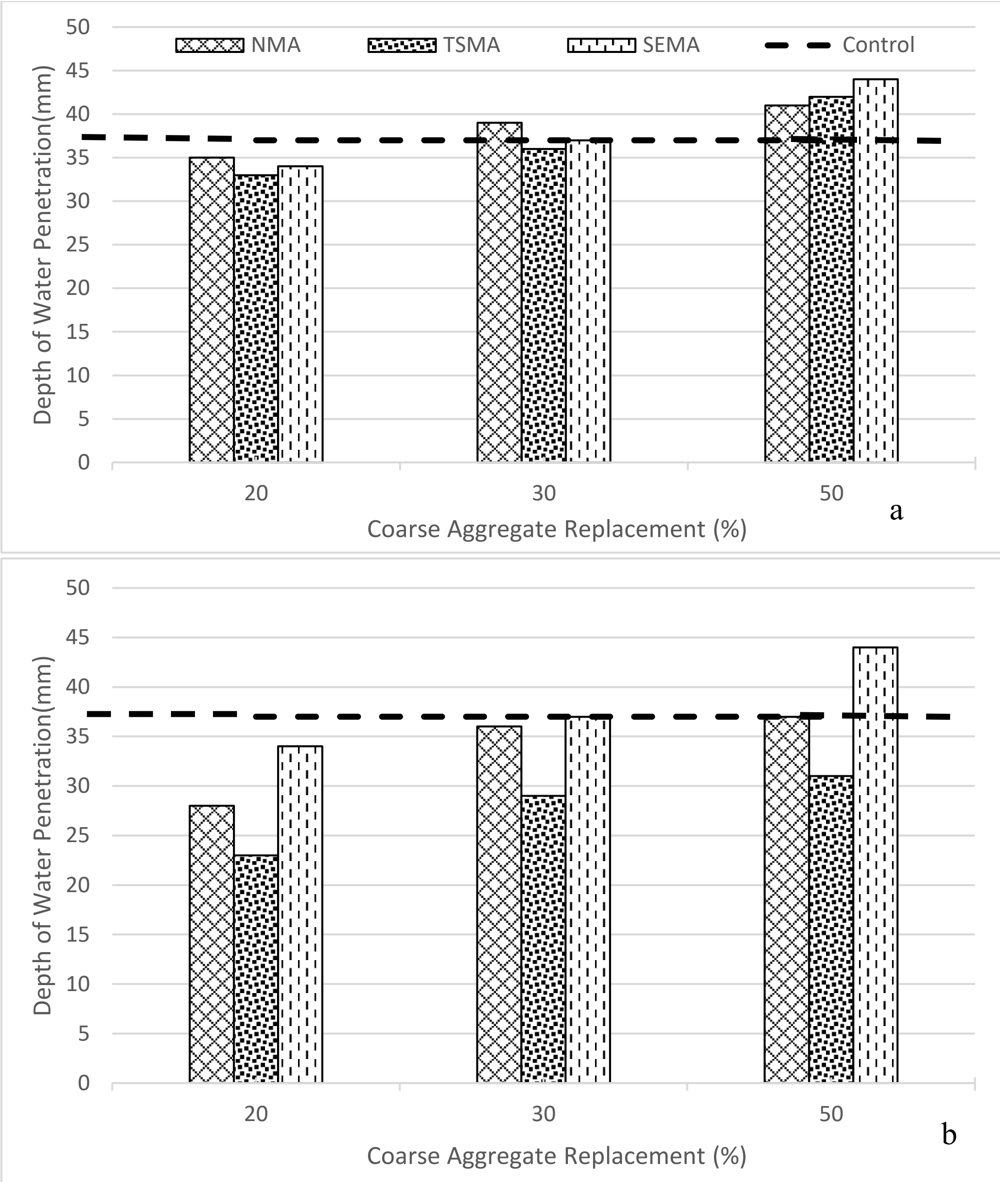


Figure 18: Water penetration depth of samples (a) RCAn series (b) RCAo series

It has been reported that water penetration depth increases in mixtures where normal aggregate is replaced by RA (Kubissa et al., 2015). Although this situation is observed in the RCAn series, the reason of why the water penetration depth is lower than the control samples at 20% replacement is the high fine content in the RCAn aggregate. This aggregate recycled from ready-mixed concrete plant waste contains more fine particles than normal limits and also contains unhydrated cement particles. This situation has improved the impermeability feature that the aggregate lost due to its highly porous structure.

Figure 18 (a) and Figure 18 (b) clearly show that TSMA method is the most effective mixing method in improving the impermeability of concrete due to the improvement of ITZ bond. In addition, it was determined that the porous structure of RA increases permeability.

Figure 19: Water penetration depth for the RCAo20NMA

## 4.11 Drying Shrinkage

Figure 20 shows the drying shrinkage of the RCAn series samples up to 140 days. The results were compared with the estimated drying shrinkage according to ACI 209.R-92. The results from the drying shrinkage test show that higher RA percentages lead to increased shrinkage.

