ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES



PERFORMANCE ASSESSMENT OF ROLLER COMPACTED CONCRETE PAVEMENTS INCORPORATING RECYCLED MATERIALS DERIVED FROM CONSTRUCTION AND DEMOLITION WASTE

M.Sc. Thesis by

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PERFORMANCE ASSESSMENT OF ROLLER COMPACTED CONCRETE PAVEMENTS INCORPORATING RECYCLED MATERIALS DERIVED FROM CONSTRUCTION AND DEMOLITION WASTE

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By

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**PERFORMANCE ASSESSMENT OF ROLLER COMPACTED CONCRETE PAVEMENTS INCORPORATING RECYCLED MATERIALS DERIVED FROM CONSTRUCTION AND DEMOLITION WASTE**" completed by **Ola Abdulrazzaq Shafeeq AL JUMAILI** under supervision of **ASSIST. PROF. DR. EMİN ŞENGÜN (Supervisor)** and **ASSOC. PROF. DR. OĞUZHAN ŞAHİN (Co-Supervisor)** we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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PERFORMANCE ASSESSMENT OF ROLLER COMPACTED CONCRETE PAVEMENTS INCORPORATING RECYCLED MATERIALS DERIVED FROM CONSTRUCTION AND DEMOLITION WASTE

ABSTRACT

This study systematically investigates the technical viability of incorporating Recycled Concrete Aggregate (RCA) obtained from construction and demolition waste (CDW) into Roller-Compacted Concrete (RCC) to promote sustainable construction practices. The research was conducted in three sequential phases: material characterization, mix design optimization, and performance evaluation. Initially, RCA was assessed for physical properties and Alkali-Silica Reaction (ASR) susceptibility, confirming its non-reactive nature and suitability for RCC applications. During the optimization phase, Concrete Waste Powder (CWP) was utilized as a micro-filler to enhance particle packing and compaction efficiency. Results indicated that the higher porosity of RCA significantly influenced the compaction dynamics, leading to a maximum increase of 33% in Optimum Moisture Content (OMC) and a corresponding 13% reduction in Maximum Dry Density (MDD) compared to the reference mixture with the usage of %100 RCA.

The performance of RCC mixtures with varying RCA replacement levels (0%, 50%, and 100%) was evaluated focusing on mechanical and durability parameters. A significant finding of this research is that even at 100% RCA replacement, the mixtures achieved a 28-day compressive strength exceeding 40 MPa (using a cement dosage of 350 kg/m³), demonstrating remarkable structural potential. However, durability assessments revealed that high replacement levels lead to increased water ingress and "high permeability" classifications in electrical resistivity tests. Consequently, to ensure long-term serviceability and a robust safety margin, a 50% RCA replacement level is recommended as the optimal threshold for field applications.

Given the massive volume of CDW generated by urban renewal and post-earthquake reconstruction in Türkiye, these findings are of paramount importance for institutions

such as the General Directorate of Highways, municipalities, and special provincial administrations. By utilizing optimized replacement levels, RCAs can be integrated into road construction as high-value materials, effectively transforming them from a waste liability into high-performance, sustainable engineering assets for Türkiye's future infrastructure projects.

Keywords: Roller-Compacted Concrete (RCC), Recycled Concrete Aggregate (RCA), Mixture Optimization, Strength, Durability, Sustainable Infrastructure.

İNŞAAT VE YIKINTI ATIKLARINDAN ELDE EDİLEN GERİ DÖNÜŞTÜRÜLMÜŞ MALZEMELER İÇEREN SİLİNDİRLE SIKIŞTIRILMIŞ BETON KAPLAMALARIN PERFORMANS DEĞERLENDİRMESİ

ÖZ

Bu çalışma, sürdürülebilir inşaat uygulamalarını teşvik etmek amacıyla inşaat ve yıkıntı atıklarından elde edilen Geri Dönüştürülmüş Beton Agregasının (GDBA), Silindirle Sıkıştırılmış Beton (SSB) içerisindeki kullanılabilirliğinin sistematik olarak araştırması üzerinedir. Çalışma; malzeme karakterizasyonu, karışım tasarımı optimizasyonu ve performans değerlendirmesi olmak üzere üç aşamada yürütülmüştür. İlk aşamada, GDBA'nın fiziksel özellikleri ve Alkali-Silika Reaksiyonu hassasiyeti değerlendirilmiş; malzemenin reaktif olmayan yapısı ve SSB uygulamaları için uygunluğu doğrulanmıştır. Optimizasyon aşamasında, tane istiflenmesini ve sıkıştırma verimliliğini artırmak amacıyla Atık Beton Tozu mikro-dolgu malzemesi olarak kullanılmıştır. Deneysel sonuçlar, GDBA'nın yüksek gözenekliliğinin sıkıştırma dinamiklerini önemli ölçüde etkilediğini; referans karışıma kıyasla Optimum Su İçeriğinde %33'lük bir artışa ve Maksimum Kuru Birim Hacim Ağırlığında %13'lük bir azalmaya neden olduğunu göstermiştir.

Farklı GDBA ikame oranlarına (%0, %50 ve %100) sahip SSB karışımlarının performansı, mekanik ve durabilite parametreleri odaklı olarak incelenmiştir. Bu araştırmanın en dikkat çekici bulgularından biri, %100 GDBA ikamesinde bile (350 kg/m³ çimento dozajı ile) 28 günlük basınç dayanımının 40 MPa eşiğini aşarak yüksek bir yapısal potansiyel sergilemesidir. Ancak durabilite analizleri, yüksek ikame seviyelerinin elektriksel direnç testlerinde "yüksek geçirimlilik" sınıfına girmesine ve basınçlı su işleme derinliğinin artmasına neden olduğunu ortaya koymuştur. Bu bağlamda, uzun vadeli servis ömrünü garanti altına almak ve çevresel etkilere karşı yeterli güvenlik marjını korumak amacıyla, saha uygulamaları için %50 GDBA ikame seviyesi optimal eşik olarak önerilmektedir.

Türkiye’de kentsel dönüşüm ve deprem sonrası yeniden yapılanma süreçleri nedeniyle ortaya çıkan muazzam miktardaki inşaat ve yıkıntı atığı göz önüne alındığında, bu bulgular Karayolları Genel Müdürlüğü, belediyeler ve il özel idareleri gibi kurumlar için optimize edilmiş ikame oranlarıyla geri dönüşümlü agregaların yol inşaatlarında katma değeri yüksek bir şekilde değerlendirilmesi ve Türkiye’nin gelecekteki altyapı projelerinde bir atık yükü olmaktan çıkarılarak yüksek performanslı ve sürdürülebilir bir mühendislik ürününe dönüştürülebilmesi açısından önemli olacaktır.

Anahtar Kelimeler: Silindirle Sıkıştırılmış Beton (SSB), Geri Dönüştürülmüş Beton Agregası (GDBA), Karışım Optimizasyonu, Dayanım, Durabilite, Sürdürülebilir Altyapı.

CONTENTS

M.Sc. THESIS EXAMINATION RESULT FORM ..... **ii**
ETHICAL DECLARATION ..... **iii**
ACKNOWLEDGMENTS ..... **iv**
ABSTRACT ..... **v**
ÖZ ..... **vii**
CONTENTS ..... **ix**
ABBREVIATIONS ..... **xii**
LIST OF TABLES ..... **xiii**
LIST OF FIGURES ..... **xiv**

CHAPTER 1 ..... **1**
INTRODUCTION **1**
1.1 Background and Motivation 1
1.2 Objectives and Scope 2
1.3 Thesis Organization 3
CHAPTER 2 ..... **5**
LITERATURE REVIEW **5**
2.1 RCC Pavements: Fundamentals 5
2.2 RCA in Cementitious Materials 7
2.2.1 RCA in Concrete Pavement 8
2.2.2 RCA in RCC Pavement 13
2.3 Research Gaps and Thesis Contribution 15
2.3.1 Thesis Contributions 16
CHAPTER 3 ..... **17**
EXPERIMENTAL STUDY **17**
3.1 Materials 17
3.2 Phase I: RCA Characterization and ASR Assessment 19
3.2.1 RCA Characterization Tests 19
3.2.2 ASR Test Method and Acceptance Criteria 20

3.3 Phase II: RCC Mix Design Matrix and Optimum Water Content 25
3.3.1 RCC Mix Proportioning and Specimen Preparation 26
3.3.2 Determination of Optimum Water Content 31
3.3.3 Vebe Tests 33
3.4 Phase III: Performance Testing of RCA incorporated RCC mixes 35
3.4.1 Physical Tests 40
3.4.2 Mechanical Tests 42
3.4.3 Durability Tests 43
3.4.3.1 Electrical Resistivity Test 43
3.4.3.2 Water Penetration test 45
3.4.3.3 Sulfate Attack Resistance Test 46
3.4.3.4 Freeze–Thaw Resistance Test 46
CHAPTER 4 48
RESULTS AND DISCUSSIONS 48
4.1 Phase I Results: RCA Characterization and ASR 48
4.1.1 RCA Characterization 48
4.1.2 ASR Performance 50
4.2 Phase II Results: Mix Design and Optimum Water Content 53
4.2.1 Evaluation of OMC and MDD Relationships for RCC Mixtures 54
4.2.1.1 Effect of CWP Content (0% RCA) 55
4.2.1.2 Effect of RCA Content (0% CWP) 56
4.2.1.3 Combined Effect of RCA and CWP Content 58
4.2.2 Optimum Water Content Selection 59
4.3 Phase III Results: Mechanical and Durability Performance 60
4.3.1 Physical and Mechanical Performance 60
4.3.1.1 Density and Strength Results 60
4.3.1.2 UPV Results 62
4.3.2 Durability Performance 63
4.3.2.1 Electrical Resistivity Test Results 63
4.3.2.2 Water Penetration Test Results 65
4.3.2.3 Sulfate Attack Resistance Test Results 67

4.3.2.4 Freeze–Thaw Resistance Test Results....68
4.3.2.5 Micro-CT Test Results....70
CHAPTER 5....72
CONCLUSION AND RECOMMENDATIONS....72
REFERENCES....75
CURRICULUM VITAE....79

ABBREVIATIONS

ACI - American Concrete Institute

ASR - Alkali-Silica Reaction

ASTM - American Society for Testing and Materials

CBR - California Bearing Ratio

CSIDB - Ministry of Environment, Urbanization and Climate Change (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı)

CWP – Concrete Waste Powder

EN – European Norm (European Standard)

ITZ – Interfacial Transition Zone

KGM – General Directorate of Highways

MDD – Maximum Dry Density

OMC - Optimum Water Content

PCC - Portland cement Concrete

RCA - Recycled Concrete Aggregate

RCC - Roller Compacted Concrete

SEM -Scanning Electron Microscopy

SSD - Saturated Surface Dry

UPV - Ultrasonic Pulse Velocity

W/C - Water-to-Cement Ratio

LIST OF TABLES

Table 2.1 Effects of RCA on hardened concrete properties and mitigation approaches in concrete paving (taken from FHWA Tech Brief [13]) 12
Table 2.2 Recommended inputs for mechanistic-empirical rigid pavement design using RCA concrete (taken from FHWA Tech Brief [13]) 12
Table 3.1 Physical Properties of Natural Aggregate (NA). 18
Table 3.2 Aggregate gradation and mass distribution used in the ASR test 21
Table 3.3 Experimental test matrix and mix proportions used in the ASR test 21
Table 3.4 Mix proportions of RCC mixtures for the determination of optimum moisture content. 28
Table 3.5 Summary of physical, mechanical, and durability tests conducted on RCC mixtures with varying RCA replacement levels. 35
Table 3.6 Classification of concrete quality ratings based on UPV test BS EN 12504-4:2021 [33] 42
Table 3.7 Classification of concrete penetration ratings based on electrical resistivity test [34] 45
Table 4.1 Physical Properties of RCA. 49
Table 4.2 Physical Properties of NA. 49
Table 4.3 OMC and MDD values for each RCC mix. 54
Table 4.4 Vebe time results at selected optimum moisture content 59
Table 4.5 Compressive strength values of each RCC specimen 61
Table 4.6 UPV results of RCC specimens. 63
Table 4.7 Electrical Resistivity of RCC specimens. 64

LIST OF FIGURES

Figure 2.1 Schematic of ITZs in RCA concrete: (a) the new ITZ forms between attached old mortar and new mortar; (b) if old mortar is partially removed [17] 8
Figure 2.2 Composition of CDW [20] 9
Figure 2.3 Concrete shoulders using RCA on I-16 in Georgia [13] 11
Figure 3.1 Natural aggregate used in the experimental program 18
Figure 3.2 Preparation of recycled concrete aggregate (RCA): (a) initial crushing of concrete cubes using an electric drill; (b)crushing and grinding machine; (c) recycled concrete aggregate (RCA) used in the experimental program 19
Figure 3.3 Preparation of materials for ASR test 22
Figure 3.4 Preparation of ASR test specimens (a) Mold preparation (b) Casting of specimens (c) Covering specimens with plastic sheets for curing 23
Figure 3.5 Curing of ASR specimens in sodium sulfate solution 24
Figure 3.6 Oven curing of ASR specimens and measurement of expansion 24
Figure 3.7 All ASR test specimens 25
Figure 3.8 Targeted RCC aggregate gradation curve and the upper/lower limits for a maximum aggregate size of 22.4 mm [2] 26
Figure 3.9 Preparation of Proctor test for RCC mixes. 31
Figure 3.10 OPC determination by using Proctor Test for RCC mixes 33
Figure 3.11 Slump Test for RCC mixes 34
Figure 3.12 Photos from the Vebe Consistency Test for RCC mixes 34
Figure 3.13 Preparation and grading of natural aggregate for use in the RCC mixtures 36
Figure 3.14 Preparation and grading of RCAs for use in the RCC mixtures 37
Figure 3.15 RCC cubes preparation for the tests 39
Figure 3.16 Preparation RCC specimens for Micro-CT test 40
Figure 3.17 UPV test setup on RCC specimens 41
Figure 3.18 Compressive strength test setup for RCC specimens. 43
Figure 3.19 Electrical resistivity measurement setup for RCC specimens 44
Figure 3.20 Water penetration test of RCC specimens 46
Figure 3.21 Setup of the freeze–thaw test for RCC specimens 47
Figure 4.1 Effect of CWP content on ASR expansion over time 51
Figure 4.2 Effect of RCA content on ASR expansion over time 52
Figure 4.3 Effect of combined RCA and CWP contents on ASR expansion over time 53
Figure 4.4 Maximum density- water content relationship for RCC-CWP-containing mixes. 56
Figure 4.5 Maximum density- water content relationship for RCC-RCA mixes 57
Figure 4.6 Maximum density- water content relationship for RCC-RCA-CWP mixes 58
Figure 4.7 Effect of RCA content on 28-day compressive strength of RCC mixtures 62
Figure 4.8 Effect of RCA content on average electrical resistivity of RCC mixtures at 28 days 65

Figure 4.9 Representative photos on water penetration depth of some RCC specimens..... 66
Figure 4.10 Effect of RCA content on average water penetration depth of specimens 66
Figure 4.11 The mass change of the specimens subjected to sulphate attack..... 68
Figure 4.12 The mass change of the specimens subjected to freeze–thaw cycles. 69
Figure 4.13 Micro-CT cross-sectional images taken from the beginning, middle, and end regions of the specimens 71

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The reuse of construction and demolition waste (CDW) has become a critical component of sustainable infrastructure development. Among potential applications, road construction is one of the most suitable fields for evaluating CDW due to its large material demand and relatively lower sensitivity to material variability compared to structural applications. In this context, Roller Compacted Concrete (RCC) pavements offer significant potential for incorporating CDW-based materials, particularly RCAs.

RCC pavements are characterized by their dry consistency, low water and cement contents, high fine aggregate ratio, and placement using asphalt-type paving and compaction equipment. Owing to advantages such as rapid construction, early opening to traffic, low maintenance requirements, and long service life, RCC pavements have emerged as a sustainable alternative to conventional rigid pavements. Historically, RCC was primarily used in industrial yards, military bases, storage areas, ports, and logistics facilities where resistance to heavy and concentrated loads and minimal maintenance were prioritized over riding comfort. With advances in compaction equipment since the 1970s, RCC pavements have increasingly been adopted for road applications, particularly in North America, and more recently in Türkiye. In Türkiye, RCC road construction has expanded significantly since 2009 under the leadership of municipalities and local administrations, exceeding a total length of 5,000 km by 2023 [1]. In parallel, the publication of the “Roller Compacted Concrete Road General Technical Specification” by the Ministry of Environment, Urbanization and Climate Change in 2020 [2], along with technical guidelines issued by TÜRKÇİMENTO, has provided a regulatory framework for RCC pavement design and construction.

At the same time, Türkiye generates large quantities of CDW due to intensive urbanization, infrastructure renewal, and recent large-scale earthquakes. The February 6, 2023 earthquakes alone resulted in an estimated 200 million tons of construction debris, creating urgent challenges for waste management and resource efficiency [3]. Uncontrolled disposal or low-value use of these materials increases environmental impacts and natural resource consumption. Considering that the construction sector accounts for a significant share of global energy and natural material use and CO_2 emissions, recycling concrete waste as aggregate presents an important opportunity to reduce natural aggregate consumption.

Although international studies have demonstrated that RCAs can be successfully used in pavement applications when properly processed and proportioned, research on the use of RCA in RCC pavements under Turkish conditions remains limited. Given the high aggregate content and performance sensitivity of RCC mixtures, a systematic evaluation of RCA based on national RCC pavement specifications is required. Therefore, this study aims to investigate the applicability of RCAs obtained from CDW in RCC pavement production through a comprehensive assessment of their physical, mechanical, and durability-related properties.

1.2 Objectives and Scope

The primary objective of this thesis is to evaluate the feasibility of using RCA derived from CDW in RCC pavement applications under Turkish conditions.

The scope of the study includes the following tasks:

- RCA characterization: Determine key aggregate properties relevant to RCC behavior (e.g., gradation, specific gravity, water absorption, fines content, and deleterious materials) using standard test methods.
- ASR assessment: Evaluate the potential alkali–silica reaction (ASR) risk associated with the RCA and interpret results against applicable acceptance criteria.

- RCC mixture design: Develop an RCC mixture design matrix and determine the optimum moisture content (OMC) using a soil-based approach to establish consistent specimen production conditions.
- Specimen production: Produce RCC specimens incorporating RCA using the selected mixture proportions and compaction procedures at the determined OMC.
- Performance evaluation: Quantify the influence of RCA on RCC performance using laboratory tests including compressive strength (cube specimens), freeze–thaw resistance, water penetration/permeability-related behavior, sulfate resistance, and electrical resistivity/resistance as a durability indicator.
- Interpretation and implications: Discuss the findings in the context of RCC pavement practice and specification-oriented material acceptance.

