MECHANICAL PROPERTIES OF GREEN RECYCLED AGGREGATE CONCRETE USING CONSTRUCTION AND DEMOLITION WASTE IN SAUDI ARABIA

BY

Abdulrahman Hasan Zaben

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This thesis, written by Abdulrahman Hasan Zaben under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING.

Dr. Salah U. Al-Dulaijan
(Advisor)

Dr. Salah U. Al-Dulaijan
Department Chairman

Prof. Mohammed Maslehuddin
(Member)

Prof. Salam A. Zummo
Dean of Graduate Studies

عمادة الدراسات العليا

DEANSHIP OF GRADUATE STUDIES

Prof. Omar S. Baghabra Al-Amoudi
(Member)

13/1/17

Date

This work is dedicated to my parents and all my family, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to accomplish

May Allah bless them in this life and in the hereafter

ACKNOWLEDGMENTS

First of all, I thank Allah for all the blessings, and for bestowing me the patience, knowledge and courage to complete this work.

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LIST OF ABBREVIATIONS

RA	:	Recycled Aggregate
RAC	:	Recycled Aggregate Concrete
RCA	:	Recycled Concrete Aggregate
RC	:	Recycled Concrete
RFA	:	Recycled Fine Aggregate
NA	:	Normal Aggregate
NAC	:	Normal Aggregate Concrete
FA	:	Fine Aggregate
CDW	:	Construction and Demolition Wastes
SP	:	Super Plasticizer
w/c	:	water/cement ratio
SEM	:	Scanning Electron Microscopy
KSA	:	Kingdom of Saudi Arabia
ITZ	:	Interfacial Transition Zone

ABSTRACT

Full Name : Abdulrahman Hasan Izzat Zaben

Thesis Title : Mechanical Properties of Green Recycled Aggregate Concrete Using Construction and Demolition Waste in Saudi Arabia

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The use of demolished concrete as a recycled aggregate (RA) to create recycled aggregate concrete (RAC) is a viable option to conserve the natural aggregate resources and to reduce the load in the landfills. The use of RAC in Saudi Arabia would be a good eco-friendly approach as there are huge quantities of demolished concrete, which are disposed of to landfills every year and as the sources if good natural aggregates are depleting. This study focused on the evaluation of the mechanical properties of RAC produced using local RA. Three series of concrete mixtures were prepared with different RA replacement levels.

The mechanical properties of RAC decreased with the incorporation of RA in a linear manner with increasing RA content. When full replacement of RA was used, the compressive strength, modulus of elasticity, splitting tensile, modulus of rupture and bond strength decreased by 40%, 42%, 37%, 33% and 55%, respectively, of the natural aggregate concrete. The incorporation of RA in concrete resulted in a small or negligible decrease in the abrasion resistance of RAC, while it resulted in a considerable increase in the drying shrinkage.

The preferable ranges of RA in RAC that can be beneficially utilized are about 20% in the concrete mixtures with low cement content, and 40% in the concrete mixtures with medium and high cement content.

ملخص الرسالة

الاسم الكامل: عبدالرحمن حسن عزت زبن

عنوان الرسالة: الخصائص الميكانيكية لخرسانة الركام معاد التدوير الخضراء و المنتجة من نفايات الابنية والهدم في المملكة العربية السعودية.

التخصص: الهندسة المدنية (الانشائية)

تاريخ الدرجة العلمية: يناير 2017م

يعتبراستخدام خرسانة المباني القديمة المهدمة كركام معاد التدوير لانتاج خرسانة الركام معاد التدوير (RAC) الخيارالحيوي للحفاظ على موارد الركام الطبيعية ولتقليل الحمل في مكبات النفايات. ان استخدام خرسانة الركام معاد التدوير (RAC) في المملكة سيكون نهج اقتصادي وصديق للبيئة لأنّ هناك كميات ضخمة من الخرسانة المهدمة التي يتم التخلص منها في مكبات النفايات سنوياً. ركزت هذه الدراسة على تقييم الخواص الميكانيكية لخرسانة الركام معاد التدوير (RAC) المنتجة باستخدام الركام المعاد تدويره محلياً. وتم اعداد ثلاث مجموعات من الخلطات الخرسانية بمستويات استبدال مختلفة من الركام المعاد تدويره لكل خلطة.