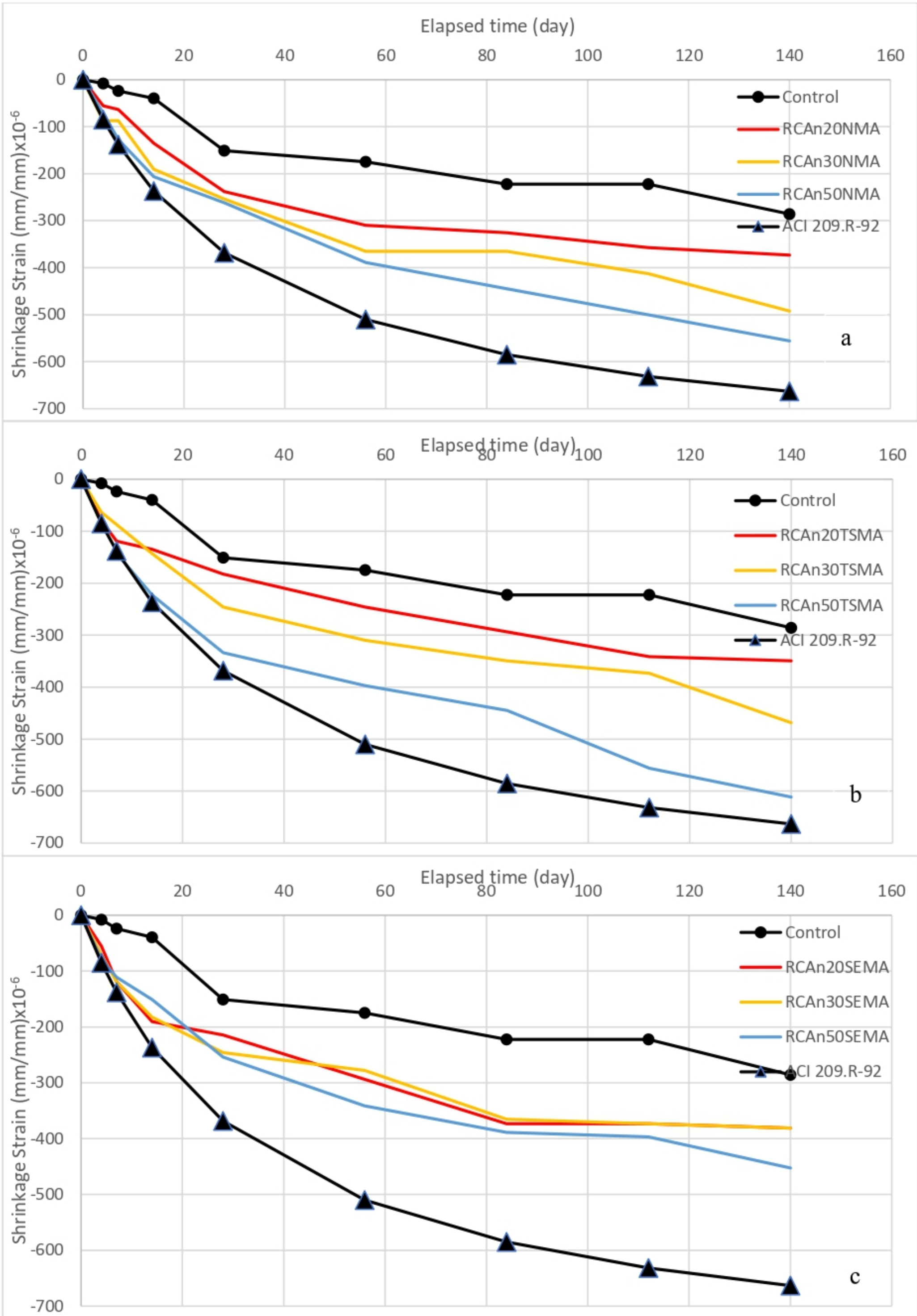


Figure 20: Drying shrinkage of the samples on the RCAn series (a) NMA (b) TSMA (c) SEMA

The 140-day drying shrinkage values for the RCAn series are between 0.000349 mm/mm and 0.000611 mm/mm. The results are consistent with other results in the literature (Brand et al., 2015). It is also understood that almost half of the drying shrinkage occurred in the first 28 days. In the samples prepared using the NMA mixing technique, 64%,52% and 47% of the total shrinkage was completed in the first 28 days for 20%, 30% and 50% replacement levels, respectively. The ratio of 4-week shrinkage to the shrinkage at the end of 140 days is 52, 52 and 55% for 20, 30 and 50% replacement in the samples prepared with the TSMA technique, while these values are 56, 56 and 64% for the SEMA mixing technique. On the other hand, when the 140-day drying shrinkage results were evaluated, it was determined that the lowest drying shrinkage increase at 20% replacement level was measured in samples prepared with the TSMA technique. The SEMA mixture technique effectively reduced drying shrinkage at 30 and 50% replacement levels.

Drying shrinkage occurs as a result of the loss of water in the capillaries due to environmental conditions, the decrease in water pressure in the capillaries and therefore the outer walls of the pores tend to shrink. Hence, shrinkage is strongly affected by the porosity of the concrete. There are two reasons for porosity in RAC. The first is the porous structure of RA, and the second is the voids caused by the high-water requirement of RA. When the amounts of water entering the mixture were examined, it was determined that the SEMA mixing technique reduced the total amount of water in RCAn series concretes, and therefore, the samples with less porous structures had a reduced amount of drying shrinkage.

The drying shrinkage values for the RCAo series samples during 84 days are shown in Figure 21. The results in the RCAo series show that as the amount of RA in the concrete increases, drying shrinkage increases like as RCAn series. Moreover, understood that the first 7-day drying shrinkage is very close or above the values predicted according to ACI 209.R-92. When the 84-day drying shrinkage was compared, the results of the samples prepared with NMA and TSMA mixing techniques in the RCAo series were found to be lower than those in the RCAn series. In the SEMA mixing technique, the results of the samples in the RCAo series were higher than those in the RCAn series. In the samples in the RCAo series, the TSMA method was the most effective mixing method on drying shrinkage for 20% and 30% replacement levels.