This thesis is limited to laboratory-scale material and mixture evaluation. Testing was conducted on cube specimens, and flexural performance was not evaluated. Full-scale field construction, long-term monitoring, and life-cycle cost or environmental assessments are outside the scope of this study.

1.3 Thesis Organization

This thesis is organized into five chapters.

- Chapter 1 introduces the background, motivation, and objectives of the study, along with the scope of the research.
- Chapter 2 presents a review of the existing literature on RCC pavements and the use of recycled concrete aggregates in cementitious and pavement applications.
- Chapter 3 details the experimental program, including material characterization, mix design procedures, and performance testing of RCC mixtures incorporating RCAs.
- Chapter 4 presents and discusses the experimental results obtained from the different testing phases.

- Chapter 5 summarizes the main conclusions of the study and provides recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

The literature review is organized into two main sections. The first part summarizes RCC pavement fundamentals, including mixture characteristics, moisture–density concepts, and construction/compaction practices used to achieve field-representative density in laboratory studies. This discussion is supported by widely used technical guidance and agency reports on RCC pavement design and construction [4]. The second part reviews RCA use in cementitious materials with highlighting on RCC pavement mixtures, focusing on how RCA affects mixture compactability, density, strength development, and durability-related behavior. Recent studies consistently show that performance is strongly governed by RCA quality (adhered mortar), moisture management, and mixture packing/density [5]. Finally, the gaps identified in the existing literature are highlighted to demonstrate the need for further investigation in this field.

2.1 RCC Pavements: Fundamentals

RCC is defined as concrete that is compacted by roller compaction and, in its unhardened state, will support a roller while being compacted. RCC is widely recognized as a practical pavement alternative because it combines concrete-like structural capacity with asphalt-like construction methods. RCC is typically placed using asphalt paving equipment and compacted using rollers, enabling rapid construction and early opening to service in many applications. Compared with conventional Portland cement concrete (PCC), RCC mixtures are proportioned at lower paste contents and lower water contents and are designed to be stiff and “zero-slump,” such that the fresh mixture can support the compaction roller during placement [6]. Although hardened RCC can achieve strength and stiffness levels comparable to conventional concrete, its performance is strongly related to construction-related variables including particularly

aggregate packing, moisture condition at placement, compaction energy, and curing because consolidation relies on external compaction rather than internal vibration.

Historically, RCC used in industrial and military facilities, ports, intermodal yards, and storage areas where resistance to heavy and concentrated loads and low maintenance requirements were prioritized over ride quality. With advances in paving and compaction equipment since the 1970s, RCC has increasingly been applied to roadway projects, including as a base layer or as a surface layer where appropriate surface characteristics can be achieved [7].

A unique feature of RCC mixture design is on maximum compacted density. Dense-graded aggregate blends are commonly selected to improve packing and reduce voids, which improves stiffness and reduces permeability. The moisture–density relationship is fundamental to proportioning RCC: the optimum moisture content (OMC) is typically established using Proctor-type methods, and the selected mixture moisture is targeted to achieve maximum (or near-maximum) compacted density under a specified compaction effort. Because density is directly linked to strength and transport properties, many agencies define field acceptance targets as a percentage of the laboratory maximum density.

Consistency control for RCC is often performed using vibrating-table methods such as the Vebe approach. In laboratory and field practice, RCC consistency and density can be determined using ASTM C1170[8], and RCC specimens can be prepared using procedures such as ASTM C1176 [9] since internal vibration are impractical for such stiff mixtures. Optimum moisture and consistency are critical: overly wet mixtures may segregate during placement, while overly dry mixtures make it difficult for compaction and reduce density, leading to lower strength and increased permeability [10].

From a performance perspective, RCC pavements can provide long service life and low maintenance when mixture proportioning, compaction, and curing are properly controlled. However, limitations may arise for high-speed applications due to smoothness and surface texture considerations, and some projects may require surface

treatments or overlays to meet ride and friction requirements [11]. Durability in cold regions is closely tied to pore structure and moisture condition; while many RCC mixtures are produced without intentional air entrainment, research and practice show that air-entraining strategies may be adopted to improve freeze–thaw and salt-scaling resistance where needed [12].

2.2 RCA in Cementitious Materials

RCA is produced by removing, crushing, and processing hardened concrete to obtain granular material that can replace virgin aggregates in a wide range of bound and unbound applications. Concrete pavements are often considered a favorable RCA source because the original concrete typically satisfied agency quality requirements, which can improve the consistency of the recycled product compared with mixed construction debris [13].

From a material perspective, the key difference between RCA and natural aggregate is the presence of adhered mortar and associated microcracking, which increases porosity and water absorption and reduces particle density. In RCA-incorporated concrete, the interfacial structure is more complex than in conventional concrete because an RCA particle typically contains residual (old) mortar attached to the original natural aggregate. This creates an old Interfacial Transition Zone (ITZ) at the boundary between the original aggregate and the old mortar, which is already part of the RCA particle. When the RCA is incorporated into new concrete, a new mortar forms around the RCA surface, generating an additional interface referred to as the new ITZ. As shown in Figure 2.1, two common scenarios may occur: Case (a): RCA coated with old mortar. If the original aggregate is largely covered by attached old mortar, the new mortar contacts the old mortar surface, and the new ITZ forms between old mortar and new mortar. In this case, the original aggregate remains separated from the new mortar by the old mortar layer and the old ITZ. Case (b): partial exposure of the original aggregate. If crushing and processing remove part of the attached mortar, the original aggregate may be locally exposed. Then, the new mortar can bond directly to the original aggregate,

and the new ITZ forms at the original aggregate–new mortar interface in those regions, while remains of old mortar and the old ITZ may still exist elsewhere within the same particle. Therefore, the composite material may contain multiple ITZ regions simultaneously (old ITZ plus one or more new ITZs), which can introduce additional weak links and preferential transport pathways due to differences in porosity, microcracking, and bond quality. Some studies report that the new ITZ formed between old and new mortar can be located on the order of ~120 μm from the old mortar boundary [14-16].

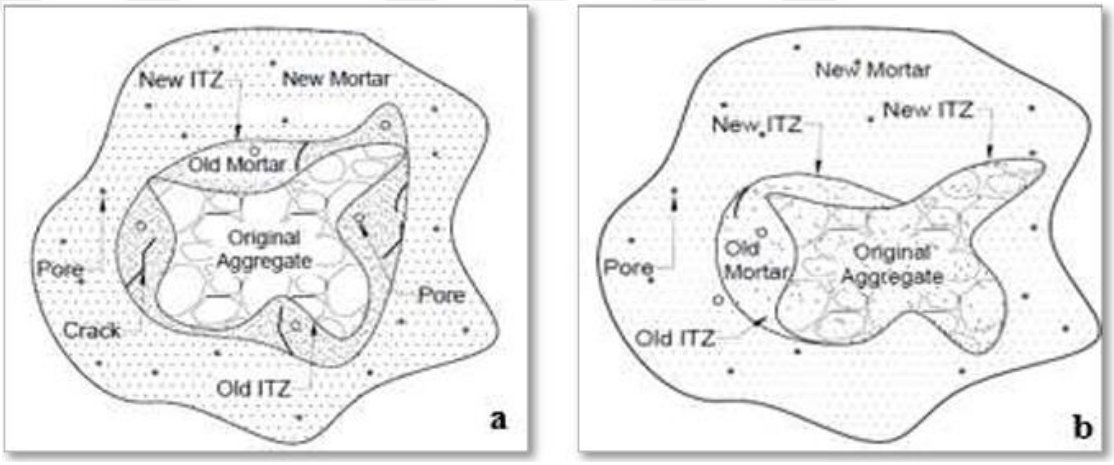


Figure 2.1 Schematic of ITZs in RCA concrete: (a) the new ITZ forms between attached old mortar and new mortar; (b) if old mortar is partially removed [17]

As a result, RCA concrete may exhibit changes in fresh behavior (moisture demand and workability) and hardened properties (stiffness, strength, and transport-related durability). These effects depend strongly on RCA quality, parent concrete characteristics, and processing/crushing intensity, which govern the amount and condition of adhered mortar [18].

2.2.1 RCA in Concrete Pavement

The construction sector generates a substantial amount of solid waste during both the construction phase and the end of service life of structures, making it one of the major contributors to environmental degradation and global carbon emissions [19]. It has been reported that approximately 50% of total construction waste originates from concrete

production and usage, which relies heavily on natural resources. Concrete waste constitutes a significant portion of CDW, accounting for nearly 70–75% of waste generated at global CDW sites. Consequently, the concrete industry is considered one of the least sustainable sectors due to extensive landfill disposal practices as shown in Figure 2.2 conducted by Fanijio et al., 2023 [20].

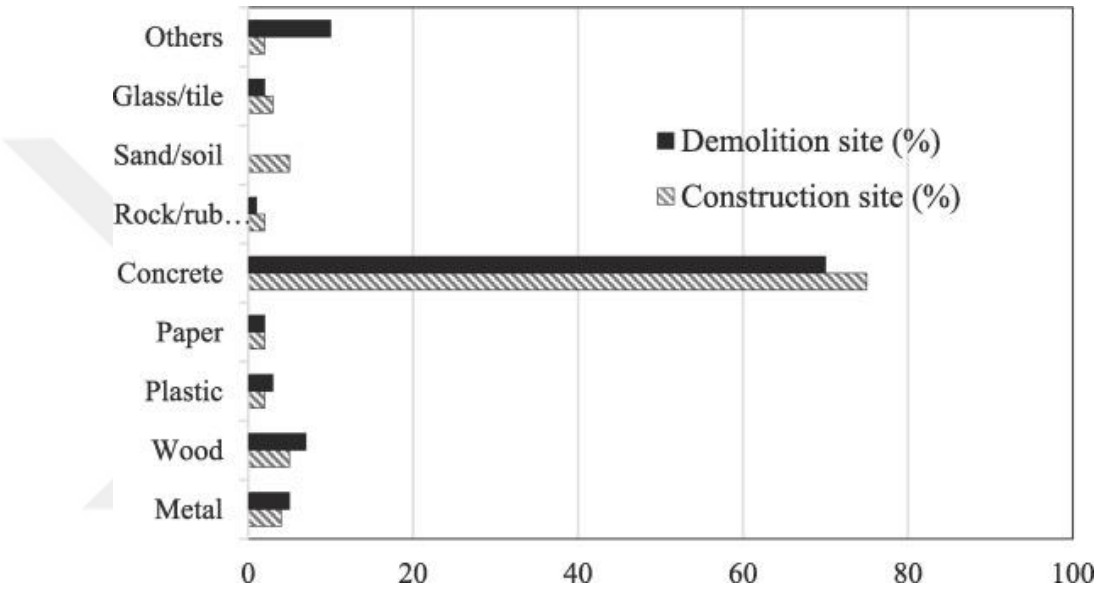


Figure 2.2 Composition of CDW [20]

In pavement engineering, the use of RCA is particularly attractive because roadway projects consume large material volumes and demolished concrete pavements can serve as relatively consistent, high-quality RCA sources. RCA has been used extensively in unbound layers; however, its application in new concrete pavement mixtures continues to expand as agencies seek to reduce virgin aggregate consumption and divert concrete waste from landfills [13].

RCA typically contains adhered mortar and microcracks, leading to higher water absorption, lower particle density, and increased variability compared with natural aggregates. These characteristics influence mixture water demand, workability, and hardened properties, and they often require additional attention during mixture proportioning and moisture management. In concrete pavement mixtures, performance is commonly discussed in terms of strength and stiffness (including compressive strength,

elastic modulus, and tensile/flexural strength), as well as durability-related indicators such as freeze–thaw resistance and permeability/transport behavior [21].

Several studies report that RCA replacement up to moderate levels can achieve comparable strength to natural aggregate concrete when mixture design is properly controlled, particularly with careful selection of water-to-binder ratio and adjustments for RCA absorption [22-23]. At higher replacement levels, reductions in strength and durability may become more pronounced; however, studies also indicate that optimized mixture design approaches and fiber reinforcement can partially mitigate these effects, particularly for flexural performance [24]. Field evidence further suggests that pavement sections containing approximately 30–40% RCA can exhibit mechanical performance comparable to control sections, while durability-related behavior may be more sensitive to RCA content and adhered mortar characteristics [25]. In this respect, freeze–thaw resistance is commonly evaluated as a key durability measure for pavement concrete exposed to seasonal cycling, and mixture proportioning (including lower w/b ratios and appropriate air-void system when required) remains critical [22].

Field projects also demonstrate the feasibility of high-RCA concrete paving applications when practical constructability issues are addressed. In the United States, more than 100 concrete pavement projects have incorporated RCA as a partial or full replacement of coarse aggregate, fine aggregate, or both, and many of these pavements have demonstrated satisfactory long-term field performance when RCA is properly processed and accounted for in mixture proportioning [13]. For example, In the GDOT I-16 project (Georgia- USA 2016), RCA obtained from the removed existing concrete pavement was used to construct new concrete shoulders. The project included approximately 90 km of truck-lane rehabilitation and inner/outer shoulder construction as shown in Figure 2.3. The existing ~10-in (≈254 mm) concrete pavement, originally built in the 1960s–1970s, was crushed at a nearby facility to produce RCA for the new shoulder concrete. Field trials reported that mixtures made with 100% RCA (as both fine and coarse aggregate) exhibited an excessively “sticky” behavior. To improve workability, RCA was blended with natural sand, and the final mixture used 80% RCA + 20% natural sand. Production

and placement operations were also adjusted to manage slump loss associated with hauling distance. This approach enabled high levels of concrete recycling while reducing the need for virgin aggregates and off-site waste disposal [13].



Georgene Geary, GGfGA, used with permission

Figure 2.3 Concrete shoulders using RCA on I-16 in Georgia [13]

The FHWA Tech Brief on the use of RCA in concrete paving mixtures provides two practical summary tables that are useful for both interpreting laboratory results and framing pavement design implications. As summarized in Table 2.1, property changes tend to be tolerable range when RCA is used only as coarse aggregate, but reductions in strength and stiffness and increases in shrinkage/transport-related vulnerability become more pronounced when RCA is used as both coarse and fine aggregate. Importantly, FHWA highlights that many of these effects are not “inevitable penalties,” but can often be managed through mixture proportioning (especially lowering w/cm and controlling moisture demand) and through design choices (e.g., panel sizing where CTE/shrinkage may elevate cracking risk).

Table 2.1 Effects of RCA on hardened concrete properties and mitigation approaches in concrete paving (taken from FHWA Tech Brief [13])

Property	RCA Used as Coarse Aggregate	RCA Used as Coarse and Fine Aggregate	Potential Adjustments
Compressive strength	0% to 24% less	15% to 40% less	Reduce w/cm ratio
Tensile strength	0% to 10% less	10% to 20% less	Reduce w/cm ratio
Strength variation	Slightly greater	Slightly greater	Increase average strength compared to specified strength
Modulus of elasticity	10% to 33% less	25% to 40% less	This may be considered a benefit with regard to cracking of slabs on grade
Specific gravity	0% to 10% lower	5% to 15% lower	None recommended
CTE (Coefficient of Thermal Expansion)	0% to 30% greater	0% to 30% greater	Reduce panel sizes
Drying shrinkage	20% to 50% greater	70% to 100% greater	Reduce panel sizes
Creep	30% to 60% greater	30% to 60% greater	Typically not an issue in pavement applications
Bond strength	Similar to conventional concrete, or slightly less		None recommended
Permeability	0% to 500% greater	0% to 500% greater	Reduce w/cm ratio

In parallel, Table 2.2 highlights a key implication for mechanistic–empirical rigid pavement design: RCA mixtures may require updated material inputs, particularly unit weight, CTE, and elastic modulus, rather than assuming values typical of virgin-aggregate concrete. From the perspective of this thesis, these FHWA summaries directly support the experimental focus on properties linked to transport and durability (e.g., permeability-related indicators, freeze–thaw and sulfate resistance) and motivate the need for careful mixture optimization and interpretation when RCA is introduced into RCC pavement mixtures.

Table 2.2 Recommended inputs for mechanistic-empirical rigid pavement design using RCA concrete (taken from FHWA Tech Brief [13])

Input Type	Input	RCA Used as Coarse Aggregate	RCA Used as Coarse and Fine Aggregate	Suggested Test Protocol and/or Additional Information
PCC	Poisson's ratio	Similar to mixture with virgin aggregates		ASTM C469
	Thickness	Select based on user preferences		
	Unit weight	0% to 10% lower	5% to 15% lower	AASHTO T 121
PCC Thermal	CTE (Coefficient of Thermal Expansion)	0% to 30% greater	0% to 30% greater	AASHTO T 336

	Thermal conductivity	0% to 40% lower (Bravo et al., 2017)		ASTM E1952
	Heat capacity	Somewhat higher (Damdelen et al., 2014)		ASTM D2766
PCC Mixture	Aggregate type	Select based on actual or expected aggregate source		
	Cementitious material content	Select based on actual or expected concrete mixture design		
	Cement type	Select based on actual or expected cement source		
	w/cm ratio	Select based on actual or expected concrete mixture design		
	Curing method	Select based on agency recommendations and practices		
	Reversible shrinkage (%)	Estimate using agency historical data or select M-EPDG defaults		
	Time to develop 50% of ultimate shrinkage	Estimate using agency historical data or select M-EPDG defaults		
Strength and Modulus	Elastic modulus	10% to 33% lower than mixture with virgin aggregates	25% to 40% less than mixture with virgin aggregates	ASTM C469
	Flexural strength	Mixture can be designed to meet specified strength with reduced w/cm ratio	—	AASHTO T 97
	Indirect tensile strength (Continuously Reinforced Concrete Pavement only)	Mixture can be designed to meet specified strength with reduced w/cm ratio	—	AASHTO T 198

2.2.2 RCA in RCC Pavement

In recent years, increasing attention has been directed toward enhancing sustainability in the highway sector, primarily by reducing the consumption of non-renewable natural resources. Pavement sustainability can be achieved through optimized mix design, innovative paving techniques, and the partial or full replacement of virgin aggregates with alternative recycled materials. In the context of RCC pavements, RCA has emerged as one of the most widely investigated alternatives due to its availability and environmental benefits. The use of RCA contributes to reducing natural aggregate extraction, lowering transportation-related emissions, and minimizing CDW disposal. However, the presence of adhered old mortar in RCA may adversely affect mechanical performance, highlighting the need for careful mix design and performance evaluation, particularly in RCC applications [26].

The concept of RCC design is that mechanical and durability performance are strongly governed by achieved density (and the associated air-void/transport structure), making

moisture optimization critical. Guidance documents and research emphasize that RCC mixture proportioning is often based on the maximum density method, in which the OMC corresponds to the MDD. When RCA is introduced, studies consistently report a tendency for higher OMC and lower MDD, primarily due to RCA's higher absorption and lower particle density resulting from adhered mortar [24-25]. From a practical point, this means RCA incorporated RCC mixtures can become more sensitive to moisture control and compaction effort, and performance comparisons must be interpreted in light of achieved density rather than mix proportions alone.