أشارت نتائج هذه الدراسة إلى أن الأداء الميكانيكي لخرسانة الركام معاد التدوير المتصلبة تدهورت بسبب اضافة الركام المعاد التدوير بطريقة متناسبة خطيا مع زيادة محتوى الركام المعاد التدوير. وعندما تم استبدال كامل الركام بركام معاد التدوير فقد انخفضت قوة الضغط، ومعامل المرونة، وقوة الفلق، ومعامل التمزق والسندات وقوة الترابط انخفضت بنسبة 40٪، 42٪، 37٪، 33٪ و55٪، على التوالي. وقد أدى اندماج الركام المعاد التدوير في الخرسانة إلى انخفاض طفيف أو تافه لمقاومة التآكل في خرسانة الركام معاد التدوير، في حين أنه أدى إلى زيادة كبيرة في انكماش التجفيف.

اظهرت نتائج هذه الدراسة أن النسب المفضلة من الركام معاد التدوير التي تسببت بانخفاض مقبول في نوعية الخرسانة، هي حوالي 20٪ من مجموع الركام الخشن في الخلطات الخرسانة التي تحتوي كمية اسمنت منخفضة، و40٪ من مجموع الركام الخشن في الخلطات الخرسانية التي تحتوي كمية اسمنت متوسطة ومرتفعة.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Since natural aggregate sources are decreasing at a rapid pace due to few available alternatives and increasing infrastructure needs, recycled aggregate concrete (RAC) is a viable option to conserve the natural resources. The use of RAC has major advantages, such as reduced use of virgin aggregates, reduced load on the landfill, transportation and environmental costs [1]. Other than concrete, construction and demolition wastes (CDW) include: bricks and blocks, tiles, glass, paint, asphalt shingles, gypsum board, wood, insulation, plastic, steel, cardboards, etc., most of which are disposed-off in landfill sites due to the absence of markets for their recycled forms. Many cities have been suffering from the scarcity of available land spaces, however, the rates of land filling have recently been increasing, which is expected to continue in the foreseeable future [2]. That is why the reuse/recycle potential of CDW has been recognized, though it is not yet fully utilized.

Over the last few years, a great attention has been given to sustainable construction in many countries. Japan, Netherland and Denmark are considered the most successful countries in recycling where the recycling rate reached to 65%, 75% and 80%, respectively [3]. These high recycling rates can be attributed to the quality of the finished new products using recycled CDW. In order to reach a similar good recycling rate in Saudi Arabia, a comprehensive plan must exist and be implemented.

The reuse of CDW is considered one of the challenges for Saudi Arabia. Such reuse must provide a sustainable solution in construction practices for the betterment of Saudi environment. Such on activity will consider using materials that are commonly found in the local landfills as a replacement for coarse aggregate in concrete, and it will produce green and sustainable concrete. "Concrete, which makes up to 52% of all CDW, is the most commonly used construction material in the world" [4]. "Natural resources can be preserved and landfill use can be reduced by using recycled aggregate (RA) for producing new concrete" [4].

The Arabian Gulf is one of the regions where there is a boom in the construction industry. This industry has grown very rapidly during the last 40 years with further potential of development. However, recent reports indicated that illegal dumping of waste from construction industry has destroyed much of Bahrain’s marine life [5]. Saudi Green Building Council (SGBC) also suggested introducing mandatory waste disposal regulations as well as recycling and reusing of the C&D wastes [6]. Abu Dhabi and Kuwait have already started to utilize their C&D waste, such as Masdar’s project in Abu Dhabi recycled 98 percent of its construction waste, while another firm, turned CDW into aggregate for roads [6]. Health, Safety and Environment Monitoring Sector of the Dubai Municipality also emphasized on the need to reconsider the specifications of building materials to increase the possibility of using recycled materials in concrete [7].

1.2 NEED FOR THIS RESEARCH

Although considerable research has been carried out on the mechanical properties and durability of RAC under normal and cold weather exposure conditions, no research has been directed on the mechanical properties of RAC under the local ambient conditions and by using local materials. Since the aggregates in the Arabian Gulf region is mainly weak limestone, it is necessary to assess the properties of resulting concrete. Therefore, in this study, the mechanical properties of recycled aggregate concretes produced using the local recycled aggregates were studied. The outcome of this study is expected to be beneficial to the local construction industry and would be helpful in updating the local construction codes of practices.

1.3 THESIS OBJECTIVE

The overall objective of this study was to assess the possibility of using recycled aggregates in the production of concrete. The specific objectives are the following:

i. Evaluate the mechanical properties of RAC produced by using local recycled aggregates,
ii. Model the mechanical properties of RAC using statistical modeling approach, and
iii. Provide recommendations on the optimum proportions of recycled coarse aggregates for the production of RAC with acceptable mechanical properties.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Every year, a tremendous volume of aggregate is required in the construction sector in Saudi Arabia and the other Arabian Gulf countries to prepare concrete for new buildings, pavements, public facilities and other infrastructures. These aggregates have significant influence on concrete properties, and many problems may be developed if there is any depletion on the good quality aggregate resources. That is why it is crucial to develop new sources of good aggregates with low cost and less consumption of the future generation resources to fulfill the increasing human needs. Using recycled aggregates may serve as a great alternative to help in solving this problem.