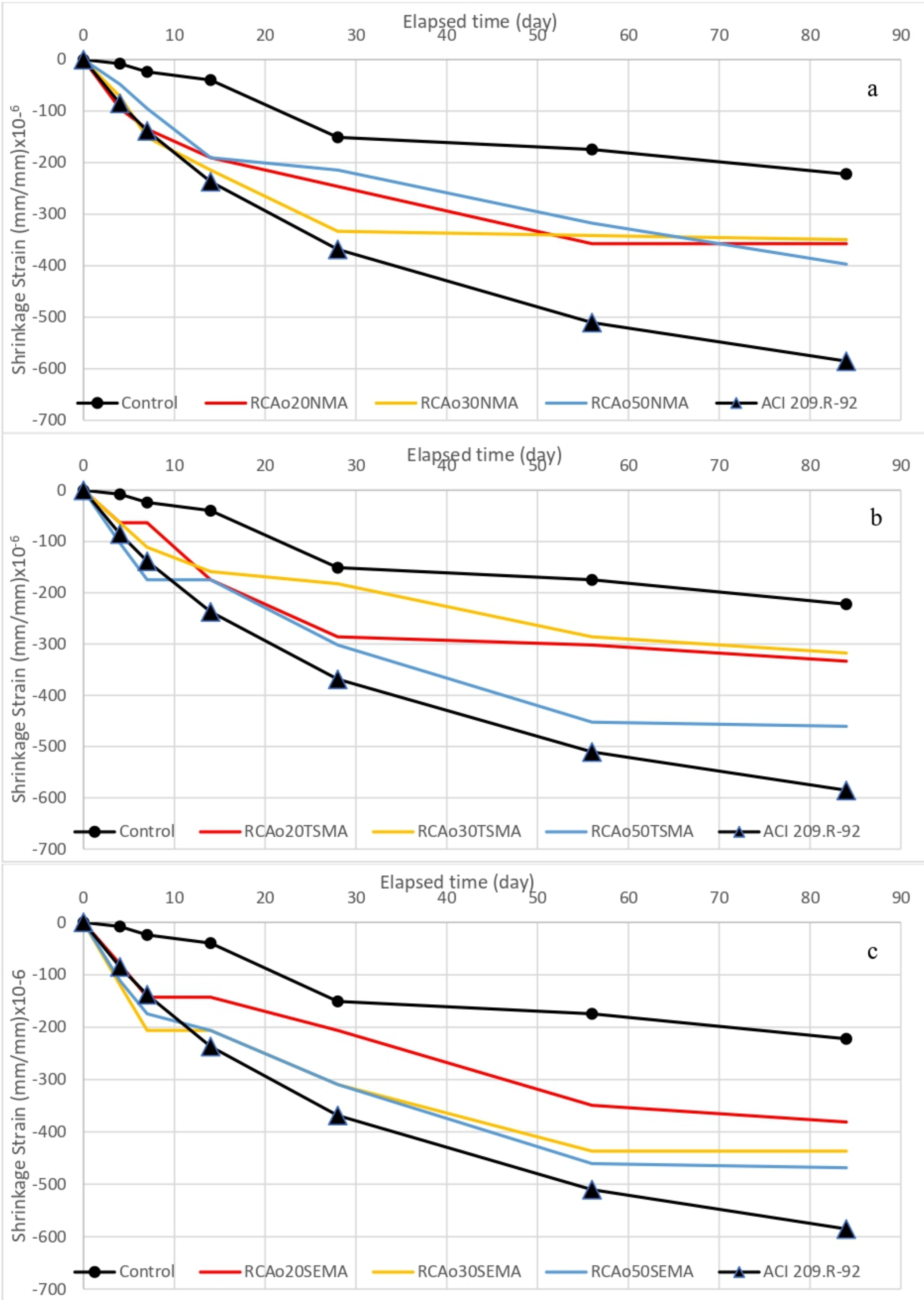



Figure 21: Drying shrinkage of the samples on the RCAo series (a)NMA (b)TSMA (c)SEMA

## 4.12 Potential Material Saving

Reducing the use of natural resources and preventing construction and demolition waste from being dumped into the environment are the main objectives of using RCA. According to the concrete mix design used in this study, the amounts of aggregate that will be saved according to the current concrete consumption in the North Cyprus when RCA is used instead of natural coarse aggregate at different rates (20-30-50%) are given in Table 10.

Table 10: Quantity of natural aggregates saved for concrete production

| Replacement level (%) | Volume of RCA in 1 $m^3$ concrete mix ($m^3$) | Total amount of natural aggregates saved for annual concrete* production ($m^3$) |
|---|---|---|
| 20 | 0.087 | 191 400 |
| 30 | 0.132 | 290 400 |
| 50 | 0.219 | 481 400 |

*: Assumed that annual concrete production in Northern Cyprus is 2.2 million $m^3$

It is estimated that 28.9% (1.65 million $m^3$) of the total amount of aggregate produced in Northern Cyprus is consumed for concrete production. As shown in Table 10, replacing the coarse aggregate with RA results in reductions of 11.6%, 17.6%, and 29.1% in aggregate consumption for concrete at replacement levels of 20%, 30%, and 50%, respectively.

While the area occupied for the required aggregate production in 2017 was 651,000 $m^2$ (İlseven and Kaşot, 2020), this area will increase to 3 368 000 $m^2$ in 2024, indicating that quarrying activities have spread over a wide area. The use of 20, 30 and 50% RCA in concrete will ensure that 0.113, 0.172 and 0.284 $km^2$ of natural area will not be used for aggregate production, respectively.