In the literature, the mechanical response of RCC containing RCA is generally governed by (i) replacement level, (ii) cement content (lean vs richer RCC), and (iii) compacted density. For example, Hosseinnezhad et al. [27] reported that increasing RCA content reduced mechanical properties overall, but up to about 25% replacement the detrimental effects were not significant, and the negative influence of RCA was more pronounced in leaner mixtures and could be reduced by increasing cement content. Fardin et al. [25] similarly evaluated RCC with coarse RCA replacement and observed measurable changes in mechanical/physical properties, reinforcing the importance of mixture proportioning and density control when RCA is incorporated. A widely cited RCC-focused study by López-Uceda et al. [29] evaluated RCC mixtures using coarse RCA replacement ratios of 0%, 50%, and 100% across multiple cement contents (110–350 kg/m³). Their results show that coarse RCA can be technically feasible in RCC mixtures—particularly for pavement base applications—when mixture design and compaction are properly managed, although performance varies with cement content and RCA level. Studies that combine RCA with other recycled constituents (e.g., Recycled Asphalt Pavement-RAP) similarly report reductions in strength and stiffness with increasing recycled content, while still meeting minimum performance needs for certain applications when supplementary cementitious materials (e.g., silica fume) and optimized proportioning are used [30]. As a result, RCA was used as a coarse RCA in international research studies, and their results recommended the use of RCA added to RCC due to its availability as a material for pavements [28-29].

The inclusion of RCA in RCC mixes significantly affects porosity. The porosity increases with higher RCA replacement levels, with coarse RCA causing approximately 28% and 46% increases at 50% and 100% replacement, respectively [29]. This increase is primarily due to the adhered old mortar on the RCA surface, which weakens the interfacial bonding with the new cement mortar, resulting in higher porosity in the interfacial transition zone. Ahmed Ashteyat et al. [30] reported that the high RCA content increased the water absorption increased which is the most significant indicator for durability of material, while the high RAP content decreased the water absorption.

Although existing studies support the feasibility of RCA use in RCC, the literature remains more mature on strength and density than on durability sets aligned with pavement exposure. Comparatively fewer RCA-related studies combine (i) moisture–density optimization, (ii) durability indicators tied to transport (e.g., penetration/permeability proxies), and (iii) environmental distress mechanisms relevant to field performance. In addition, microstructure-informed interpretation (e.g., using imaging approaches that relate void structure and heterogeneity to transport/durability behavior) is still not routinely integrated into RCA-incorporated RCC studies, motivating the use of micro-CT in this thesis as a supporting interpretive tool.

2.3 Research Gaps and Thesis Contribution

Despite the expanding literature on RCC pavements and the use of RCA, several issues still limit confident implementation of RCA in RCC mixtures, especially under specification-oriented practice and local material conditions. Although many studies show that RCC can incorporate RCA with acceptable strength for certain applications, results vary widely due to differences in RCA quality (adhered mortar, absorption, contaminants), mix proportioning approaches, and—most importantly—the achieved compacted density and moisture state. Therefore, performance trends reported only in terms of “RCA replacement level” are often not directly transferable without a clear moisture–density and quality-control basis.

In addition, RCC performance is highly dependent on the OMC/MDD framework, yet some RCA-incorporated RCC studies report strength and durability without demonstrating comparable density across mixtures; this can make interpretation difficult. The literature also remains more mature on strength than durability: fewer studies evaluate pavement-relevant durability mechanisms—such as freeze–thaw, sulfate exposure, and transport/permeability behavior—within a unified test program. Moreover, transport-related indicators (e.g., electrical resistivity/resistance as a proxy for pore connectivity) and microstructure-based evidence are not routinely integrated, even though RCA introduces additional ITZs and microcracking that can govern durability. Finally, despite the increasing use of RCC in Türkiye, systematic evaluation of locally sourced RCA with respect to Turkish RCC pavement requirements and durability performance remains limited.

2.3.1 Thesis Contributions

To address these gaps, this thesis presents a structured, laboratory-based evaluation of RCA-incorporated RCC mixtures with emphasis on moisture control, durability, and interpretation. The study establishes an RCC moisture–density framework by determining OMC/MDD using five moisture levels, then evaluates RCA effects using a durability-oriented test set including freeze–thaw, alkali-silica reactivity (ASR), sulfate exposure, and water penetration/permeability-related behavior. Electrical resistivity/resistance is used as a complementary indicator of pore connectivity and transport potential, while micro-CT imaging supports mechanistic interpretation through assessment of internal void structure and heterogeneity. The findings are synthesized in a specification-oriented manner to provide practical guidance for material selection and preliminary RCC mix design for sustainable pavement applications in Türkiye.

CHAPTER 3

EXPERIMENTAL STUDY

This chapter presents the experimental program adopted in this study to evaluate the use of recycled concrete aggregate (RCA) and concrete waste powder (CWP) in roller-compacted concrete–related investigations. In the first phase, preliminary laboratory tests, including alkali–silica reaction (ASR), Proctor compaction, and Vebe consistency tests, were conducted to assess the influence of different replacement levels of RCA and CWP on material behavior. Based on the outcomes of these preliminary investigations, the second phase focused on the production and testing of RCC mixtures incorporating RCA as a replacement for natural aggregate, while CWP was not included in the RCC mixes. This chapter describes the materials used, mix design parameters, specimen preparation procedures, and the test methods applied to evaluate the physical, mechanical, and durability performance of the RCC mixtures.

3.1 Materials

This section describes the materials used in the experimental program, including cement, natural aggregate, RCA, CWP, and water. All materials were selected based on their availability and relevance to RCC applications.

Ordinary Portland cement of type CEM I 42.5R was used as the primary binder in all concrete mixtures in this study. This type of cement complies with the European standard EN 197-1 and is characterized by high strength and good workability when mixed with aggregates and water. No independent tests were conducted on the cement, and it was used directly according to the proportions specified in the mix designs to ensure consistency of the experimental results.

Crushed stone was used as both fine and coarse natural aggregate in the concrete mixtures investigated in this study (Figure 3.1). The natural aggregate was sieved to

obtain the required particle size distributions in accordance with the relevant test standards and experimental requirements. For all standard laboratory tests, the aggregate particle sizes ranged from 0.063 to 16 mm, corresponding to material passing the 31.5 mm sieve. For the ASR test, a finer grading was adopted, with particle sizes ranging from 0.15 to 2.36 mm, corresponding to material passing the 4.75 mm sieve, as specified by the applicable test standards.



Figure 3.1 Natural aggregate used in the experimental program

The physical properties of the natural aggregate, including particle density (oven-dry, saturated surface-dry and apparent particle density) and water absorption, were determined experimentally in the laboratory. The measured values for each size fraction are summarized in Table 3.1.

Table 3.1 Physical Properties of Natural Aggregate (NA).

Sieve Size Range (mm)	Apparent Particle Density (g/cm³)	Oven-Dry Particle Density (g/cm³)	SSD Particle Density (g/cm³)	Water Absorption (%)
16–32	2.84	2.83	2.83	0.18
8–16	2.71	2.71	2.72	0.28
4–8	2.81	2.77	2.78	0.52
2–4	2.85	2.78	2.81	0.88
1–2	2.53	2.12	2.28	4.00

The properties of RCA materials are characterized subsections in detail. Phase I of the experimental program focused on the characterization of RCA and the evaluation of

their ASR potential prior to their incorporation into RCC mixtures. This phase aimed to ensure the suitability of the prepared RCA in terms of grading and chemical stability, particularly with respect to ASR-related expansion, which may adversely affect the durability and long-term performance of concrete.

3.2 Phase I: RCA Characterization and ASR Assessment

3.2.1 RCA Characterization Tests

RCA were used in concrete mixtures at different replacement ratios. The RCA was obtained by crushing previously used concrete cubes. The cubes were initially broken using an electric drill, followed by additional crushing and grinding using an electric crushing machine. The resulting material was then sieved to obtain the required aggregate gradations in accordance with the relevant ASTM test specifications. For all tests, particle sizes ranged from 0.063 to 16 mm, corresponding to material passing the 31.5 mm sieve. For the alkali–silica reaction (ASR) test, a particle size range of 0.15 to 2.36 mm was used, corresponding to material passing the 4.75 mm sieve. No additional treatment was applied to the RCA prior to its use in the concrete mixtures. Prepared RCA is shown Figure 3.2.



(a) (b) (c)

Figure 3.2 Preparation of recycled concrete aggregate (RCA): (a) initial crushing of concrete cubes using an electric drill; (b)crushing and grinding machine; (c) recycled concrete aggregate (RCA) used in the experimental program

CWP was utilized as a powder material to partially replace ordinary Portland cement in concrete mixtures prepared for laboratory tests on both natural and recycled aggregates. These tests included the ASR test, Proctor test, and Vebe test, aiming to evaluate the effect of CWP on the physical and mechanical properties of the mixtures. It should be noted that CWP was not used in the preparation of RCC mixes.

3.2.2 ASR Test Method and Acceptance Criteria

The RCA was characterized by using a series of tests to evaluate its suitability for concrete applications. The ASR test was conducted to assess the potential reactivity of the aggregate with cement alkalis, ensuring durability against expansion and cracking. Additionally, a Proctor test was performed to determine the optimal compaction and bulk density of the RCA. To examine the effect of RCA on concrete workability, the Vebe test was carried out on concrete mixtures incorporating the RCA. These tests collectively provided essential information on the physical and chemical performance of the RCA, contributing to its proper application in the concrete mix design.

ASR is a deleterious chemical reaction that occurs between reactive silica in certain aggregates and the alkaline pore solution of concrete, leading to the formation of an expansive gel that may cause internal stresses, cracking, and long-term deterioration of concrete. Therefore, assessing the ASR potential of aggregates, particularly RCA, is essential to ensure the durability and dimensional stability of concrete mixtures.

In this study, the ASR potential of RCA was evaluated using an accelerated mortar bar test conducted in accordance with ASTM C1260. The test assesses aggregate reactivity by measuring the length change of mortar bar specimens under accelerated alkaline conditions. According to ASTM C1260, an expansion value exceeding 0.10% at 14 days indicates potentially deleterious ASR behavior, and this criterion was adopted in the present study to evaluate the suitability of RCA for use in RCC mixtures.

The aggregate gradation and quantities used in the ASR test were selected in accordance with the relevant ASTM specifications and are presented in Table 3.2.

Table 3.2 Aggregate gradation and mass distribution used in the ASR test

Passing	Retaining	Mass %	Weight (g)
No.4 (4.75mm)	No.8 (2.36mm)	10	99
No.8 (2.36mm)	No.16 (1.18mm)	25	248
No.16 (1.18mm)	No.30 (0.6mm)	25	248
No.30 (0.6mm)	No.50 (0.3mm)	25	248
No.50 (0.3mm)	No.100 (0.150mm)	15	149
			990

The experimental test matrix and mix proportions of the nine mortar mixtures prepared in this study are summarized in Table 3.3.

Table 3.3 Experimental test matrix and mix proportions used in the ASR test

Mix No	Mix ID	NA -RCA Agg. (ratio)	OPC-CWP (ratio)	Normal Cement Amount	CWP Cement Amount	Natural Aggregate Amount	Recycled Aggregate Amount	Water amount
1	RCC-0%RCA-0%CWP	100%-0%	100%-0%	440	0	990	0	206.8
2	RCC-0%RCA-30%CWP	100%-0%	70%-30%	308	132	990	0	206.8
3	RCC-0%RCA-50%CWP	100%-0%	50%-50%	220	220	990	0	206.8
4	RCC-50%RCA-0%CWP	50%-50%	100%-0%	440	0	495	495	206.8
5	RCC-50%RCA-30%CWP	50%-50%	70%-30%	308	132	495	495	206.8
6	RCC-50%RCA-50%CWP	50%-50%	50%-50%	220	220	495	495	206.8
7	RCC-100%RCA-0%CWP	0-100%	100%-0%	440	0	0	990	206.8
8	RCC-100%RCA-30%CWP	0-100%	70%-30%	308	132	0	990	206.8
9	RCC-100%RCA-50%CWP	0-100%	50%-50%	220	220	0	990	206.8

In the Table 3.3, NA, RCA denote natural and recycled aggregate and OPC and CWP refer to ordinary Portland cement and recycled cement powder sourced from demolished

building waste materials, respectively. Based on the aggregate gradation and mix proportions, the ASR mortar bar specimens were prepared with a water-to-cement ratio of 0.47, following the procedures specified in ASTM C1260.

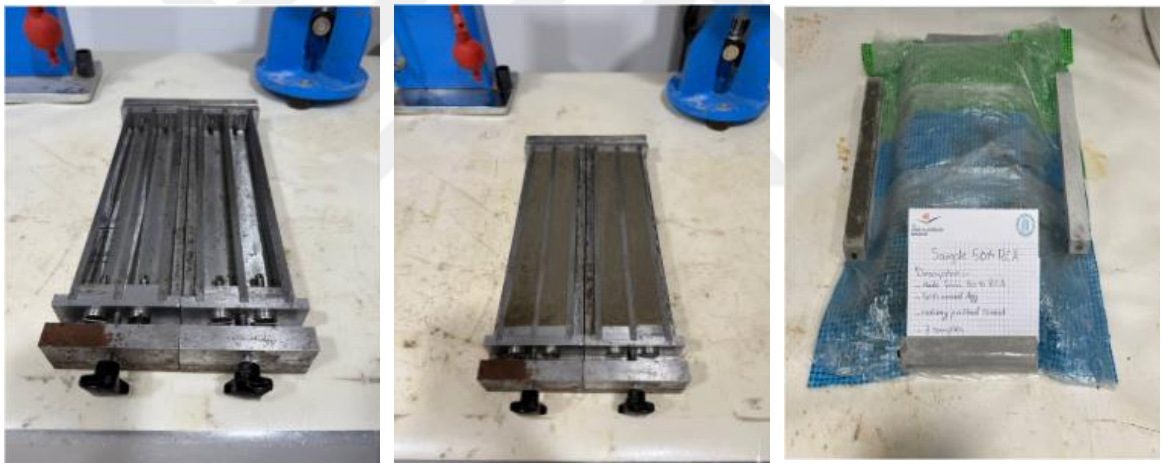
The natural and recycled concrete aggregates were sieved and separated according to the gradation presented in Table 3.2. OPC was used as main binder, while CWP was employed as replacement material. Drinking water was used for mixing, and all materials were prepared according to the proportions and quantities specified in Table 3.3.

According to ASTM C305, the mixing process should be carried out in three stages: slow, medium, and fast revolutions. The laboratory mixer used in this study had two available speeds: slow at) 62 rev/min (and medium at) 165 rev/min. For each mortar mix, all dry materials including NA, RCA, OPC, and CWP were first combined in a dry state. The dry mix was initially stirred at slow speed for 30 seconds to ensure uniform consistency among the particles. Water was then added according to the required water-to-cement ratio for each mix, after which the mixer speed was increased to medium. The mixer was allowed to stand for 60 seconds to ensure complete homogenization of all mortar collected at the bottom. Finally, the mixer housing was closed and mixing continued at medium speed for an additional 60 seconds. These speeds were considered acceptable based on the standard. Figure 3.3 shows preparation of materials for ASR test.



Figure 3.3 Preparation of materials for ASR test

For each mortar mix, at least three molds were cast. Each mold was equipped with two identical pins to facilitate expansion measurements. Prior to casting, the molds were thoroughly cleaned using dry wipes to remove any dust. The inner surfaces of the molds, including the areas where the pins were placed, were coated with oil to prevent corrosion and to facilitate the easy removal of the mortar bars without breakage. The mortar was poured into the molds in two layers within two minutes after mixing. Each layer was compacted by hammering approximately 15–30 times to eliminate entrapped air, and the surface of the molds was trimmed to remove excess mortar. Several hours after casting, the mold surfaces were covered with a damp sheet to maintain internal humidity and prevent rapid evaporation. The specimens were then stored at room temperature (24°C) for one day. Figure 3.4 shows preparation of ASR test specimens.

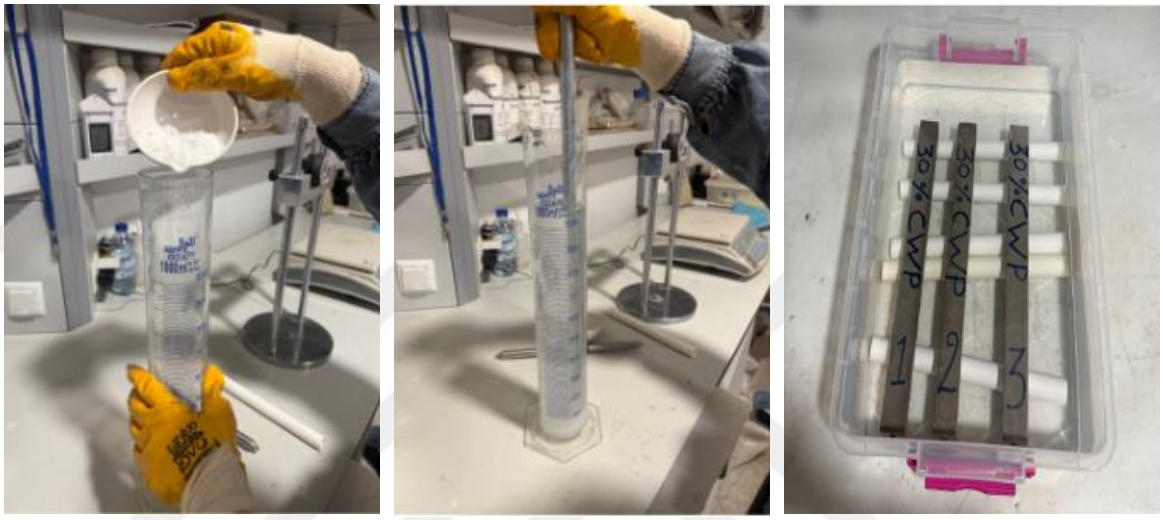


(a) (b) (c)

Figure 3.4 Preparation of ASR test specimens (a) Mold preparation (b) Casting of specimens (c) Covering specimens with plastic sheets for curing

Then, the mortar bars were removed from the molds and immersed in water, and the specimens were stored in the oven according to the description of each mix. After one day, the initial length was measured using a reading device. Subsequent to the initial measurement, the samples must be submerged in an alkaline solution for duration of 28 days. This experimental study utilized sodium hydroxide as a solution for immersing the samples for the designated duration of the experiment (Figure 3.5). The sodium hydroxide solution required for all samples was consistently 1M (equal to one mole of solute per litre of solution) and must be dissolved in distilled water. The experiment

utilized 40 g of sodium hydroxide dissolved in 1000 ml of distilled water, with the water added to a glass flask and the sodium hydroxide combined. Due to the corrosive properties of sodium hydroxide on skin and eyes, adherence to safety protocols is imperative.



(a) (b) (c)

Figure 3.5 Curing of ASR specimens in sodium sulfate solution

After preparing the sodium hydroxide solution, the mortar bars were fully immersed in it and placed in an oven at 80°C for all mixes. The expansion of the mortar length was measured every three days and recorded as shown in Figure 3.6.



Figure 3.6 Oven curing of ASR specimens and measurement of expansion

The acceptance criteria for the ASR test define the maximum permissible expansion of the mortar specimens over the specified curing period. According to ASTM C1260, a specimen is considered acceptable if the expansion does not exceed 0.1% at 14 days and 0.2% at 28 days. Expansions beyond these limits indicate a higher susceptibility to ASR, which may lead to potential durability issues in the concrete. These criteria provide a clear reference for evaluating the performance of different concrete mixtures and their potential risk of ASR-induced damage. The expansion of each specimen was calculated using Eq. 3.1.

$$L = [((L_t - L_{rt}) - (L0 - LR_0))/250]*100 \quad \text{Eq. 3.1}$$

L_0=Initial comparator reading, L_{R0}= Initial reference bar reading, L_t=at t day, comparator reading, L_{rt} = at t day, reference bar reading, G = Effective Gage length, 250 mm, L=Change in length at t day, %. All specimens are shown Figure 3.7.



Figure 3.7 All ASR test specimens

3.3 Phase II: RCC Mix Design Matrix and Optimum Water Content

In this phase, the mix design for RCC was developed, considering different proportions of NA and RCA, as well as OPC and CWP. The main objective was to determine the optimum water content required to achieve adequate workability and compaction while maintaining the desired mechanical properties. A total of nine RCC mixtures were prepared, and each mixture was replicated five times. For each replicate, five different water-to-cement ratios were tested to identify the optimum content for each mixture.

3.3.1 RCC Mix Proportioning and Specimen Preparation

Aggregate gradation is one of the most critical parameters in the design of RCC, as it directly influences density, compaction efficiency, and void content. In this study, the aggregate gradation was carefully selected based on laboratory sieve analysis to ensure compliance with the recommended gradation limits for RCC mixtures.

The aggregate gradations for the RCC mixtures were developed in accordance with the "General Technical Specification for Roller Compacted Concrete Roads /Silindirle Sıkıştırılmış Beton Yol Genel Teknik Şartnamesi" published by the Turkish Ministry of Environment, Urbanization and Climate Change in 2020 [2]. For a maximum aggregate size of 22.4 mm, the targeted RCC aggregate blended gradation curve was established by calculating the average of the upper and lower limits provided in the specification, as illustrated in Figure 3.8.

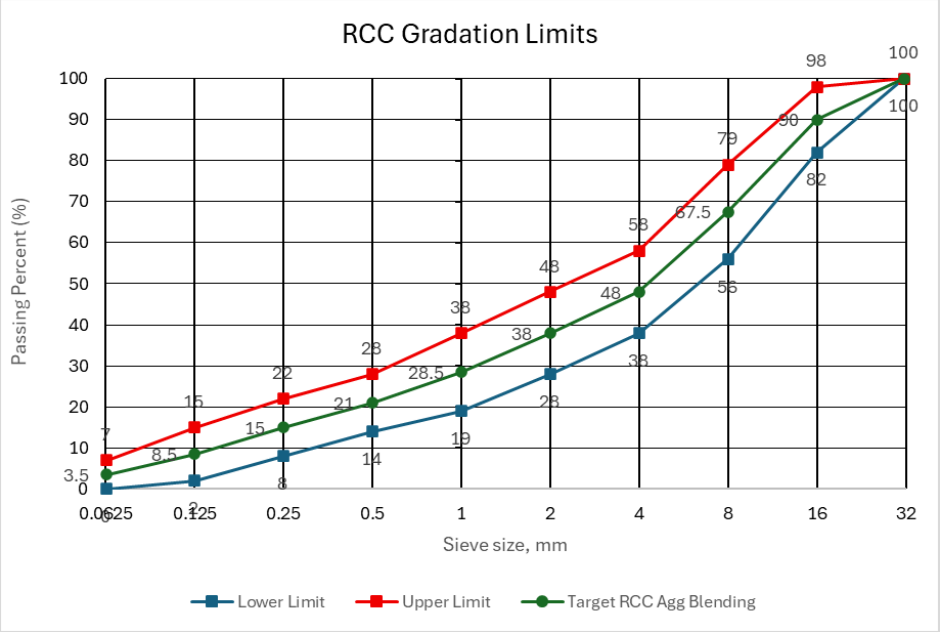


Figure 3.8 Targeted RCC aggregate gradation curve and the upper/lower limits for a maximum aggregate size of 22.4 mm [2]

The experimental program was structured to evaluate three distinct aggregate sources: 100% NA, 100% RCA, and a 50/50 blend of NA and RCA. To achieve the targeted blended gradation for each source, the mass retained on each individual sieve was

precisely calculated and adjusted to ensure all mixtures adhered to the same reference distribution curve.

A primary distinction of RCC compared to conventional concrete pavement is the requirement for an Optimum Moisture Content (OMC). In accordance with national specifications and international guidelines from the RCC Pavement Council and the American Concrete Pavement Association (ACPA), a soil mechanics-based approach was adopted. Consequently, five different water contents (4.5%, 5.5%, 6.5%, 7.5%, and 8.5%) were investigated for each reference group. The relationship between dry density and moisture content was established using Standard/Modified Proctor compaction tests to identify the Maximum Dry Density (MDD) and its corresponding OMC.

The study investigated a total of 45 unique RCC mixtures, incorporating three aggregate types and three levels of CWP as a partial replacement for OPC at dosages of 0%, 30%, and 50%. The mix designs were developed following the classical weight/volume proportioning methodology described in the CP Tech Center RCC Guidelines [4]. The detailed mix proportions for all 45 mixes are summarized in Table 3.4.

Table 3.4 Mix proportions of RCC mixtures for the determination of optimum moisture content.

No	Mix ID	Cement (kg/m^3)		Water			Aggregates (kg/m^3)		Unit Weight
		OPC	CWP	W (%)	(kg/m^3)	W/C	NA	RCA	kg/m^3
1	RCC-0%RCA-0%CWP -4.5%	350	0	4.5	107	0.30	2020	0	2477
2	RCC-0%RCA-0%CWP -5.5%	350	0	5.5	127	0.36	1965	0	2442
3	RCC-0%RCA-0%CWP -6.5%	350	0	6.5	147	0.42	1913	0	2410
4	RCC-0%RCA-0%CWP -7.5%	350	0	7.5	166	0.47	1863	0	2379
5	RCC-0%RCA-0%CWP -8.5%	350	0	8.5	184	0.53	1814	0	2349
6	RCC-0%RCA-30%CWP-4.5%	245	105	4.5	107	0.30	2020	0	2477
7	RCC-0%RCA-30%CWP-5.5%	245	105	5.5	127	0.36	1965	0	2442
8	RCC-0%RCA-30%CWP-6.5%	245	105	6.5	147	0.42	1913	0	2410
9	RCC-0%RCA-30%CWP-7.5%	245	105	7.5	166	0.47	1863	0	2379
10	RCC-0%RCA-30%CWP-8.5%	245	105	8.5	184	0.53	1814	0	2349
11	RCC-0%RCA-50%CWP -4.5%	175	175	4.5	107	0.30	2020	0	2477
12	RCC-0%RCA-50%CWP -5.5%	175	175	5.5	127	0.36	1965	0	2442
13	RCC-0%RCA-50%CWP -6.5%	175	175	6.5	147	0.42	1913	0	2410
14	RCC-0%RCA-50%CWP -7.5%	175	175	7.5	166	0.47	1863	0	2379
15	RCC-0%RCA-50%CWP -8.5%	175	175	8.5	184	0.53	1814	0	2349
16	RCC-50%RCA-0%CWP-4.5%	350	0	4.5	104	0.30	1013	959	2427
17	RCC-50%RCA-0%CWP-5.5%	350	0	5.5	125	0.36	986	934	2394
18	RCC-50%RCA-0%CWP-6.5%	350	0	6.5	144	0.41	960	909	2364
19	RCC-50%RCA-0%CWP-7.5%	350	0	7.5	163	0.47	935	886	2334
20	RCC-50%RCA-0%CWP-8.5%	350	0	8.5	181	0.52	912	864	2306
21	RCC-50%RCA-30%CWP-4.5%	245	105	4.5	104	0.30	1013	959	2427
22	RCC-50%RCA-30%CWP-5.5%	245	105	5.5	125	0.36	986	934	2394
23	RCC-50%RCA-30%CWP-6.5%	245	105	6.5	144	0.41	960	909	2364

Table 3-4 (Continued)

No	Mix ID	Cement (kg/m^3)		Water			Aggregates (kg/m^3)		Unit Weight
		OPC	CWP	W(%)	(kg/m^3)	W/C	NA	RCA	kg/m3
24	RCC-50%RCA-30%CWP-7.5%	245	105	7.5	163	0.47	935	886	2334
25	RCC-50%RCA-30%CWP-8.5%	245	105	8.5	181	0.52	912	864	2306
26	RCC-50%RCA-50%CWP-4.5%	175	175	4.5	104	0.30	1013	959	2427
27	RCC-50%RCA-50%CWP-5.5%	175	175	5.5	125	0.36	986	934	2394
28	RCC-50%RCA-50%CWP-6.5%	175	175	6.5	144	0.41	960	909	2364
29	RCC-50%RCA-50%CWP-7.5%	175	175	7.5	163	0.47	935	886	2334
30	RCC-50%RCA-50%CWP-8.5%	175	175	8.5	181	0.52	912	864	2306
31	RCC-100%RCA-0%CWP-4.5%	350	0	4.5	102	0.29	0	1924	2376
32	RCC-100%RCA-0%CWP-5.5%	350	0	5.5	122	0.35	0	1874	2346
33	RCC-100%RCA-0%CWP-6.5%	350	0	6.5	141	0.41	0	1826	2317
34	RCC-100%RCA-0%CWP-7.5%	350	0	7.5	160	0.46	0	1780	2290
35	RCC-100%RCA-0%CWP-8.5%	350	0	8.5	177	0.51	0	1736	2263
36	RCC-100%RCA-30%CWP-4.5%	245	105	4.5	102	0.29	0	1924	2376
37	RCC-100%RCA-30%CWP-5.5%	245	105	5.5	122	0.35	0	1874	2346
38	RCC-100%RCA-30%CWP-6.5%	245	105	6.5	141	0.41	0	1826	2317
39	RCC-100%RCA-30%CWP-7.5%	245	105	7.5	160	0.46	0	1780	2290
40	RCC-100%RCA-30%CWP-8.5%	245	105	8.5	177	0.51	0	1736	2263
41	RCC-100%RCA-50%CWP-4.5%	175	175	4.5	102	0.29	0	1924	2376
42	RCC-100%RCA-50%CWP-5.5%	175	175	5.5	122	0.35	0	1874	2346
43	RCC-100%RCA-50%CWP-6.5%	175	175	6.5	141	0.41	0	1826	2317
44	RCC-100%RCA-50%CWP-7.5%	175	175	7.5	160	0.46	0	1780	2290
45	RCC-100%RCA-50%CWP-8.5%	175	175	8.5	177	0.51	0	1736	2263

Note: NA = Natural Aggregate; RCA = Recycled Concrete Aggregate; CWP = Cement Waste Powder.

The compaction tests were conducted using a standard Proctor mold in accordance with ASTM D698. The mold had an internal diameter of 101.5 mm (4.0 in.) and a height of 116.8 mm (4.6 in.), corresponding to a total volume of approximately 945 cm^3 (0.000945 m^3).Compaction was performed using a standard Proctor rammer with a mass of 5.50 lbf (24.5 N), which was allowed to fall freely from a height of 305 mm (12.0 in.). This procedure produced a standard compactive effort of approximately 600 $kN \cdot m/m^3$ (12,400 $ft \cdot lbf/ft^3$), as specified in ASTM D698. The Proctor mold and rammer were inspected and cleaned prior to testing to ensure proper alignment and consistent compaction energy throughout the experimental program. In addition, five moisture containers were prepared for each mixture to determine the moisture content at different water levels.

All materials were prepared in accordance with the aggregate gradation tables and the mixture proportion matrix. The required quantities of NA, RCA, OPC, and CWP were measured for each mixture based on the designated mix design. The water content was adjusted according to the selected trial water levels to evaluate the compaction behavior and to determine the optimum water content for each mixture. The materials were thoroughly mixed manually with water until a uniform and homogeneous mixture was achieved, as permitted by ASTM D698. The prepared RCC mixture was placed into the Proctor mold in three equal layers. Each layer was compacted by applying 25 blows using the standard Proctor rammer. The blows were uniformly distributed over the surface of each layer to ensure consistent compaction. After completing the compaction of the third layer, the excess material was carefully trimmed and the surface was leveled flush with the top of the mold to obtain a smooth and even surface prior to weighing. Figure 3.9 illustrates the material preparation and the execution of Proctor compaction tests for the RCC mixtures.



Figure 3.9 Preparation of Proctor test for RCC mixes.

3.3.2 Determination of Optimum Water Content

The OMC for each RCC mixture was determined based on the compaction curves derived from Proctor tests. For each unique mixture, five specimens were prepared at varying moisture contents to establish the relationship between water content and dry unit weight. The OMC was identified as the moisture content corresponding to the MDD. This established value was subsequently employed in the preparation of all specimens for further mechanical and durability testing. Detailed results and the resulting compaction curves are presented and discussed in Chapter 4.

The testing procedure followed a rigorous laboratory protocol to ensure accuracy. Initially, the mass of the empty Proctor mold (W_m) was recorded. After the RCC was compacted in the mold and the surface was leveled, the total mass of the mold and the compacted specimen (W_{wet} + W_m) was measured. The mass of the compacted wet specimen (W_{wet}) was then calculated by subtracting the mold weight. To determine the precise moisture content, a representative sample was extracted from the middle portion of the compacted specimen. The mass of the empty moisture container (W_{cont}) and the container with the wet sample (W_{cont} + $W_{wetsample}$) were recorded. The specimens were then oven-dried at 110 ºC for 24 hours. After drying, the mass of the container with the dry sample (W_{cont} + $W_{drysample}$) was measured. The wet unit weight (γ_{wet}) and dry unit weight (γ_{dry}) were calculated using the following relationships:

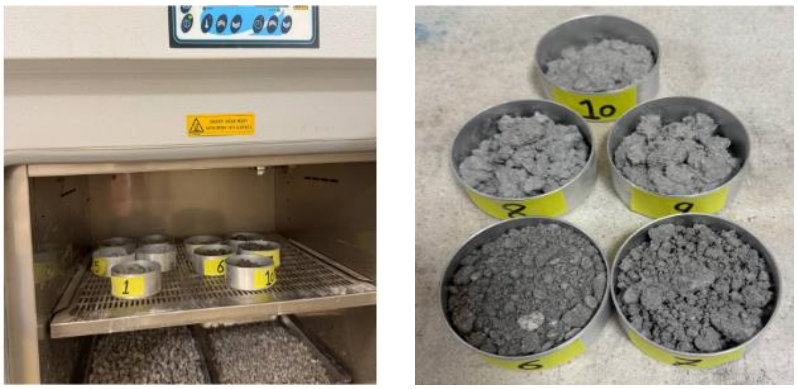
$$\gamma_{wet} = \frac{W_{wet}}{V_m} \quad \text{Eq. 3.2}$$

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + w} \quad \text{Eq. 3.3}$$

where V_m is the volume of the Proctor mold and w is the moisture content (expressed as a decimal). This process was repeated across five different moisture levels for each of the 45 mixtures to construct the compaction curves required to identify the OMC. Figure 3.10 illustrates the laboratory procedures for determining the OMC through Proctor compaction testing.



Wet RCC specimens



Dry RCC specimens and drying oven

Figure 3.10 OPC determination by using Proctor Test for RCC mixes

3.3.3 Vebe Tests

The Vebe consistency test, performed in accordance with ASTM C1170, is the standard method for evaluating the workability and compaction characteristics of RCC mixtures. Unlike conventional concrete, the stiff nature of RCC requires vibration and a surcharge load to achieve consolidation. The test measures the time (in seconds) required for a concrete mass to change from a conic shape to a cylindrical shape under vibration, reflecting the mixture's ease of consolidation and the internal distribution of materials.

Following the determination of the OMC described in the previous section, Vebe tests were conducted at these optimum moisture levels to characterize the consistency of the mixtures. For this phase of the study, three representative mixtures were selected for comparative analysis: 1- 0% RCA – 0% CWP (Control/Reference), 2- 0% RCA – 50% CWP, 3- 100% RCA – 0% CWP with OMC.

The materials were prepared according to the mix proportions and aggregate gradations established in Section 3.3.1, ensuring adherence to the targeted OMC to maintain uniformity and accuracy across the specimens.

First, the materials for each mixture were manually mixed thoroughly to ensure uniform distribution of all constituents. Subsequently, a slump test was performed for each

mixture to verify the initial flowability before placing the concrete in the Vebe apparatus (Figure 3.11).



Figure 3.11 Slump Test for RCC mixes

The mixture was then poured into the Vebe cylinder, which was placed on a level surface (Figure 3.12). The apparatus was operated, and the time required for the concrete to achieve full compaction under vibration was measured. This time represents the workability and compaction characteristics of the mixture. The test was repeated for all three mixtures: 0% RCA – 0% CWP, 0% RCA – 50% CWP, and 100% RCA – 0% CWP, and the Vebe time for each mixture was recorded in seconds.



Figure 3.12 Photos from the Vebe Consistency Test for RCC mixes

3.4 Phase III: Performance Testing of RCA incorporated RCC mixes

Phase III of the experimental program focuses on evaluating the performance of RCC mixtures containing RCA at different replacement levels. This phase aims to assess the physical, durability, and mechanical properties of the mixtures to understand the influence of RCA content on concrete performance.

For this phase, three distinct mixtures were selected based on their RCA replacement levels: RCC-0%RCA-0%CWP, RCC-50%RCA-0%CWP, and RCC-100%RCA-0%CWP. These formulations were prepared using the OMC values established in Phase II. Notably, CWP was excluded from this specific phase to isolate the influence of RCA substitution and minimize the number of experimental variables, ensuring a clearer analysis of the recycled aggregate's impact.

The material proportions for each mixture-including cement, natural aggregate, and RCA—were strictly controlled based on the pre-determined design matrix (Table 3.4). For each of the three formulations, 12 cubic specimens (15x15x15cm^3) were cast for standardized testing. The comprehensive suite of tests conducted during this phase is summarized in Table 3.5.

Table 3.5 Summary of physical, mechanical, and durability tests conducted on RCC mixtures with varying RCA replacement levels.