# Chapter 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

In this study, eighteen different mixtures with a constant amount of cement were prepared using two different RCA. One control mix had no RCA, and the other eighteen mixes had RCA with the following specifications: Two series with three different mixing techniques of normal mixing, two-stage mixing and sand envelope mixing, three different volume fractions (20%, 30%, and 50%) of RCA were selected for testing. The results obtained after testing fresh and hardened properties of RAC led to the following conclusions. These are presented below:

The use of RCA increases the amount of water required for the desired consistency of concrete. TSMA and SEMA mixing techniques help reduce mixing water and reduce the effective w/c ratio.

The unit weight of fresh concrete decreases as the RCA replacement level increases. The TSMA and SEMA techniques yield better unit weight results than the NMA technique due to less mixing water required.

There is an inverse proportion between the dry unit weight of hardened concrete and RCA replacement level, as in the fresh unit weight.

According to the 28-day concrete compression test results for the RCAn series, the most effective mixing technique for 20% and 30% replacement levels is TSMA. For samples in the RCAo series, the 28-day compressive strengths exceed those of the control samples across all mixing techniques for 20% and 30% replacement levels. Moreover, the 90-day compressive strengths of all samples in the RCAo series are higher than the reference concrete.

TSMA and SEMA mixing methods have no apparent effect on RCAo, however, they do improve the tensile strength of RCAn aggregates. For both RCAn and RCAo, the TSMA approach yielded the best splitting tensile strength results at a 30% replacement level.

The ratios between splitting tensile strength and compressive strength for the RCAn and RCAo series are 0.073 and 0.067, respectively.

The amount of RA increases, the ultrasonic pulse velocity decreases. The UPV values of the samples in the RCAn series are higher than those in the RCAo series.

The rebound values of the concrete samples in the RCAo series were determined to be higher than the samples in the RCAn series. At 20% replacement level, samples prepared with TSMA and SEMA techniques have higher rebound values.

As the RCA change rate increases, the elastic modulus of concrete decreases. For 30% and 20% replacement levels, the elastic modulus of the concrete obtained using the

TSMA mixing method was higher than the samples obtained using the NMA and SEMA mixing methods on the RCAn series.

At a 30% replacement level, the NMA mixing technique had no significant effect on the modulus of elasticity of concrete, whereas the TSMA and SEMA techniques resulted in a 5% reduction.

TSMA method is the most effective mixing method in improving the impermeability of concrete due to the improvement of ITZ bond.

RCA replacement increases the drying shrinkage of concrete. The SEMA mixture technique effectively reduced drying shrinkage at 30 and 50% replacement levels for RCAn series.

The petrographic origin of the RCA affects the mechanical properties of the RAC. While the TSMA technique provides a positive contribution to the mechanical properties in concrete samples prepared with RA having the same origin as normal aggregate, since it improves ITZ, the reason for the improvement in the results in the RCAo series is the durable structure of the RA.

The results indicate that RAC can be incorporated into structural concrete production at replacement levels of up to 30% without compromising mechanical or durability properties, provided that an appropriate mixing technique is employed.

Due to the saving of natural resources and the diminishing of environmental pollution caused by construction and demolition waste, the production of concrete with RA using different mixing techniques is a low-budget and environmentally friendly solution.

## 5.2 Recommendations for Future Studies

There are a number of tests that were not included in the overall scope of the study. Based on the experiences gained from the research, recommendations for guiding future research are presented below:

-The microstructure of the RAC can be studied for the same replacement levels.

-Effects of RCA and mixing techniques on the mechanical behavior and performance of concrete can be investigated at percentages higher than 50%.

-The use of RCA in non-structural concrete or concrete products (concrete block, permeable concrete etc.) and their mechanical and thermal properties can be investigated.

-The mechanical properties of RCA can be improved by mechanical treatment and the effects of the treated aggregates and mixture on the properties of concrete can be investigated.

## 5.3 Limitations of the Study

The most significant limitation of the study is the absence of plant production and national standards for recycled aggregates in the country. Time, being a limited resource, is a key factor that was anticipated to affect both the quality and schedule of this research. Some of the intended test methods were time sensitive and long-term drying shrinkage experiments were not performed due to limitations. This limitation significantly impacted the overall duration required to complete the study.

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# APPENDICES

# Appendix A: Splitting Tensile Test Results of RAC (RCAn series)

| Mix ID | Sample No | Splitting Tensile Strength $f_{ct}$ (28 days) (MPa) | Average Splitting Tensile Strength $f_{ct\text{-}mean}$ (28 days) (MPa) | Standard Deviation |
|---|---|---|---|---|
| CONTROL | 1 | 3.582 | 3.573 | 0.041 |
| | 2 | 3.528 | | |
| | 3 | 3.608 | | |
| RCAn20NMA | 1 | 3.413 | 3.286 | 0.270 |
| | 2 | 2.976 | | |
| | 3 | 3.469 | | |
| RCAn30NMA | 1 | 2.710 | 2.810 | 0.113 |
| | 2 | 2.788 | | |
| | 3 | 2.932 | | |
| RCAn50NMA | 1 | 2.670 | 2.469 | 0.381 |
| | 2 | 2.030 | | |
| | 3 | 2.708 | | |
| RCAn20TSMA | 1 | 2.862 | 2.898 | 0.134 |
| | 2 | 3.047 | | |
| | 3 | 2.786 | | |
| RCAn30TSMA | 1 | 3.298 | 3.159 | 0.125 |
| | 2 | 3.054 | | |
| | 3 | 3.126 | | |
| RCAn50TSMA | 1 | 2.236 | 2.691 | 0.428 |
| | 2 | 2.753 | | |
| | 3 | 3.085 | | |
| RCAn20SEMA | 1 | 3.225 | 3.456 | 0.313 |
| | 2 | 3.331 | | |
| | 3 | 3.813 | | |
| RCAn30SEMA | 1 | 3.108 | 3.214 | 0.110 |
| | 2 | 3.328 | | |
| | 3 | 3.208 | | |
| RCAn50SEMA | 1 | 3.057 | 3.007 | 0.065 |
| | 2 | 2.934 | | |
| | 3 | 3.032 | | |