No	Standard Test	Procedure	Sample dimension	Replication
1	Fresh density	ASTM C138	15x15x15 cm	each cube
2	28 days compressive strength test	EN 12390-3	15x15x15 cm	4
3	Ultrasonic pulse velocity (UPV)	ASTM C597	15x15x15 cm	
4	Eletrical resistance test (kOhm·cm)	AASHTO T358	15x15x15 cm	
5	Water pressure test	EN 12390-8,	15x15x15 cm	2
6	Freezing Thawing Test	ASTM	15x15x15 cm	3
7	Sulfate Attack Test	ASTM	15x15x15 cm	3
8	Micro CT tests			
			Total	12

For the cube specimens' preparations, the natural aggregate was sieved, and its particle size fractions were separated and stored in plastic containers. RCA was produced by crushing and grinding previously used concrete cubes using a drill and crushing/grinding machines, after which it was sieved, and its particle size fractions were separated and stored in plastic containers. Both natural (Figure 3.13) and recycled aggregates (Figure 3.14) were prepared for use in this phase.



Figure 3.13 Preparation and grading of natural aggregate for use in the RCC mixtures

Due to the limited capacity of the mixing equipment, each mixture was divided into three separate batches while maintaining the same mix proportions. The aggregates were weighed according to their designated size fractions and placed in plastic bags for direct

use during mixing, while the mixing water was measured accurately to ensure consistency among all batches.



Figure 3.14 Preparation and grading of RCAs for use in the RCC mixtures

The RCC mixtures were prepared using a mechanical mixer in accordance with standard RCC mixing procedures. First, the dry materials, including cement and aggregates, were mixed to ensure uniform distribution of the constituents. Mixing water was then added gradually while mixing continued to achieve a stiff and homogeneous RCC mixture with low workability, suitable for compaction. After mixing, the fresh RCC mixtures were placed into cubic molds with dimensions of 150 × 150 × 150 mm and compacted using an electric drill to simulate the compaction energy applied in roller-compacted concrete. Compaction was performed in layers to achieve adequate density and reduce air voids.

Upon completion of compaction, the surfaces of the specimens were leveled, and the molds were covered to prevent moisture loss. In some batches of the RCC mixtures, a reduction in the mixing water content was applied during the preparation of the second batch of the control mixture with 0% RCA (0% RCA). This reduction, amounting to 22.5%, was initially introduced unintentionally; however, it resulted in improved consistency and compaction behavior of the RCC mixture. Accordingly, the same water reduction ratio was subsequently adopted for selected batches of the mixtures containing 50% RCA and 100% RCA to maintain consistency in the mixing and compaction characteristics among all mixtures.

The specimens were demolded after 24 hours and subsequently cured in water at laboratory temperature for a period of 28 days prior to testing. Figure 3.15 shows the sequential stages of casting and preparing the RCC cube specimens.





Figure 3.15 RCC cubes preparation for the tests

In addition to the standard RCC specimens, three cubic specimens were cast for each mixture for Micro-Computed Tomography/Micro-CT analysis. Each specimen had dimensions of 150 × 150 × 50 mm. The three specimens were prepared using the same mix proportions, aggregate gradation, and mixing and compaction procedures as the main RCC specimens, with the only difference being the reduced height of 50 mm. After casting, the molds were covered to prevent moisture loss and were removed from the molds after 24 hours. The specimens were then cured in water for a period of 28 days under laboratory conditions. During the curing period, the specimens were regularly sprayed with water to maintain adequate moisture. After completing the curing process, the specimens were cut into smaller sections suitable for Micro-CT scanning (Figure 3.16).



Figure 3.16 Preparation RCC specimens for Micro-CT test

3.4.1 Physical Tests

This section presents the physical and non-destructive tests conducted to evaluate the properties of RCC mixtures incorporating RCA. These tests were performed to assess the fresh physical characteristics of the mixtures and to investigate the internal structure and material uniformity of the hardened concrete without causing damage to the specimens. The physical and non-destructive tests included the Fresh Density Test, Ultrasonic Pulse Velocity Test (UPV), and Micro-Computed Tomography (Micro-CT) analysis.

The fresh density of the RCC mixtures was determined in accordance with ASTM C138 by measuring the mass of the fresh concrete placed in cubic molds. Initially, the empty molds were weighed to obtain their tare weight. After casting and compacting the fresh concrete into the molds, the molds filled with concrete were weighed. The mass of fresh concrete was then calculated by subtracting the weight of the empty mold from the total weight. The fresh density was measured for all specimens, including 12 samples per mixture, resulting in a total of 36 specimens.

The UPV test was conducted in accordance with ASTM C597 to evaluate the quality, uniformity, and internal condition of the RCC mixtures without causing damage to the specimens. This test provides an indication of concrete density, homogeneity, and the

presence of internal defects such as voids or cracks. For each RCC mixture, four cubic specimens were selected for the UPV test (Figure 3.17). The test was performed on specimens RCC5, RCC6, RCC7, and RCC8, representing each mixture group. Prior to testing, the concrete surfaces were cleaned, and a suitable coupling agent was applied to ensure proper contact between the transducers and the specimen surfaces.



Figure 3.17 UPV test setup on RCC specimens

The ultrasonic pulse velocity was determined in accordance with Eq. 3.4. In this study, a digital UPV testing apparatus was utilized, which provided direct velocity readouts in m/s. Consequently, the measured values were recorded directly from the device display for each specimen. The fundamental relationship used for the calculation is expressed as:

$$V = \frac{L}{T} \qquad \text{Eq. 3.5}$$

Where: V is the ultrasonic pulse velocity (m/s), L is the path length (m), T is the transit time (s). Classification of concrete quality ratings based on UPV test is shown in Table

Table 3.6 Classification of concrete quality ratings based on UPV test BS EN 12504-4:2021 [33]

Pulse Velocity (km/s)	Concrete Quality (Rating)
≥ 4.5	Excellent (E)
3.5 – 4.5	Good (G)
3.0 – 3.5	Medium (M)
2.0 – 3.0	Doubtful (D)
≤ 2.0	Very Weak (VW)

To provide a high-resolution, non-destructive characterization of the internal microstructure, Micro-CT was employed on selected RCC specimens. This advanced imaging technique utilizes X-ray attenuation to generate a three-dimensional reconstruction of the concrete matrix, enabling the precise quantification of the air-void system, pore connectivity, and the spatial distribution of the recycled constituents. In the context of this study, Micro-CT was instrumental in visualizing the complex ITZ between the RCA and the new mortar matrix. By analyzing the volumetric data, the influence of RCA substitution on the internal density and morphological characteristics of the porous structure was evaluated with high spatial precision.

3.4.2 Mechanical Tests

Mechanical tests are essential for evaluating the structural performance and load-bearing capacity of concrete mixtures. These tests provide insight into the behavior of concrete under different types of mechanical stresses, helping to assess its suitability for construction applications. In this study, the mechanical tests were conducted on RCC mixtures containing different proportions of RCA.

The compressive strength test was conducted to evaluate the mechanical performance of the RCC mixtures containing different proportions of RCA (Figure 3.18). Compressive strength is a key parameter for assessing the load-bearing capacity and structural performance of concrete. The test was performed in accordance with EN 12390-3 (Testing hardened concrete – Part 3: Compressive strength of test specimens). For this study, four cubic specimens from each mixture were used, resulting in a total of 12 specimens. Before testing, the dimensions of each cube were measured, and the specimens were positioned in the testing machine. The specimens were loaded until

failure, and the maximum load and corresponding compressive strength were recorded. To ensure accurate results, the load was applied on a flat surface of the cube, not the top surface, because the top surface was not perfectly level. The recorded compressive strength values were later analyzed to compare the effect of different RCA contents on the mechanical performance of the RCC mixtures.



Figure 3.18 Compressive strength test setup for RCC specimens.

3.4.3 Durability Tests

Durability is a crucial property of concrete, reflecting its ability to withstand environmental and chemical attacks over time without significant loss of performance. In this study, several tests were conducted to evaluate the performance of RCC mixtures containing different proportions of RCA, including electrical resistivity, water penetration under pressure, resistance to sulfate attack, and freeze–thaw resistance. These tests provide insight into the long-term behavior of the concrete and its suitability for various construction conditions.

3.4.3.1 Electrical Resistivity Test

The electrical resistivity of the RCC specimens containing different proportions of RCA was measured to assess their durability and pore structure. The test was performed in accordance with AASHTO T358 [34], which provides a standardized method for evaluating the bulk resistivity of concrete.

A total of 12 cubic specimens were prepared for each mixture, resulting in 36 specimens overall. Prior to testing, the surface of each specimen was lightly moistened with water to ensure proper contact with the measurement device. The resistivity meter was then positioned directly on the surface of the specimen. The device applies an electrical current and measures the resulting voltage, providing a direct reading of the bulk electrical resistivity (ρ) of the concrete. This procedure allows for the assessment of concrete's ability to resist the ingress of deleterious ions, such as chlorides, which are known to promote reinforcement corrosion. Higher resistivity values indicate a denser microstructure and lower permeability, which are associated with improved durability. The measurements were recorded for all specimens and later analyzed to investigate the effect of varying RCA content on the electrical resistivity and durability performance of the RCC mixtures. Figure 3.19 illustrates the testing setup used for measuring the electrical resistivity of the specimens.



Figure 3.19 Electrical resistivity measurement setup for RCC specimens

The following Table 3.7 provides the standard levels for evaluating concrete penetration based on electrical resistivity at 28 days based on AASHTO T358 [34].

Table 3.7 Classification of concrete penetration ratings based on electrical resistivity test [34]

Chloride Ion Penetration	Surface Resistivity	
	100 × 200 mm Cylinder (kΩ·cm) ***a = 1.5***	**150 × 300 mm Cylinder (kΩ·cm)** ***a = 1.5***
High	< 12	< 9.5
Moderate	12 – 21	9.5 – 16.5
Low	21 – 37	16.5 – 29
Very low	37 – 254	29 – 199
Negligible	> 254	> 199

***Note**: a represents the Wenner probe tip spacing.*

3.4.3.2 Water Penetration test

The water penetration under pressure test was conducted to evaluate the impermeability of the RCC mixtures containing different proportions of RCA. This test assesses the ability of concrete to resist the ingress of water under applied pressure, which is critical for durability, especially in structures exposed to moisture and aggressive environments. The test was carried out in accordance with EN 12390-8. For each mixture, two specimens (numbers 5 and 6) were selected, resulting in a total of six specimens tested. Prior to testing, the specimen surfaces were cleaned and properly sealed, leaving only the test surface exposed to water. Water pressure was then applied to the specimens for a duration of three days, and the depth of water penetration into the concrete was measured after splitting the specimens. The results provide an indication of the concrete resistance to water ingress. Lower penetration depths indicate higher impermeability and better durability performance. The recorded measurements were analyzed to compare the effect of varying RCA contents on the water penetration resistance of the RCC mixtures. Figure 3.20 illustrates the setup of the water pressure test on the RCC specimens.



Figure 3.20 Water penetration test of RCC specimens

3.4.3.3 Sulfate Attack Resistance Test

The sulfate attack resistance test was conducted to evaluate the ability of the RCC mixtures to resist chemical degradation in a sulfate-rich environment. The test was carried out in accordance with ASTM C1012. Typically, three cubic specimens are used per mixture; however, in this study, one cube from each mixture was selected, resulting in three specimens overall. The selected cubes were fully immersed in a 5% sodium sulfate (Na_2SO_4) solution, which corresponds to 50 g of Na_2SO_4 per 1 liter of water, for 28 days. During this period, the weight of each specimen was measured weekly to monitor changes caused by sulfate attack, and the specimens were periodically observed for expansion, cracking, or surface deterioration.

3.4.3.4 Freeze–Thaw Resistance Test

The freeze–thaw resistance test was conducted to evaluate the durability of the RCC mixtures containing different proportions of RCA under cyclic freezing and thawing.

This test is essential for assessing the ability of concrete to withstand harsh cold climates and repeated temperature fluctuations without significant deterioration. As shown in Figure 3.21, the test was performed in accordance with ASTM C666. Although typically three cubic specimens are used for each mixture, in this study, specimen number 12 from each mixture was selected, resulting in a total of three specimens. The selected specimens were fully immersed in water prior to testing to ensure proper saturation and then placed in a freeze–thaw chamber. The specimens were subjected to repeated freeze–thaw cycles, with temperatures alternately lowered below 0°C and then raised above freezing. The testing period lasted 28 days, during which the weight of each specimen was measured weekly. The specimens were periodically observed for signs of cracking, scaling, or other surface deterioration. This procedure provides insight into the ability of RCC mixtures to resist freeze–thaw damage, which is a critical factor in the long-term durability of concrete structures exposed to cold climates.



Figure 3.21 Setup of the freeze–thaw test for RCC specimens

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents and discusses the experimental results obtained from the three main phases of the study. Phase I focuses on the characterization of RCA and the evaluation of ASR potential to assess the suitability of RCA for use in RCC. Phase II addresses the mix design process, with particular emphasis on compaction behavior and the determination of optimum water content for different mixture compositions. Phase III focuses on the evaluation of the mechanical performance and durability of RCC incorporating different proportions of RCA. The results are interpreted to quantify how RCA affects compaction behavior, strength development, and durability indicators, and to derive practical implications for using RCA in RCC pavement applications.

4.1 Phase I Results: RCA Characterization and ASR

Phase I of this study focuses on the characterization of RCA and the assessment of its ASR potential. This phase aims to evaluate the fundamental physical and mechanical properties of RCA and to determine its suitability for use in RCC mixtures. Understanding the behavior of RCA at this stage is essential, as the quality and reactivity of RCAs directly influence the performance, durability, and long-term stability of RCC mixtures. The results obtained in this phase provide a basis for mix design optimization and performance evaluation in the subsequent phases of the study.

4.1.1 RCA Characterization

The physical properties of the RCA and natural aggregate (NA) were determined through laboratory testing, and the results are presented in Table 4.1 and Table 4.2, respectively.

Table 4.1 Physical Properties of RCA.

Sieve Size Range (mm)	Apparent Particle Density (g/cm³)	Oven-Dry Particle Density (g/cm³)	SSD Particle Density (g/cm³)	Water Absorption (%)
16–32	2.39	2.24	2.31	2.75
8–16	2.65	2.37	2.48	4.78
4–8	2.63	2.33	2.44	5.00
2–4	2.51	2.08	2.25	8.30
1–2	2.45	2.02	2.19	8.74

Table 4.2 Physical Properties of NA.

Sieve Size Range (mm)	Apparent Particle Density (g/cm³)	Oven-Dry Particle Density (g/cm³)	SSD Particle Density (g/cm³)	Water Absorption (%)
16–32	2.84	2.83	2.83	0.18
8–16	2.71	2.71	2.72	0.28
4–8	2.81	2.77	2.78	0.52
2–4	2.85	2.78	2.81	0.88
1–2	2.53	2.12	2.28	4.00

A comparative analysis between RCA and NA reveals that RCA exhibits significantly lower apparent and oven-dry density values across all size fractions. Conversely, the water absorption rates for RCA are clearly higher, particularly within the finer fractions. This behavior is primarily attributed to the porous structure of the adhered cement mortar on the RCA particles and the formation of micro-cracks during the mechanical crushing process. The presence of capillary voids within the residual mortar, combined with these crushing-induced micro-fractures, simultaneously reduces the particle density and enhances the water absorption capacity.

The physical characteristics of RCA lead to variations in fresh concrete behavior compared to NA-based mixtures. Specifically, as water absorption values in the fine fractions approach 10%, a substantial portion of the mixing water is absorbed by the aggregate. This phenomenon can lead to a rapid loss of workability. Consequently, when utilizing RCA, it is necessary to implement "water correction" strategies or use the aggregates in a pre-wetted or SSD condition to maintain consistency.

Furthermore, the content of material finer than 75 μm (passing the No. 200 sieve) was found to be higher in the RCA fractions, ranging from 1.92% to 2.21%, compared to 0.29% to 0.71% for the NA. Excessive fines can negatively impact workability and

strength by increasing the water demand of the paste and creating a weak layer at the ITZ, which degrades the aggregate-paste bond.

Regarding mechanical durability, the Los Angeles (LA) Abrasion coefficients for the RCA ranged from 21% to 27%, whereas the values for NA were notably lower, between 18% and 20%. The higher LA coefficients for RCA fractions, particularly in the coarser ranges, highlight their increased sensitivity to mechanical wear and fragmentation compared to natural aggregates.

4.1.2 ASR Performance

The ASR expansion results of the RCC mixtures are presented and discussed in this section. The ASR test was conducted to evaluate the potential expansion behavior of RCC incorporating different proportions of RCA. The development of ASR expansion with time was monitored up to 28 days in accordance with ASTM C1260. According to this standard, an expansion limit of 0.10% at 14 days is commonly used to assess the potential reactivity of aggregates. In the present study, all RCC mixtures exhibited ASR expansion values below this limit at 14 days, indicating that the aggregates can be classified as non-reactive. Although a slight increase in expansion was observed beyond 14 days, the recorded values remained within acceptable limits up to 28 days.

The effect of CWP content on ASR expansion—isolated from the influence of RCA—is illustrated in Figure 4.1. Figure 4.1, where 30% and 50% CWP mixtures are compared against the control. The results indicate that the incorporation of CWP led to slightly higher expansion values throughout the monitoring period. At early ages, mixtures with 30% and 50% CWP showed marginally higher expansion rates, likely due to increased alkali availability within the pore solution introduced by the CWP. By the end of the testing period, the 50% CWP mixture reached the highest expansion of 0.0257%, followed closely by the 30% CWP mixture at 0.0250%. Despite this upward trend, the magnitude of the increase is negligible, suggesting that CWP does not induce deleterious ASR behavior.

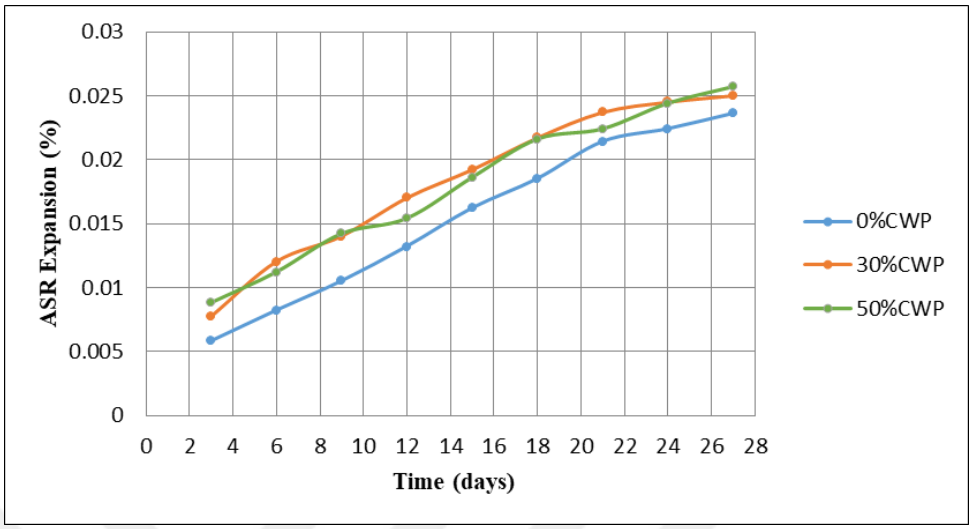


Figure 4.1 Effect of CWP content on ASR expansion over time

The individual effect of RCA substitution (0%, 50%, and 100%) is shown in Figure 4.2. As expected, ASR expansion increased progressively with testing age for all mixtures. The control mixture (0% RCA) exhibited the lowest expansion, reaching a maximum of 0.0236% at 27th days. While the 50% RCA mixture initially showed lower expansion than the control, it ultimately reached a slightly higher value of 0.0254%. The 100% RCA mixture demonstrated the highest expansion throughout the test, peaking at 0.032%. This behavior is attributed to the adhered old mortar on the RCA particles, which increases the internal moisture availability and potentially raises the alkali concentration of the system. However, even at full replacement, the expansion remained significantly below the 0.10% limit, confirming that the RCA used in this study does not pose an ASR risk.

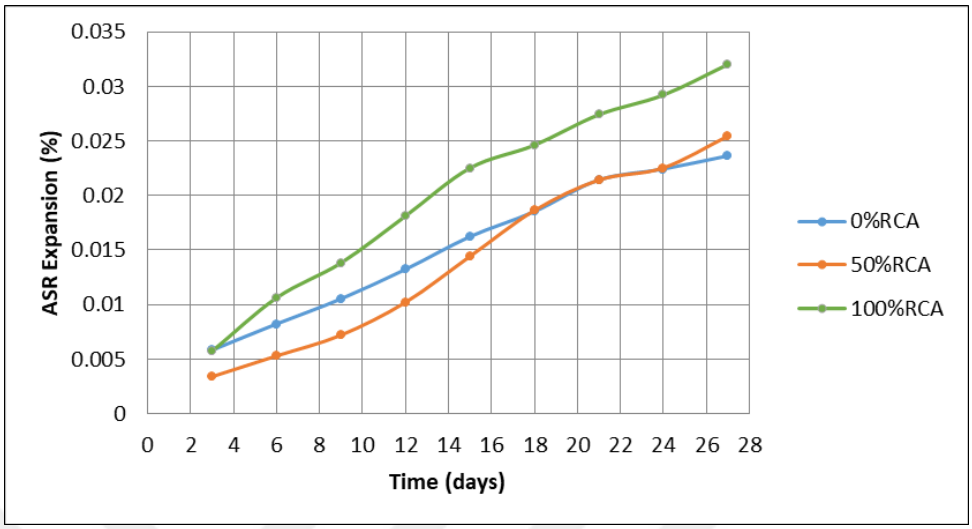


Figure 4.2 Effect of RCA content on ASR expansion over time

The interaction between RCA and CWP was further analyzed by examining mixtures containing both recycled components and illustrated in Figure 4.3. The addition of CWP to 50% RCA mixtures influenced the expansion according to the replacement level. The 50% RCA–30% CWP mixture reached 0.0277% at 27 days. Increasing the CWP content to 50% resulted in a maximum expansion of 0.0285%. This slight increase is likely a result of the combined high porosity of the RCA and the additional alkalis supplied by the CWP. Mixtures incorporating 100% RCA exhibited the most pronounced expansion, particularly at later ages. The 10% RCA–30% CWP mixture reached 0.0334%, while the 100% RCA–50% CWP mixture recorded the highest expansion of all tested formulations at 0.0376%. Nevertheless, the peak value of 0.0376% remains safely below the critical threshold, indicating that even the most heavily substituted recycled RCC mixtures maintain high resistance to ASR.

Overall, the results indicate that high RCA replacement levels significantly influence ASR expansion, and that increasing CWP content further amplifies this effect. Nevertheless, the measured expansion values remained within acceptable limits, indicating that the mixtures did not exhibit deleterious ASR behavior.

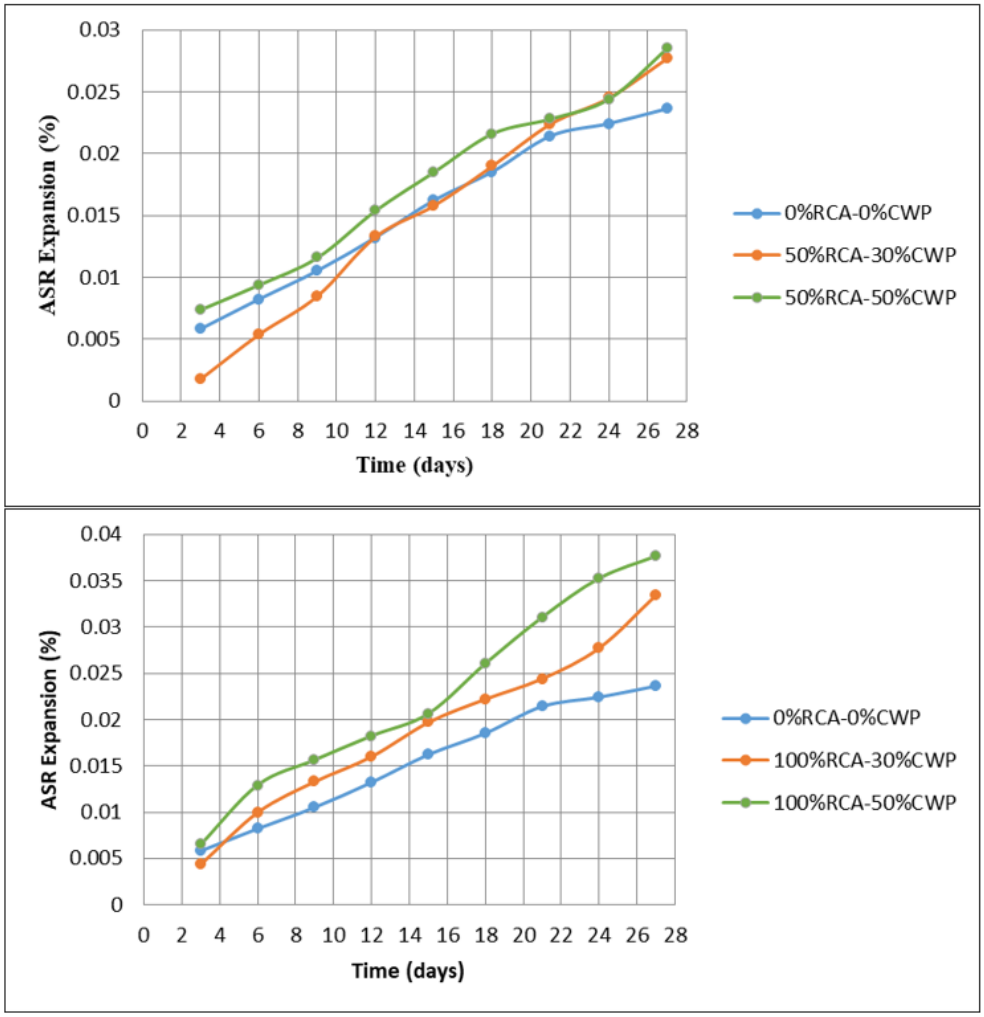


Figure 4.3 Effect of combined RCA and CWP contents on ASR expansion over time

4.2 Phase II Results: Mix Design and Optimum Water Content

This phase focuses on the evaluation of the compaction and density behavior of RCC mixtures in order to determine the optimum water content for mix design. The influence of water content and RCA replacement level on compaction characteristics was investigated through Proctor compaction and Vebe time tests across mixtures incorporating varying levels of RCA and CWP. The outcomes of this phase form the basis for selecting appropriate water contents used in the design of RCC mixtures evaluated in Phase III.

4.2.1 Evaluation of OMC and MDD Relationships for RCC Mixtures

The relationship between moisture content, aggregate type, and binder composition was established by constructing five-point compaction curves for each mixture. The summary of the resulting OMC and MDD values is presented in Table 4.3.

Table 4.3 OMC and MDD values for each RCC mix.

No	Mix ID	OMC (%) -OD condition	γdry (kg/m^3)
1	Reference (RCC-0RCA-0CWP)	8.4%	2253
2	RCC-30%CWP	8.8%	2220
3	RCC-50%CWP	8.9%	2217
4	RCC-50%RCA	9.7%	2131
5	RCC-100%RCA	11.2%	2010
6	RCC-50%RCA-30%CWP	9.6%	2105
7	RCC-50%RCA-50%CWP	9.6%	2110
8	RCC-100%RCA-30%CWP	10.2%	2031
9	RCC-100%RCA-50%CWP	11.2%	1962
No	**Mix ID**	**OMC (%) -SSD condition**	**γdry (kg/m^3)**
1	Reference (RCC-0RCA-0CWP)	~6.5%	2253
2	RCC-30%CWP		2220
3	RCC-50%CWP		2217
4	RCC-50%RCA		2131
5	RCC-100%RCA		2010
6	RCC-50%RCA-30%CWP		2105
7	RCC-50%RCA-50%CWP		2110
8	RCC-100%RCA-30%CWP		2031
9	RCC-100%RCA-50%CWP		1962

The results indicate a clear correlation between the incorporation of recycled materials and the compaction energy required to reach maximum density. As the RCA replacement level increased from 0% to 100%, a significant increase in the OMC was observed under Oven-Dry (OD) aggregate conditions, accompanied by a substantial reduction in MDD. This trend is primarily attributed to the physical properties of the RCA, which, as established in Section 4.1, possesses significantly lower particle density and higher water absorption compared to natural aggregate.

The influence of CWP on compaction behavior was found to be less dominant than that of RCA. While CWP caused only marginal shifts in the OMC, its impact on MDD was more pronounced at the 50% replacement level. Under Saturated Surface Dry (SSD)

conditions, where aggregate absorption is pre-accounted for, the effective moisture content required for optimal lubrication and compaction stabilized at approximately 6.5% for all mixtures at this specific cement dosage. However, the resulting dry densities varied significantly depending on the mix constituents: The incorporation of RCA led to a pronounced decline in MDD. The most significant reduction occurred in the RCC-100%RCA-50%CWP mixture, which yielded an MDD of 1962 kg/m^3. This represents an approximately 13% reduction in density compared to the reference mixture (2253 kg/m^3). While CWP substitution slightly lowered the density, the cumulative effect of high RCA and CWP dosages resulted in the lowest recorded unit weights, reflecting the higher porosity of the recycled material-containing system.

The following subsections provide a detailed analysis of the individual and synergistic effects of CWP and RCA on the compaction curves and consistency of the RCC mixtures.

4.2.1.1 Effect of CWP Content (0% RCA)

The influence of CWP on the compaction characteristics of RCC mixtures—isolated at a 0% RCA substitution level—is illustrated in the compaction curves presented in Figure 4.4. A comparative analysis of these curves reveals that increasing the CWP content leads to a gradual shift in the OMC toward higher values, accompanied by a marginal reduction in the MDD. As detailed in Table 4.3, the reference mixture (0% CWP) achieved an MDD of 2253 kg/m^3 at an OMC of 8.4% (under Oven-Dry aggregate conditions). With the incorporation of 30% and 50% CWP, the OMC values increased to 8.8% and 8.9%, respectively. This slight rise in water demand is primarily attributed to the higher specific surface area and the inherently porous nature of the CWP compared to OPC. The fine particles of the CWP necessitate additional moisture to lubricate the mixture and achieve the desired degree of compaction. Simultaneously, the MDD decreased slightly to 2220 kg/m^3 for the 30% CWP mixture and 2217 kg/m^3 for the 50% CWP mixture. This downward trend in dry density indicates that while CWP acts as a

mineral filler, its lower particle density relative to the constituents it replaces leads to a slight reduction in the overall unit weight of the compacted RCC matrix.

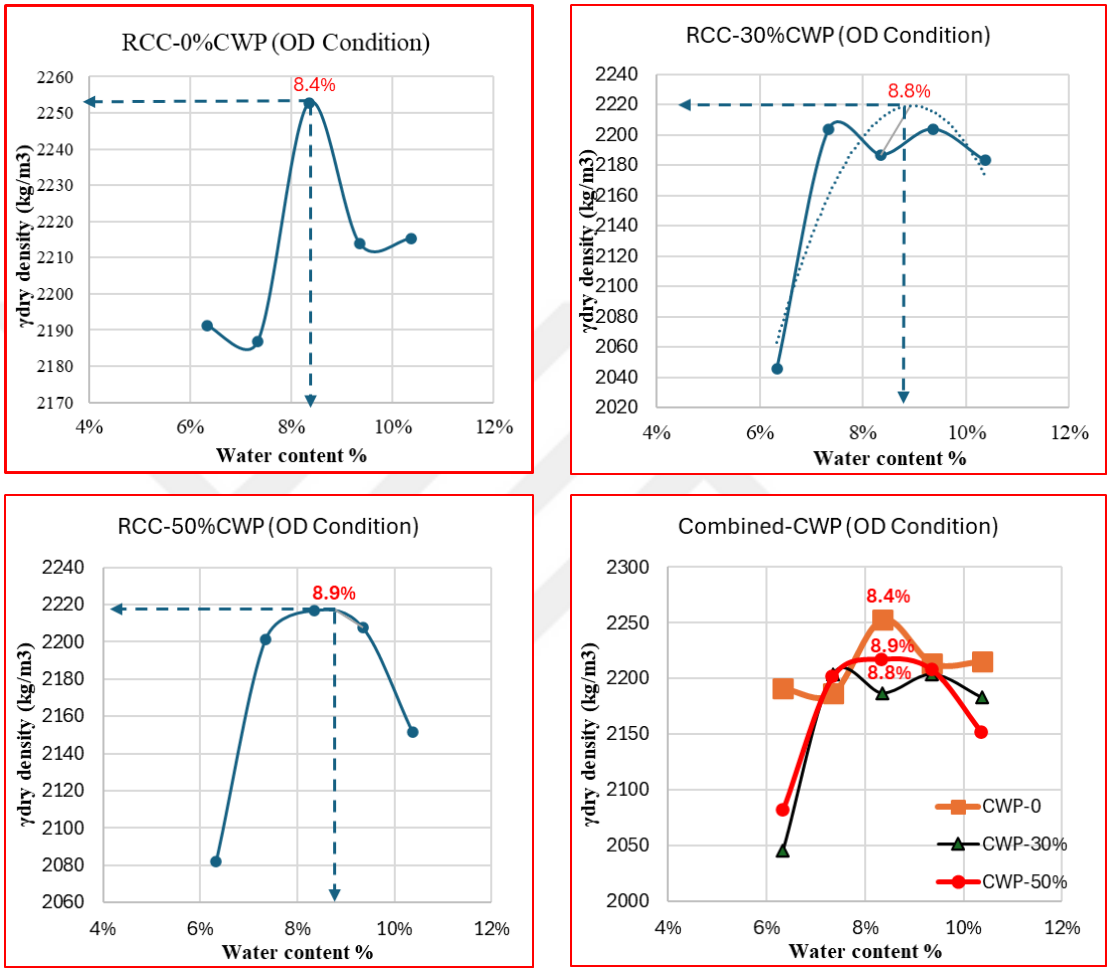


Figure 4.4 Maximum density- water content relationship for RCC-CWP-containing mixes.

4.2.1.2 Effect of RCA Content (0% CWP)

In contrast to the minimal variations observed with CWP, the incorporation of RCA employs a dominant and highly clear influence on the compaction behavior of the RCC mixtures. As illustrated in the compaction curves in Figure 4.5, increasing the RCA substitution level results in a pronounced rightward shift in the OMC and a significant downward shift in the MDD. As summarized in Table 4.3, the reference mixture achieved an MDD of 2253 kg/m3 at an OMC of 8.4%. With the introduction of 50% and

100% RCA, the moisture demand increased substantially to 9.7% and 11.2%, respectively. Compared to the reference mixture (8.4%), this represents a maximum (11.2%) increases of approximately 33% for OMC. This sharp rise in OMC is directly correlated with the high-water absorption capacity of the RCA fractions, which reaches as high as 8.74% in the finer gradations due to the presence of porous adhered mortar. This old mortar matrix necessitates significantly higher moisture levels to lubricate the aggregate particles and achieve a consolidated state during the Proctor compaction process.

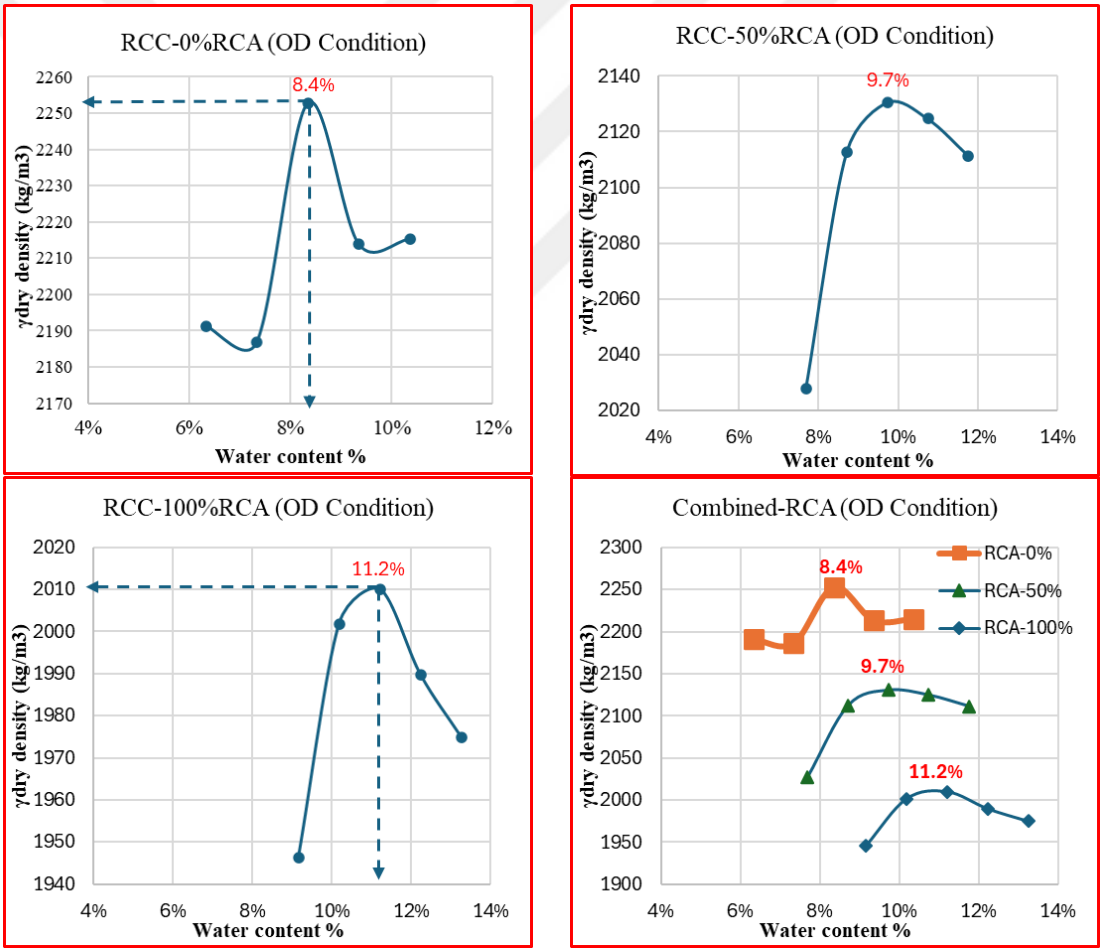


Figure 4.5 Maximum density- water content relationship for RCC-RCA mixes.