# Appendix B: Splitting Tensile Test Results of RAC (RCAo series)

| Mix ID | Sample No | Splitting Tensile Strength $f_{ct}$ (28 days) (MPa) | Average Splitting Tensile Strength $f_{ct\text{-}mean}$ (28 days) (MPa) | Standard Deviation |
|---|---|---|---|---|
| RCAo20NMA | 1 | 3.529 | 3.742 | 0.304 |
| | 2 | 4.090 | | |
| | 3 | 3.608 | | |
| RCAo30NMA | 1 | 3.464 | 3.543 | 0.069 |
| | 2 | 3.572 | | |
| | 3 | 3.592 | | |
| RCAo50NMA | 1 | 3.403 | 3.394 | 0.051 |
| | 2 | 3.44 | | |
| | 3 | 3.339 | | |
| RCAo20TSMA | 1 | 3.631 | 3.532 | 0.099 |
| | 2 | 3.432 | | |
| | 3 | 3.532 | | |
| RCAo30TSMA | 1 | 3.298 | 3.631 | 0.291 |
| | 2 | 3.838 | | |
| | 3 | 3.758 | | |
| RCAo50TSMA | 1 | 3.112 | 3.339 | 0.256 |
| | 2 | 3.287 | | |
| | 3 | 3.617 | | |
| RCAo20SEMA | 1 | 3.392 | 3.497 | 0.101 |
| | 2 | 3.507 | | |
| | 3 | 3.593 | | |
| RCAo30SEMA | 1 | 3.351 | 3.414 | 0.063 |
| | 2 | 3.415 | | |
| | 3 | 3.477 | | |
| RCAo50SEMA | 1 | 2.701 | 2.766 | 0.057 |
| | 2 | 2.806 | | |
| | 3 | 2.79 | | |

# Appendix C: Test Results of Modulus of Elasticity Test

| Mix ID | Sample No | Stress 1 (%40 ultimate load) (MPa) | Stress 2 (0.0005-longitidinal strain) (MPa) | Longitudinal Strain Produced by Stress 1 | Modulus of Elasticity (GPa) | Average (GPa) |
|---|---|---|---|---|---|---|
| Control | 1 | 12.02040 | 3.27050 | 0.00029005 | 36.45 | 35.88 |
| | 2 | 11.98578 | 3.18263 | 0.00029935 | 35.30 | |
| RCAn20NMA | 1 | 14.02298 | 2.81025 | 0.00038720 | 33.25 | 33.01 |
| | 2 | 14.02298 | 2.92660 | 0.00038860 | 32.77 | |
| RCAn30NMA | 1 | 12.03667 | 2.85892 | 0.00038690 | 27.24 | 28.83 |
| | 2 | 12.01969 | 2.90023 | 0.00034975 | 30.42 | |
| RCAn50NMA | 1 | 11.01805 | 2.26077 | 0.00039230 | 25.58 | 26.34 |
| | 2 | 11.01239 | 2.91155 | 0.00034895 | 27.10 | |
| RCAn20TSMA | 1 | 13.04401 | 1.88671 | 0.00037290 | 34.55 | 34.38 |
| | 2 | 13.03270 | 2.01234 | 0.00037220 | 34.20 | |
| RCAn30TSMA | 1 | 15.03034 | 2.70218 | 0.00042365 | 32.99 | 32.28 |
| | 2 | 15.07098 | 2.96934 | 0.00043345 | 31.56 | |
| RCAn50TSMA | 1 | 13.03265 | 2.33603 | 0.00045005 | 26.74 | 27.50 |
| | 2 | 13.02699 | 2.98738 | 0.00040535 | 28.25 | |
| RCAn20SEMA | 1 | 13.50235 | 2.38570 | 0.00042005 | 30.04 | 31.27 |
| | 2 | 13.51346 | 2.76550 | 0.00038065 | 32.51 | |
| RCAn30SEMA | 1 | 16.03192 | 2.75027 | 0.00046890 | 31.71 | 29.91 |
| | 2 | 16.03758 | 2.93249 | 0.00051615 | 28.11 | |
| RCAn50SEMA | 1 | 14.02298 | 2.95965 | 0.00045285 | 27.46 | 28.28 |
| | 2 | 14.02298 | 2.68462 | 0.00043970 | 29.10 | |
| RCAo20NMA | 1 | 16.03192 | 2.89231 | 0.00038815 | 38.86 | 38.52 |
| | 2 | 16.02060 | 3.17243 | 0.00038645 | 38.19 | |
| RCAo30NMA | 1 | 18.02388 | 4.17294 | 0.00043255 | 36.21 | 35.45 |
| | 2 | 18.01822 | 3.31900 | 0.00047365 | 34.70 | |
| RCAo50NMA | 1 | 16.02060 | 2.51599 | 0.00048710 | 30.90 | 31.46 |
| | 2 | 16.02060 | 2.81874 | 0.00046215 | 32.03 | |
| RCAo20TSMA | 1 | 17.02224 | 3.15489 | 0.00046060 | 33.77 | 34.59 |
| | 2 | 17.01658 | 2.95682 | 0.00044710 | 35.41 | |
| RCAo30TSMA | 1 | 15.01896 | 3.33032 | 0.00038865 | 34.52 | 34.13 |
| | 2 | 15.01896 | 2.99530 | 0.00040630 | 33.75 | |
| RCAo50TSMA | 1 | 16.02626 | 2.91777 | 0.00047125 | 31.12 | 31.20 |
| | 2 | 16.02626 | 2.94550 | 0.00046815 | 31.28 | |
| RCAo20SEMA | 1 | 16.02626 | 3.03605 | 0.00042325 | 34.80 | 33.76 |
| | 2 | 16.02060 | 3.43840 | 0.00043450 | 32.72 | |
| RCAo30SEMA | 1 | 14.02863 | 3.43557 | 0.00035835 | 34.35 | 34.07 |
| | 2 | 14.02298 | 3.29353 | 0.00036765 | 33.78 | |
| RCAo50SEMA | 1 | 12.01969 | 2.98342 | 0.00032975 | 32.30 | 31.03 |
| | 2 | 12.03667 | 3.22562 | 0.00034610 | 29.76 | |