The impact on dry density is equally significant. The MDD decreased from 2253 kg/m^3 (Reference) to 2131 kg/m^3 for the 50% RCA mixture, and further to 2010 kg/m^3 for the

100% RCA formulation. This represents an approximate 11% reduction in the maximum dry density at full aggregate replacement. This decline is fundamentally driven by the lower particle density of the RCA—ranging from 2.02 to 2.37 g/cm^3 in oven-dry conditions—compared to the significantly denser natural aggregate fractions, which reach up to 2.83 g/cm^3.

4.2.1.3 Combined Effect of RCA and CWP Content

The cumulative impact of incorporating both RCA and CWP on the compaction characteristics of RCC is illustrated in the combined curves of Figure 4.6.

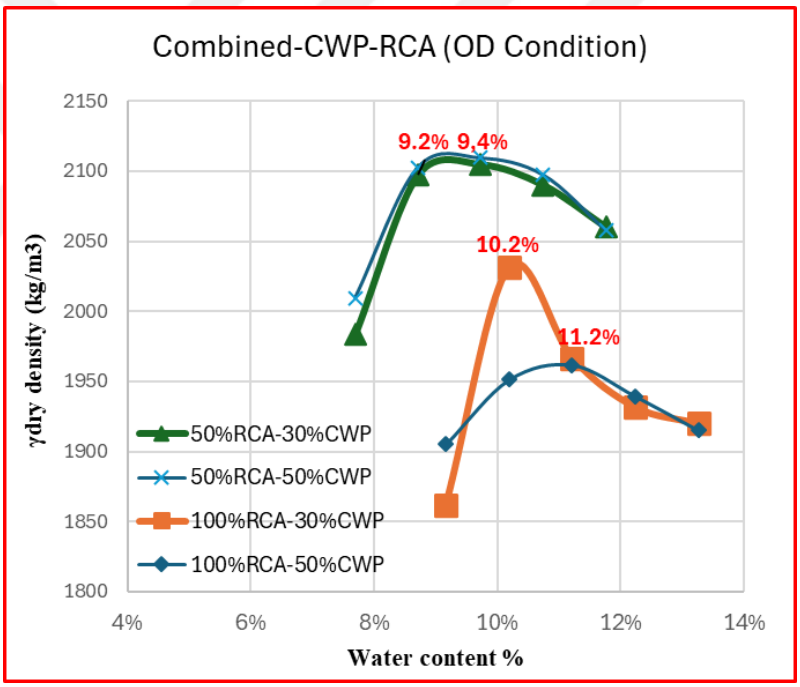


Figure 4.6 Maximum density- water content relationship for RCC-RCA-CWP mixes

The results indicate that while RCA remains the dominant factor influencing both the reduction in density and the increase in water demand, the addition of CWP further amplifies these effects, though to a more limited extent. As detailed in Table 4.3, the most significant reduction in MDD was observed in the mixture featuring 100% RCA and 50% CWP, which yielded a value of 1962 kg/m^3. Compared to the reference mixture (2253 kg/m^3), this represents an overall reduction of approximately 13%. For comparison, the use of 100% RCA alone resulted in an 11% decrease in MDD (2010

kg/m^3); the subsequent introduction of CWP contributed only an additional 2% drop in unit weight. This confirms that the density loss is primarily driven by the lower particle density of the RCA (2.02g/cm^3 for fine fractions) rather than the binder substitution.

4.2.2 Optimum Water Content Selection

Based on the compaction test results presented in Section 4.2.1, the OMC for each RCC mixture was initially identified from the peaks of the moisture-density relationship curves. To validate the practical suitability of these values for field placement and to ensure adequate workability, Vebe consistency tests were conducted on representative mixtures. A critical finding in this phase was the disparity between the OMC determined under OD and SSD aggregate conditions. While the OD moisture requirement increased significantly with recycled material substitution—ranging from 8.4% for the reference to 11.2% for the 100% RCA mixtures—the effective moisture content remained consistent when aggregate absorption was pre-compensated. As detailed in previous section, all mixtures achieved their MDD at an effective moisture content of approximately 6.5% under SSD conditions.

To confirm that this 6.5% SSD moisture level provided sufficient consolidation energy, the Vebe times were recorded and are summarized in Table 4.4. The observed increase in Vebe times is attributed to the higher internal friction and the porous nature of the recycled constituents, which demand more vibrational energy for full consolidation. However, all measured times remain within the acceptable range for RCC applications, indicating that the mixtures maintain a stiff but workable consistency.

Table 4.4 Vebe time results at selected optimum moisture content

Mix ID	RCA (%)	CWP (%)	Vebe time (s)
0% RCA – 0% CWP	0%	0%	35
0% RCA – 50% CWP	0%	50%	42
100% RCA – 0% CWP	100%	0%	47

Accordingly, the 6.5% SSD moisture content was adopted as the optimum design for all RCC mixtures in the Phase III experimental investigations.

4.3 Phase III Results: Mechanical and Durability Performance

After evaluating the RCA in Phase I for alkali–silica reactivity, which confirmed their non-reactive behavior and suitability for use in RCC mixtures, Phase II focused on determining the optimum water content for each mixture using the Proctor test and Vebe measurements, followed by the design and preparation of the mixtures based on these parameters.

The primary focus of this phase is to quantify the mechanical and durability characteristics of the mixtures. To isolate the specific influence of RCA substitution and minimize experimental variables, CWP was excluded from this stage of the investigation. Consequently, three reference mixtures featuring 0%, 50%, and 100% RCA were evaluated using the standardized effective moisture content of ~6.5% (SSD) established previously. The performance assessment encompasses a wide array of standardized tests, including density, compressive strength, ultrasonic pulse velocity, electrical resistivity, and water penetration under pressure, as well as evaluating the effects of freeze–thaw cycles, sulfate exposure, and microstructural observations.

Finally, this section provides a comparative analysis of the results to highlight the impact of varying RCA replacement levels, offering a technical basis for the viability of RCAs in sustainable RCC applications.

4.3.1 Physical and Mechanical Performance

4.3.1.1 Density and Strength Results

The fresh density results of RCC mixtures determined in accordance with ASTM C138. The reported values represent the average of 12 specimens tested for each mixture. The control mixture containing natural aggregates (0% RCA) exhibited the highest fresh density, with an average value of approximately 2.45 g/cm³. When the RCA replacement level increased to 50%, the fresh density decreased to about 2.38 g/cm³, while the mixture with 100% RCA showed the lowest fresh density, with an average value of approximately 2.28 g/cm³, corresponding to an overall reduction of approximately 7%

compared to the control mixture. This reduction in fresh density can be attributed to the lower specific gravity and higher porosity of RCAs compared to natural aggregates. The presence of adhered old mortar on RCA particles contributes to increased void content, resulting in lighter RCC mixtures. It should also be noted that the water content was reduced by approximately 22.5% in selected mixtures to maintain adequate workability. Despite this significant reduction in added water, the consistent downward trend in density confirms that the physical properties of the aggregate skeleton exert a more dominant influence on the unit weight of RCC than the variations in water dosage.

The 28-day compressive strength results of RCC mixtures were determined in accordance with EN 12390-3 and are presented in Table 4.5 and Figure 4.7.

Table 4.5 Compressive strength values of each RCC specimen

RCC-0%RCA				
NO	Age (Days)	Maximum Load (KN)	Cross-sectional Area(mm²)	Compressive Strength (Mpa)
RCC1	28	1162.3	22500	51.658
RCC2	28	1277.8	22500	56.791
RCC3	28	1134	23100	49.091
RCC4	28	1211.9	22650	53.506
RCC-50%RCA				
NO	Age (Days)	Maximum Load (KN)	Cross-sectional Area(mm²)	Compressive Strength (Mpa)
RCC1	28	1026.3	23250	44.142
RCC2	28	1144.5	22800	50.197
RCC3	28	1092.7	22650	48.243
RCC4	28	967.4	22950	42.153
RCC-100%RCA				
NO	Age (Days)	Maximum Load (KN)	Cross-sectional Area(mm²)	Compressive Strength (Mpa)
RCC1	28	1092.9	22650	48.252
RCC2	28	957.9	22950	41.739
RCC3	28	1008.5	22500	44.822
RCC4	28	924.9	22800	40.566

The reported values represent the average of four specimens tested for each mixture. The control mixture exhibited the highest compressive strength, with an average value of 53 MPa. Increasing the RCA replacement level to 50% resulted in a reduction in compressive strength to 46 MPa, corresponding to a decrease of approximately 13%

compared to the control mixture. A further increase in RCA content to 100% led to the lowest compressive strength value of 44 MPa, representing a total reduction of about 17%.

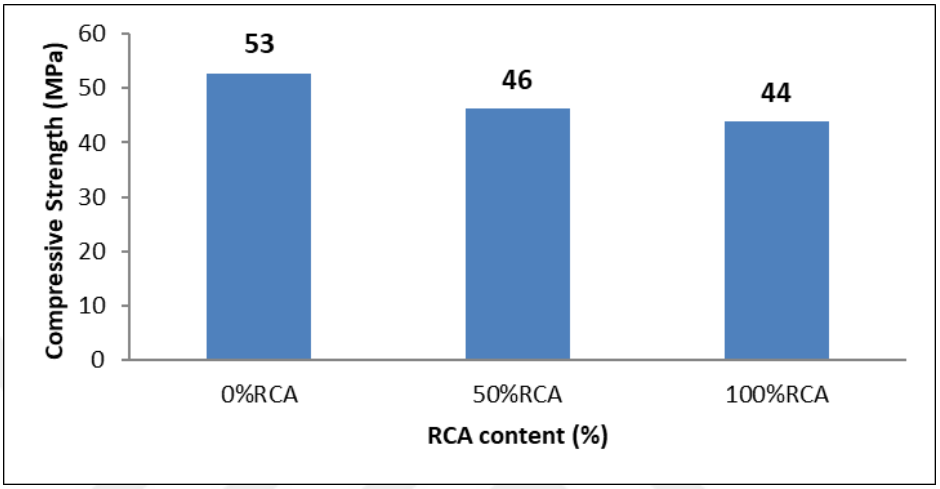


Figure 4.7 Effect of RCA content on 28-day compressive strength of RCC mixtures

The difference between the 7% loss in density and the 17% loss in compressive strength suggests that the mechanical degradation is not solely a function of mass reduction. Instead, the lower strength is likely pushed by the weaker ITZ associated with the pre-existing mortar on the RCA, which acts as a site for stress concentration and micro-crack propagation under axial loading. Nevertheless, even at 100% RCA substitution, the strength remains above 40 MPa, demonstrating that RCA-incorporated RCC can meet the structural requirements for heavy-duty pavement applications.

4.3.1.2 UPV Results

The UPV test was conducted in accordance with ASTM C597 to evaluate the internal quality and homogeneity of the RCC mixtures. The pulse velocity results, representing the average of four specimens per formulation, are summarized in Table 4.6.

The control mixture containing natural aggregates (0% RCA) exhibited the highest pulse velocity, with an average value of 5081.75 m/s, indicating a dense microstructure and good material continuity. When the RCA substitution level increased to 50%, the velocity decreased significantly to 4268.25 m/s. This drop is primarily attributed to the

increased internal heterogeneity and higher porosity inherent to RCAs, specifically the micro-cracks and capillary voids within the adhered old mortar.

For the mixture incorporating 100% RCA, the UPV value was 4283.25 m/s, which is slightly higher than that of the 50% RCA mixture but still clearly lower than the control mixture. This behavior may be attributed to variations in aggregate packing, compaction efficiency, and the distribution of adhered old mortar on RCA particles.

Table 4.6 UPV results of RCC specimens.

RCC-0%RCA			RCC-50%RCA			RCC-100%RCA		
No	Path Length (mm)	Pulse Velocity (km/s)	No	Path Length (mm)	Pulse Velocity (km/s)	No	Path Length (mm)	Pulse Velocity (km/s)
1	150	5169	1	150	3427	1	150	4182
2	150	5137	2	150	4438	2	150	4297
3	150	5007	3	150	4578	3	150	4323
4	150	5014	4	150	4630	4	150	4331
	Average	5081.75		Average	4268.25		Average	4283.25

Based on the general classification of concrete quality, the control mixture (> 4.5 km/s) can be categorized as "Excellent," while the RCA-incorporated mixtures, falling within the 3.5–4.5 km/s range, are classified as being of "Good" quality.

4.3.2 Durability Performance

4.3.2.1 Electrical Resistivity Test Results

The electrical resistivity test was conducted in accordance with AASHTO T 358 to assess the durability-related performance of the RCC mixtures. The electrical resistivity results of the RCC mixtures at 28 days are presented in Table 4.7 and illustrated in Figure 4.8. The reported values represent the average of twelve specimens tested for each mixture. Electrical resistivity is a key indicator of the concrete's pore structure and its resistance to ionic transport and is therefore closely related to durability performance.

Table 4.7 Electrical Resistivity of RCC specimens.

RCC-0%RCA			RCC-50%RCA			RCC-100%RCA		
No	Age (Days)	Average Resistivity (kΩ·cm)	No	Age (Days)	Average Resistivity (kΩ·cm)	No	Age (Days)	Average Resistivity (kΩ·cm)
1	28	11.5	1	28	9.8	1	28	8.6
2	28	11.4	2	28	9.6	2	28	7.4
3	28	10.8	3	28	9.1	3	28	7.9
4	28	11	4	28	9.2	4	28	7.5
5	28	22.3	5	28	9.7	5	28	7.6
6	28	21.1	6	28	10.2	6	28	7.7
7	28	19.1	7	28	9.6	7	28	7.6
8	28	19.8	8	28	9.7	8	28	7.1
9	28	14.4	9	28	13.7	9	28	12.2
10	28	12	10	28	14.3	10	28	12
11	28	11.3	11	28	13.3	11	28	9.6
12	28	12.1	12	28	13.9	12	28	10.6

The control mixture (0% RCA) exhibited the highest electrical resistivity with an average value of 14.73 kΩ·cm. Based on AASHTO T 358 [34] criteria, this value classifies the control RCC as having "Moderate" chloride ion permeability, indicating a relatively continuous pore network typical of zero-slump mixtures. As the RCA replacement level increased to 50%, the resistivity decreased to 11 kΩ·cm and further dropped to 8.82 kΩ·cm for the 100% RCA mixture.

As the RCA replacement level increased to 50%, the resistivity decreased to 11 kΩ·cm. While this remains within the "Moderate" category (9.5 - 16.5 kΩ·cm), it is critically close to the high-permeability threshold, suggesting that even partial substitution of natural aggregates significantly enhances the continuity of the internal pore network. A further reduction was observed for the mixture incorporating 100% RCA, which recorded a resistivity of 8.82 kΩ·cm. This value officially falls into the "High" chloride ion penetrability range (< 9.5 kΩ·cm), a transition driven by the porous nature of the adhered old mortar and the high-water absorption capacity of the recycled fractions.

Overall, the observed reduction in electrical resistivity with increasing RCA content is consistent with the trends observed in fresh density, compressive strength, and UPV results. These findings indicate that while higher RCA contents may negatively influence durability-related properties due to increased permeability, the measured resistivity values remain within acceptable ranges for RCC applications, suggesting that the mixtures can still be considered suitable for practical use under controlled conditions.

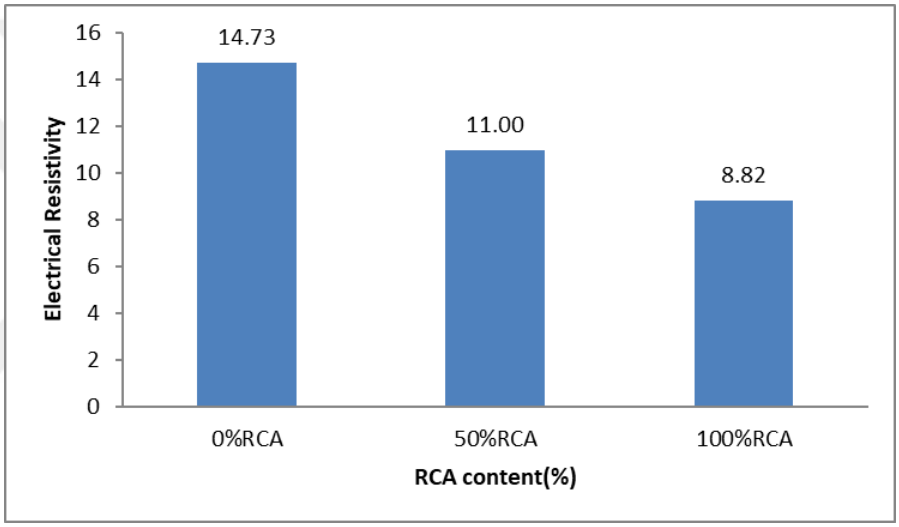


Figure 4.8 Effect of RCA content on average electrical resistivity of RCC mixtures at 28 days

4.3.2.2 Water Penetration Test Results

The resistance of the RCC mixtures to pressurized water ingress was evaluated in accordance with EN 12390-8. This test serves as a critical indicator of the permeability and potential durability of the concrete matrix under hydraulic pressure. Typical cross-sections of the split specimens, illustrating the water penetration fronts for various RCA replacement levels, are displayed in Figure 4.9. The quantitative results, representing the average of two specimens per mixture, are summarized in Figure 4.10. Furthermore, following the water pressure application, splitting tensile tests were performed to evaluate the residual mechanical integrity of the saturated specimens.