# Appendix D: Fresh Unit Weight of the Mixtures

| Mix ID | Fresh Unit Weight (kg/m$^3$) | Mix ID | Fresh Unit Weight (kg/m$^3$) |
|---|---|---|---|
| Control | 2 439 | | |
| RCAn20NMA | 2 404 | RCAo20NMA | 2 416 |
| RCAn30NMA | 2 352 | RCA30NMA | 2 401 |
| RCAn50NMA | 2 291 | RCAo50NMA | 2 377 |
| RCAn20TSMA | 2 381 | RCAo20TSMA | 2 423 |
| RCAn30TSMA | 2 376 | RCAo30TSMA | 2 395 |
| RCAn50TSMA | 2 300 | RCAo50TSMA | 2 360 |
| RCAn20SEMA | 2 398 | RCAo20SEMA | 2 430 |
| RCAn30SEMA | 2 376 | RCAo30SEMA | 2 384 |
| RCAn50SEMA | 2 333 | RCAo50SEMA | 2 349 |

## Appendix E: Hardened Unit Weight (density) of 28-day Cube Samples

| Mix ID | Sample No | Hardened density (kg/m³) | | | Average (kg/m³) | Std. Dev. (kg/m³) |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | | |
| Control | | 2 462 | 2 443 | 2 519 | 2 475 | 39 |
| RCAn20NMA | | 2 476 | 2 431 | 2 479 | 2 462 | 27 |
| RCAn30NMA | | 2 416 | 2 379 | 2 422 | 2 406 | 23 |
| RCAn50NMA | | 2 350 | 2 378 | 2 354 | 2 360 | 15 |
| RCAn20TSMA | | 2 421 | 2 413 | 2 304 | 2 379 | 66 |
| RCAn30TSMA | | 2 319 | 2 479 | 2 364 | 2 387 | 82 |
| RCAn50TSMA | | 2 311 | 2 387 | 2 400 | 2 366 | 48 |
| RCAn20SEMA | | 2 422 | 2 341 | 2 459 | 2 407 | 61 |
| RCAn30SEMA | | 2 356 | 2 333 | 2 391 | 2 360 | 29 |
| RCAn50SEMA | | 2 313 | 2 378 | 2 373 | 2 355 | 36 |
| RCAo20NMA | | 2 412 | 2 476 | 2 443 | 2 443 | 32 |
| RCAo30NMA | | 2 458 | 2 412 | 2 464 | 2 444 | 28 |
| RCAo50NMA | | 2 413 | 2 428 | 2 373 | 2 405 | 28 |
| RCAo20TSMA | | 2 483 | 2 354 | 2 473 | 2 437 | 72 |
| RCAo30TSMA | | 2 391 | 2 440 | 2 458 | 2 430 | 35 |
| RCAo50TSMA | | 2 384 | 2 393 | 2 329 | 2 368 | 35 |
| RCAo20SEMA | | 2 441 | 2 471 | 2 464 | 2 459 | 15 |
| RCAo30SEMA | | 2 468 | 2 390 | 2 338 | 2 399 | 66 |
| RCAo50SEMA | | 2 430 | 2 401 | 2 308 | 2 380 | 64 |