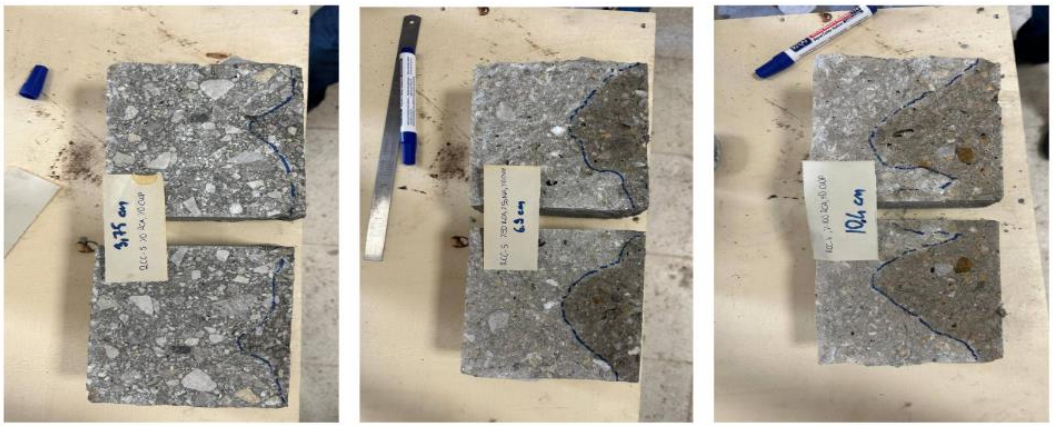


Figure 4.9 Representative photos on water penetration depth of some RCC specimens

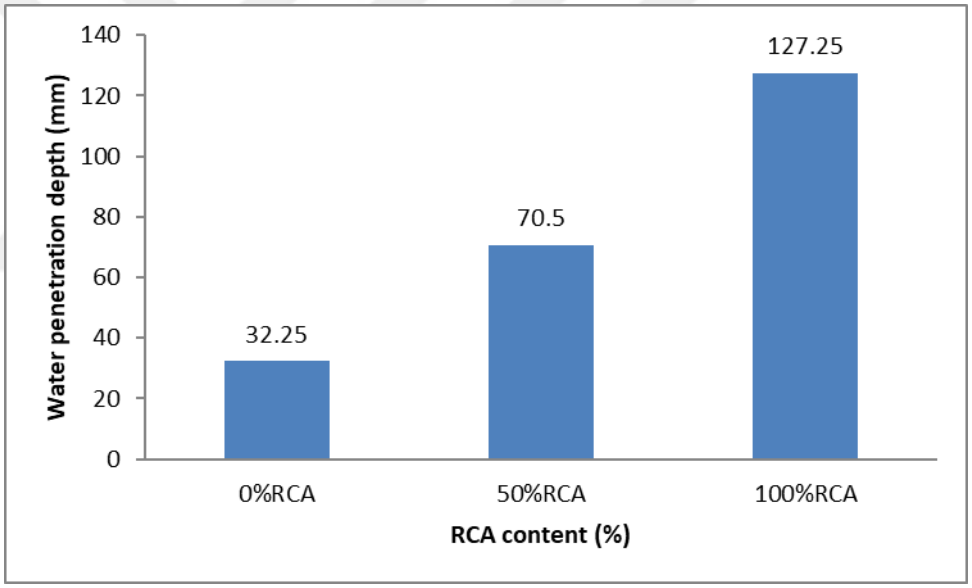


Figure 4.10 Effect of RCA content on average water penetration depth of specimens

The control mixture (0% RCA), composed entirely of natural aggregates, demonstrated the most robust resistance to water ingress, with a mean penetration depth of 32.25 mm. This performance is indicative of a relatively dense microstructure and a well-developed ITZ, which limits the connectivity of the capillary pore network. The corresponding splitting tensile strength was recorded as 3.66 MPa.

The introduction of RCA had a significantly detrimental effect on permeability-related properties. For 50% RCA replacement, the penetration depth increased significantly to

70.5 mm (a 118% increase relative to the control), while the splitting tensile strength dropped to 2.06 MPa. This shift reflects the increased tortuosity and higher effective porosity introduced by the recycled components. For 100% RCA replacement, the most pronounced reduction in durability performance was observed at full replacement, where the penetration depth reached 127.25 (~4 times higher to control) mm and the splitting tensile strength diminished to 1.71 MPa.

The substantial increase in water ingress with higher RCA content can be attributed to several factors:

- The presence of old, porous mortar attached to the RCA particles acts as a preferential pathway for water migration.
- Unlike conventional concrete, RCA-incorporated RCC contains "double ITZs" (one between the old mortar and the original aggregate, and another between the new paste and the RCA), which are often the weakest and most permeable regions of the matrix.
- The crushing process used to produce RCA often induces micro-fissures within the aggregate particles, further facilitating capillary suction and pressure-driven flow.

These findings are highly consistent with the previously discussed trends in UPV, electrical resistivity, and compressive strength. The high correlation between these parameters confirms that the increased RCA content leads to a more interconnected pore structure. While the use of RCA at moderate replacement levels remains viable for RCC applications with lenient permeability requirements, high replacement levels (e.g., 100%) may necessitate additional measures—such as a lower water-cement ratio or the use of mineral admixtures—to ensure long-term durability in hydraulic environments.

4.3.2.3 Sulfate Attack Resistance Test Results

The mass change of the specimens after sulphate exposure is shown in Figure 4.11. As shown in the figure, an increase in mass was observed for all mixtures with increasing sulfate exposure time. The highest mass gain occurred in the mixture containing 100%

RCA, followed by the 50% RCA and 0% RCA mixtures. This trend can be attributed to the more open and interconnected pore structure associated with higher RCA contents, which facilitates the ingress of sulfate ions into the internal structure, and promoting the generation of reaction products.

It should be noted that the mass increase observed at the early stages of sulfate exposure may represent a transient phase related to the formation of secondary reaction products. Therefore, to achieve a more comprehensive evaluation of sulfate resistance and long-term durability, tests with longer exposure durations should be conducted.

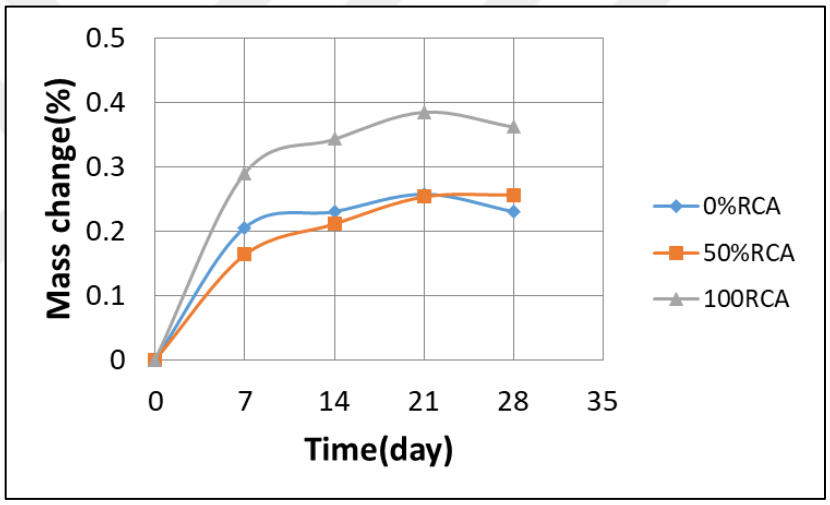


Figure 4.11 The mass change of the specimens subjected to sulphate attack

4.3.2.4 Freeze–Thaw Resistance Test Results

The mass change of the specimens after freeze–thaw cycles is shown in Figure 4.12. As shown in figure, the mass loss of the specimens increased progressively with freeze–thaw exposure time for all mixtures. However, a clear dependence on the RCA replacement ratio can be observed.

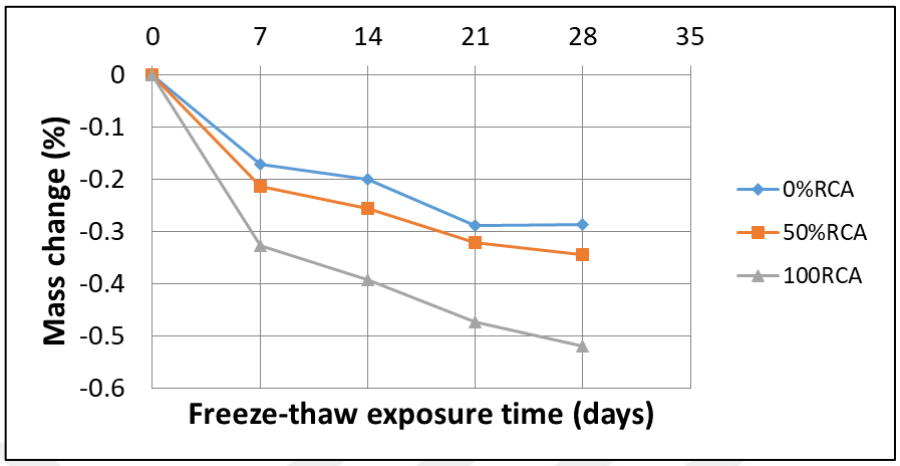


Figure 4.12 The mass change of the specimens subjected to freeze–thaw cycles.

The control mixture (0% RCA) exhibited the lowest mass loss throughout the test period, remaining below approximately ~−0.30% even after 28 days of freeze–thaw cycling. The mixture containing 50% RCA showed moderately higher mass loss values, indicating a slight reduction in freeze–thaw resistance compared to the control mixture (0% RCA). In contrast, the mixture containing 100% RCA experienced the most pronounced mass loss, reaching about ~−0.55% at the end of the exposure period. The steeper mass-loss trend observed for higher RCA contents suggests that increasing RCA replacement adversely affects freeze–thaw durability. This behavior can be attributed to the higher porosity, increased water absorption, and weaker interfacial transition zones associated with RCA particles, which make the material more susceptible to internal damage under repeated freezing and thawing. Overall, Figure 4.12 demonstrates that partial RCA replacement (50%) leads to acceptable but reduced durability, while full replacement (100% RCA) significantly compromises resistance to freeze–thaw action. Nevertheless, it should be noted that more meaningful and comprehensive conclusions could be drawn by conducting freeze–thaw tests over longer exposure durations, which would allow a clearer assessment of long-term durability and damage evolution mechanisms.

4.3.2.5 Micro-CT Test Results

Micro-CT test was employed to investigate the internal microstructural characteristics of the specimens containing different RCA replacement ratios. Representative cross-sectional images taken from the beginning, middle, and end regions of each specimen are presented in Figure 4.13 for mixtures incorporating 0%, 50%, and 100% RCA.

The control specimen (0% RCA) exhibits a relatively dense and homogeneous internal structure throughout the specimen length, with limited pore presence and a well-integrated aggregate–matrix interface. In contrast, the incorporation of RCA leads to a progressive increase in visible pores and structural heterogeneity. The 50% RCA-containing mixture shows a more irregular internal structure, while the 100% RCA mixture presents the highest pore density and the most pronounced heterogeneity across all sections.

Notably, mixtures containing RCA display a more distinct and discontinuous interfacial transition zone (ITZ) due to the presence of adhered old mortar on RCAs. This weaker and more porous ITZ facilitates crack initiation and pore connectivity, contributing to increased transport pathways within the material. These microstructural characteristics are consistently observed along the specimen length, although slightly higher void concentrations are evident in the middle and end sections for higher RCA contents.

Overall, the Micro-CT observations confirm that increasing RCA replacement adversely affects internal structural continuity, primarily through the development of a more porous ITZ and interconnected pore network, which helps explain the durability trends observed in the accompanying experimental results.

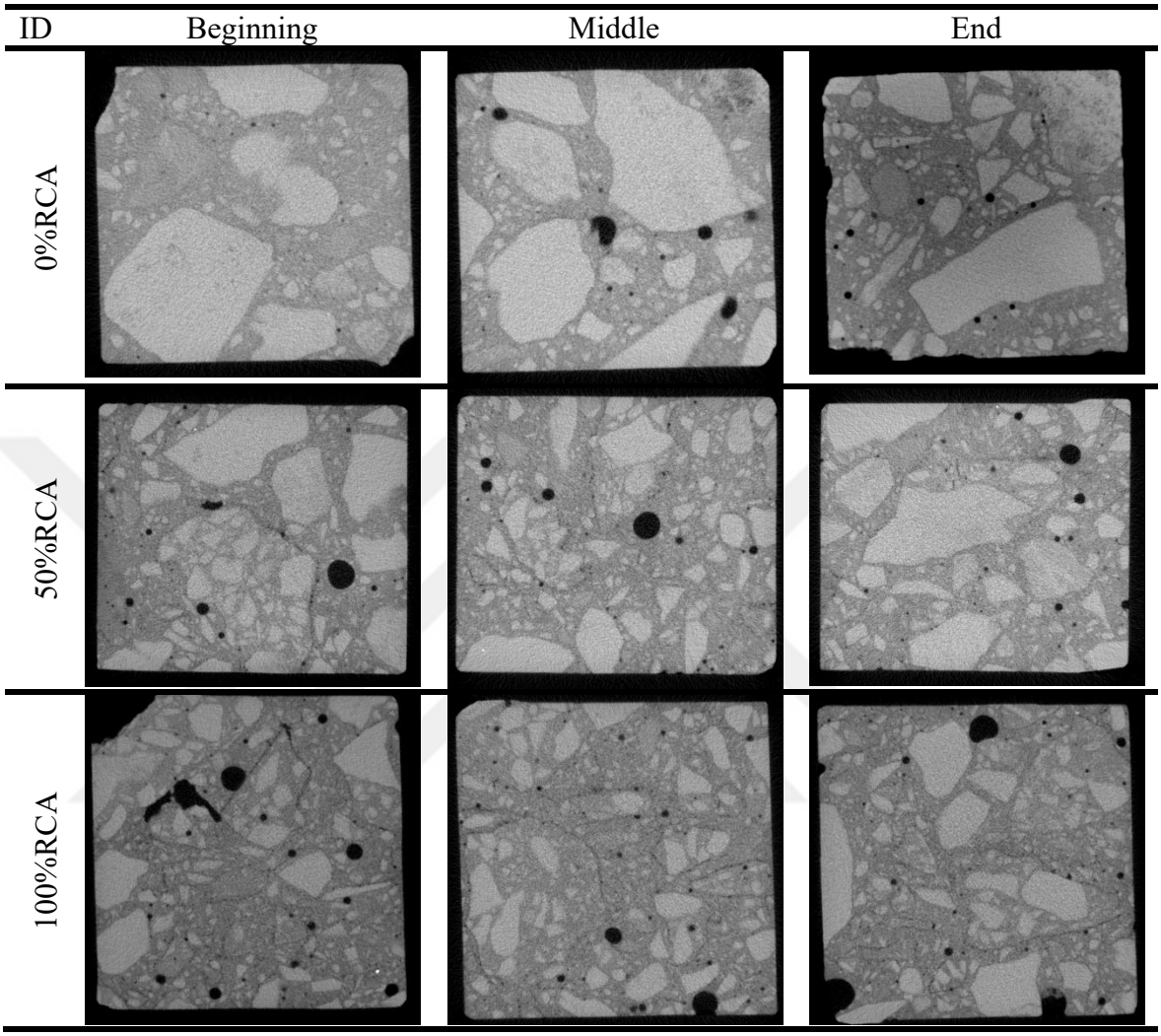


Figure 4.13 Micro-CT cross-sectional images taken from the beginning, middle, and end regions of the specimens

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This research provided a multi-phased investigation into the performance of RCC incorporating demolition waste recycle aggregates.

In Phase I, RCA characterization and ASR evaluation were conducted to determine the suitability of recycled aggregates for RCC applications. Physical and mechanical tests indicated that RCA met the general requirements for use in concrete, although higher water absorption was observed due to adhered mortar. ASR testing revealed that all mixtures remained below the expansion limit defined by ASTM C1260, indicating non-reactive behavior. While higher RCA contents slightly increased expansion, the values stayed well within acceptable limits.

Phase II focused on mix design optimization, particularly identifying the optimum water content for RCC mixtures. Compaction tests and Vebe measurements showed that RCA content had a dominant influence on compaction behavior, as mixtures with higher RCA showed lower maximum dry density and required higher water content to achieve adequate workability. The combination of compaction curves and Vebe results allowed determination of suitable water content for each mixture, ensuring proper placement and initial stiffness for RCC.

In Phase III, the performance of RCC mixtures containing varying levels of RCA was assessed, focusing on mechanical properties, durability indicators, and permeability. Density and 28-day compressive strength decreased progressively with increasing RCA content, reflecting the lower specific gravity, higher porosity, and presence of adhered mortar in RCA. UPV tests indicated reduced homogeneity with higher RCA content, while electrical resistivity and water penetration tests highlighted increased permeability associated with recycled aggregates. Despite these reductions, mixtures with moderate RCA replacement exhibited satisfactory performance suitable for RCC applications.

Overall, the findings demonstrate that RCA can replace natural coarse aggregates effectively, provided that moisture control and compaction are carefully managed.

The experimental results and analytical evaluations lead to the following significant conclusions:

- RCA exhibited higher water absorption and lower specific gravity compared to natural aggregates, primarily due to the presence of porous adhered mortar.
- According to ASTM C1260 criteria, all investigated mixtures non-reactive behavior.
- The use of CWP (up to 30%) acted as a micro-filler, enhancing the particle packing density and improving the lubrication of the aggregate skeleton during compaction. At 50% replacement, CWP increased the specific surface area significantly, leading to higher water demand and a subsequent reduction in the MDD.
- RCA content was the primary driver of moisture sensitivity. The higher porosity and initial suction of the recycled aggregates required significant adjustments to the OMC.
- The OMC reached a maximum of 11.2% in the 100%-RCA mixtures, representing a 33% relative increase compared to the reference mixture (8.4%). In contrast, the MDD exhibited a reduction of approximately 13% relative to the control.
- Although a progressive decline in compressive and splitting tensile strength was observed with increasing RCA content, even at 100% RCA substitution, the mixtures achieved a 28-day compressive strength exceeding 40 MPa (cube specimens).
- A direct correlation was established between RCA content and depth of water ingress. The 100% RCA mixtures showed a significant increase in permeability (up to 127.25 mm), reflecting a highly interconnected capillary pore system.

- The reduction in UPV and electrical resistivity further validates that RCA introduces higher effective porosity into the RCC matrix.

In conclusion, although the 100% RCA mixtures achieved a remarkable compressive strength exceeding 40 MPa with a cement dosage of 350 kg/m³ -a result that underscores the significant structural potential for high-volume recycled aggregate utilization within the Turkish construction sector, the corresponding durability performance needs a more conservative application strategy. While these mechanical results demonstrate that recycled materials can meet structural requirements, the durability analysis, particularly the electrical resistivity and pressurized water penetration tests, categorized the 100% RCA mixtures within a moderate-high permeability range, indicating potential risks for long-term serviceability. Consequently, to ensure structural integrity and maintain a safety margin against environmental degradation, a 50% RCA replacement level can be recommended as the optimal threshold for RCC pavements. In a country like Türkiye, where the volume of construction and demolition waste is exceptionally high due to mandatory urban renewal and post-earthquake reconstruction efforts, the strategic evaluation of this potential by the General Directorate of Highways, municipalities, and special provincial administrations is of paramount importance for promoting a sustainable circular economy and effective resource management.

Limitations and future work**:** The current conclusions are based on short-term laboratory tests. Long-term durability aspects, including freeze–thaw cycles, sulfate exposure, and detailed microstructural analysis were not yet included and should be addressed in future studies to provide a comprehensive assessment. Additionally, the source and quality of RCA may influence performance, and further research is recommended to optimize mix proportions for large-scale field applications.

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