## Appendix F: Compressive Strength Test Results of RAC (RCAn-series)

| | 3 days | | | 7 days | | | 28 days | | | 90 days | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix ID** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** |
| Control | 32.7 | 31.4 | 1.8 | 37.2 | 37.2 | 1.4 | 46.1 | 47.1 | 0.9 | 50.8 | 50.0 | 1.0 |
| | 29.3 | | | 38.6 | | | 47.9 | | | 48.8 | | |
| | 32.1 | | | 35.7 | | | 47.4 | | | 50.4 | | |
| RCAn20NMA | 26.7 | 27.2 | 0.9 | 34 | 35.6 | 1.4 | 40.8 | 41.9 | 0.9 | 47.7 | 44.5 | 3.8 |
| | 26.5 | | | 36.6 | | | 42.6 | | | 45.5 | | |
| | 28.3 | | | 36.1 | | | 42.3 | | | 40.3 | | |
| RCAn30NMA | 22.5 | 23.3 | 0.7 | 31.2 | 32.5 | 1.3 | 39.6 | 40.4 | 0.7 | 45.8 | 43.7 | 2.9 |
| | 23.9 | | | 32.5 | | | 40.9 | | | 44.9 | | |
| | 23.4 | | | 33.8 | | | 40.8 | | | 40.3 | | |
| RCAn50NMA | 21.6 | 21.9 | 0.4 | 30.9 | 29.4 | 1.4 | 36.1 | 36.7 | 0.6 | 34.4 | 38.0 | 3.1 |
| | 22.4 | | | 28.2 | | | 37.3 | | | 39.4 | | |
| | 21.7 | | | 29.2 | | | 36.8 | | | 40.2 | | |
| RCAn20TSMA | 27.4 | 26.9 | 0.7 | 39.9 | 38.6 | 1.1 | 46.3 | 46.1 | 0.2 | 49 | 50.4 | 1.6 |
| | 26 | | | 38 | | | 46.1 | | | 49.9 | | |
| | 27.2 | | | 37.8 | | | 46 | | | 52.2 | | |
| RCAn30TSMA | 26.3 | 27.0 | 0.6 | 35.9 | 34.9 | 1.0 | 40.7 | 41.0 | 0.5 | 48.1 | 47.5 | 1.2 |
| | 27.6 | | | 34.8 | | | 41.6 | | | 48.2 | | |
| | 27 | | | 33.9 | | | 40.8 | | | 46.1 | | |
| RCAn50TSMA | 23.8 | 24.5 | 1.5 | 33.7 | 33.5 | 0.3 | 37.5 | 40.1 | 2.4 | 45.3 | 45.2 | 0.3 |
| | 26.2 | | | 33.2 | | | 42.3 | | | 44.9 | | |
| | 23.5 | | | 33.5 | | | 40.6 | | | 45.5 | | |
| RCAn20SEMA | 34 | 33.4 | 0.8 | 38.4 | 38.8 | 0.4 | 41.8 | 44.1 | 2.3 | 51.7 | 52.3 | 1.0 |
| | 32.5 | | | 38.9 | | | 46.4 | | | 51.7 | | |
| | 33.7 | | | 39.2 | | | 44 | | | 53.5 | | |

| | 3 days | | | 7 days | | | 28 days | | | 90 days | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix ID** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** |
| RCAn30SEMA | 22.5 | 21.9 | 0.6 | 29 | 29.8 | 0.7 | 39.8 | 41.4 | 1.6 | 47.5 | 45.7 | 1.6 |
| | 21.2 | | | 30 | | | 41.4 | | | 45.1 | | |
| | 22 | | | 30.3 | | | 43.1 | | | 44.4 | | |
| RCAn50 SEMA | 23 | 23.6 | 0.8 | 31.7 | 31.7 | 1.0 | 39.7 | 40.2 | 2.8 | 43.5 | 45.0 | 1.6 |
| | 23.3 | | | 32.8 | | | 37.7 | | | 44.7 | | |
| | 24.5 | | | 30.7 | | | 43.2 | | | 46.7 | | |

# Appendix G: Compressive Strength Test Results of RAC (RCAo-series)

| Mix ID | 3 days | | | 7 days | | | 28 days | | | 90 days | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $f_c$ (MPa) | Average (MPa) | Std. Dev. | $f_c$ (MPa) | Average (MPa) | Std. Dev. | $f_c$ (MPa) | Average (MPa) | Std. Dev. | $f_c$ (MPa) | Average (MPa) | Std. Dev. |
| RCAo20NMA | 29 | 28.0 | 1.0 | 40.3 | 39.6 | 0.6 | 56.1 | 55.2 | 1.0 | 60 | 60.1 | 0.4 |
| | 27.1 | | | 39.1 | | | 54.1 | | | 60.5 | | |
| | 27.8 | | | 39.3 | | | 55.3 | | | 59.7 | | |
| RCAo30NMA | 31.6 | 31.1 | 0.4 | 41.9 | 42.5 | 0.7 | 52.8 | 52.3 | 1.3 | 59.3 | 58.5 | 1.3 |
| | 30.9 | | | 43.3 | | | 50.8 | | | 59.3 | | |
| | 30.9 | | | 42.4 | | | 53.3 | | | 57 | | |
| RCAo50NMA | 22.8 | 22.2 | 0.5 | 35.2 | 34.5 | 0.7 | 49.4 | 45.9 | 3.4 | 56.1 | 55.9 | 1.3 |
| | 22.2 | | | 34.3 | | | 42.6 | | | 54.5 | | |
| | 21.7 | | | 33.9 | | | 45.7 | | | 57 | | |
| RCAo20TSMA | 24.7 | 24.4 | 0.3 | 37.9 | 37.6 | 0.8 | 58.5 | 57.0 | 1.5 | 64.3 | 58.6 | 5 |
| | 24 | | | 36.6 | | | 55.4 | | | 55.6 | | |
| | 24.4 | | | 38.2 | | | 57.2 | | | 55.8 | | |
| RCAo30TSMA | 21.9 | 21.5 | 0.4 | 34.5 | 34.7 | 0.8 | 53.2 | 51.5 | 1.6 | 55.8 | 57.0 | 1.2 |
| | 21.6 | | | 35.6 | | | 50.1 | | | 56.8 | | |
| | 21 | | | 34 | | | 51.2 | | | 58.3 | | |
| RCAo50TSMA | 16.8 | 16.1 | 0.6 | 28.5 | 27.9 | 1.3 | 44.6 | 44.9 | 0.7 | 55.4 | 52.2 | 2.8 |
| | 15.5 | | | 26.4 | | | 44.5 | | | 50.9 | | |
| | 16.1 | | | 28.9 | | | 45.7 | | | 50.3 | | |
| RCAo20SEMA | 26.8 | 28.5 | 1.5 | 40.6 | 41.2 | 0.5 | 54.2 | 54.6 | 0.8 | 58.6 | 61.7 | 2.9 |
| | 28.9 | | | 41.5 | | | 55.6 | | | 62.3 | | |
| | 29.7 | | | 41.4 | | | 54.1 | | | 64.3 | | |

| | **3 days** | | | **7 days** | | | **28 days** | | | **90 days** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix ID** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** | **$f_c$ (MPa)** | **Average (MPa)** | **Std. Dev.** |
| RCAo30SEMA | 20.8 | 21.0 | 0.4 | 33.3 | 32.9 | 0.4 | 51.5 | 49.3 | 2.4 | 60.1 | 59.1 | 0.9 |
| | 21.4 | | | 32.4 | | | 49.8 | | | 58.8 | | |
| | 20.7 | | | 32.9 | | | 46.7 | | | 58.3 | | |
| RCAo50SEMA | 17.4 | 16.8 | 0.5 | 27.8 | 27.8 | 0.1 | 45.4 | 43.3 | 2.3 | 49.1 | 49.4 | 2.0 |
| | 16.6 | | | 27.9 | | | 43.8 | | | 51.5 | | |
| | 16.4 | | | 27.8 | | | 40.8 | | | 47.6 | | |

## Appendix H: Drying Shrinkage Test Results of RAC (RCAn-series)

| | Average Drying Shrinkage Strain (mm/mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mix ID** | **4 days** | **7 days** | **14 days** | **28 days** | **56 days** | **84 days** | **112 days** | **140 days** |
| Control | -0.00000794 | -0.00002382 | -0.0000397 | -0.00015086 | -0.00017468 | -0.00022232 | -0.00022232 | -0.00028584 |
| RCAn20NMA | -0.00005558 | -0.00006352 | -0.00013498 | -0.0002382 | -0.00030966 | -0.00032554 | -0.0003573 | -0.00037318 |
| RCAn30NMA | -0.00008734 | -0.00008734 | -0.00019056 | -0.00025408 | -0.00036524 | -0.00036524 | -0.00041288 | -0.00049228 |
| RCAn50NMA | -0.00007146 | -0.00012704 | -0.00020644 | -0.00026202 | -0.00038906 | -0.00044464 | -0.00050022 | -0.0005558 |
| RCAn20TSMA | -0.0000794 | -0.0001191 | -0.00013498 | -0.00018262 | -0.00024614 | -0.00029378 | -0.00034142 | -0.00034936 |
| RCAn30TSMA | -0.00006352 | -0.00008734 | -0.00024614 | -0.00024614 | -0.00030966 | -0.00034936 | -0.00037318 | -0.00046846 |
| RCAn50TSMA | - | -0.00014292 | -0.00022232 | -0.00033348 | -0.000397 | -0.00044464 | -0.0005558 | -0.00061138 |
| RCAn20SEMA | -0.00005558 | -0.0001191 | -0.00019056 | -0.00021438 | -0.00029378 | -0.00037318 | -0.00037318 | -0.00038112 |
| RCAn30SEMA | -0.00007146 | -0.0001191 | -0.00018262 | -0.00024614 | -0.0002779 | -0.00036524 | -0.00037318 | -0.00038112 |
| RCAn50SEMA | -0.0000794 | -0.00011116 | -0.00015086 | -0.00025408 | -0.00034142 | -0.00038906 | -0.000397 | -0.00045258 |

## Appendix I: Drying Shrinkage Test Results of RAC (RCAn-series)

| | Average Drying Shrinkage Strain (mm/mm) | | | | | |
|---|---|---|---|---|---|---|
| **Mix ID** | **4 days** | **7 days** | **14 days** | **28 days** | **56 days** | **84 days** |
| Control | -0.00000794 | -0.00002382 | -0.0000397 | -0.00015086 | -0.00017468 | -0.00022232 |
| RCAo20NMA | -0.00009528 | -0.00013498 | -0.00019056 | -0.00024614 | -0.0003573 | -0.0003573 |
| RCAo30NMA | -0.00007146 | -0.00015086 | -0.00021438 | -0.00033348 | -0.00034142 | -0.00034936 |
| RCAo50NMA | -0.00004764 | -0.00009528 | -0.00019056 | -0.00021438 | -0.0003176 | -0.000397 |
| RCAo20TSMA | -0.00006352 | -0.00006352 | -0.00017468 | -0.00028584 | -0.00030172 | -0.00033348 |
| RCAo30TSMA | -0.00006352 | -0.00011116 | -0.0001588 | -0.00018262 | -0.00028584 | -0.0003176 |
| RCAo50TSMA | -0.00010322 | -0.00017468 | -0.00017468 | -0.00030172 | -0.00045258 | -0.00046052 |
| RCAo20SEMA | -0.0000794 | -0.00014292 | -0.00014292 | -0.00020644 | -0.00034936 | -0.00038112 |
| RCAo30SEMA | -0.0001191 | -0.00020644 | -0.00020644 | -0.00030966 | -0.0004367 | -0.0004367 |
| RCAo50SEMA | -0.00011116 | -0.00017468 | -0.00020644 | -0.00030966 | -0.00046052 | -0.00046846 |