This study attempted to develop sustainable concrete mixtures that achieve the main requirements in the Arabian Gulf area, utilizing the construction and demolition waste in Saudi Arabia as a recycled aggregate (RA). This part of the study will focus on the mechanical properties development of the RAC, and the second complimentary part paid more attention on developing the desired durability and to reducing the environmental deterioration of the RAC [8].

A brief review of literature on the use of RA in concrete is provided in the following sub-sections.

2.2 PROPERTIES OF RECYCLED AGGREGATE

Throughout the last two decades, many studies were conducted to examine the properties of recycled concrete aggregate (RCA) produced using the current state of the art concrete recycling technology. In the following review, the results of the previous studies on different properties of RA including the density, water absorption, toughness and soundness as well as the effect of various production parameters including the type of the crushing process, particle size of aggregates on the properties of RAC are reported.

Physical and mechanical properties of RAC with recycled fine and recycled coarse aggregates are usually inferior to that of RAC with virgin fine and recycled coarse aggregates. Therefore, the utilization of fine recycled aggregate in RAC for structural use is generally not recommended because of the high cohesion and high water absorption of fine RA which makes it very difficult to control the concrete quality [9].

The findings of some reported studies on the properties of RA, compared to natural aggregate (NA), are summarized in Table 2.1.

Table 2.1: Properties of Recycled Aggregate (RA) Compared to Natural Aggregate (NA).

Property	RA compared to NA	References
Density	Lower density	Topcu and Şengel [10]
Absorption Capacity	Higher	Topcu and Şengel [10], Hassanean, Rashwan et al. [11].
Toughness (Abrasion and Impact Resistance)	30% more abrasion losses.	Tabsh and Abdelfatah. [12], Bravo, de Brito et al. [13]
Soundness	More prone to soundness problem	Tabsh and Abdelfatah [12]

2.3 PROPERTIES OF RECYCLED AGGREGATE CONCRETE

Recycling of concrete is mandatory for sustainability and preservation of natural resources. So far, there have been many studies on the mechanical properties of RAC all over the world, and some basic conclusions have been achieved. In order to review the related earlier research, a comprehensive literature review on issues related to this research study was carried out. The outcome of the survey is presented in the following paragraphs:

Katz [14] studied the effect of recycled aggregate from partially-hydrated old concrete on the properties of new concrete made with these aggregates. He reported that the concrete made of 100% RA suffered a strength reduction of up to 25% when using the same w/c ratio regardless of the crushing age of old concrete. The splitting tensile, flexural strength and drying shrinkage exhibited a similar trend.

Topcu and Sengel [15] investigated the mechanical properties of RAC along with freeze-thaw resistance. They prepared a set of mixes with recycled aggregate in amounts of 30%, 50%, 70%, and 100%. It was reported that the specific gravity of RAC was lower than that of NAC and the water absorption was higher. They also reported that the compressive strength decreased in proportion to the RA content. The major point reported was the workability problem, where the maximum proportion of RA in the mix cannot exceed 30% to maintain the same slump without the use of admixture, and increase this proportion will affect the quality and strength of RAC.

Corinaldesi [16] performed an investigation to study the mechanical behavior and modulus of elasticity of RAC. He prepared several mixes by using two different recycled aggregate fractions “Coarse and finer coarse” with five different w/c ratios (0.4, 0.45, 0.5, 0.55 and 0.6) and 30% replacement of RA for both fractions. The results indicated that 30% replacement of NA by RA can give a structural concrete up to C32/40 strength class (about 32 MPa) with 15% lower modulus of elasticity and lower shrinkage strain, especially for earlier curing time.

Butter and West [17] performed a study to test the influence of using RA on the bond strength between the RAC and reinforcing steel. They used two types of RA with different absorption percentages (3.98% and 5.76%) and different properties. Two different concrete mixes were developed. Beam-end specimens were used to determine the bond strength, as shown in Figure 2.1. It was reported that the bond strength of RAC was 9 to 19% less than that of normal concrete. However, it seemed that the aggregate crushing value and bond strength correlate well for all concrete types.

Fazl and Razaqpur [18] investigated the effects of RA on the drying shrinkage and creep of concrete using a new mixture method called Equivalent Mortar Volume (EMV). In this method, the RCA mix was adjusted to have the same volume of virgin aggregate and total mortar of the reference new aggregate, this is based on the treatment of RCA as two component composite material which consists of natural aggregate and residual mortar. The results of laboratory tests showed that the drying shrinkage and creep of RAC proportioned by the EMV method are comparable or a little lower than that of NAC.

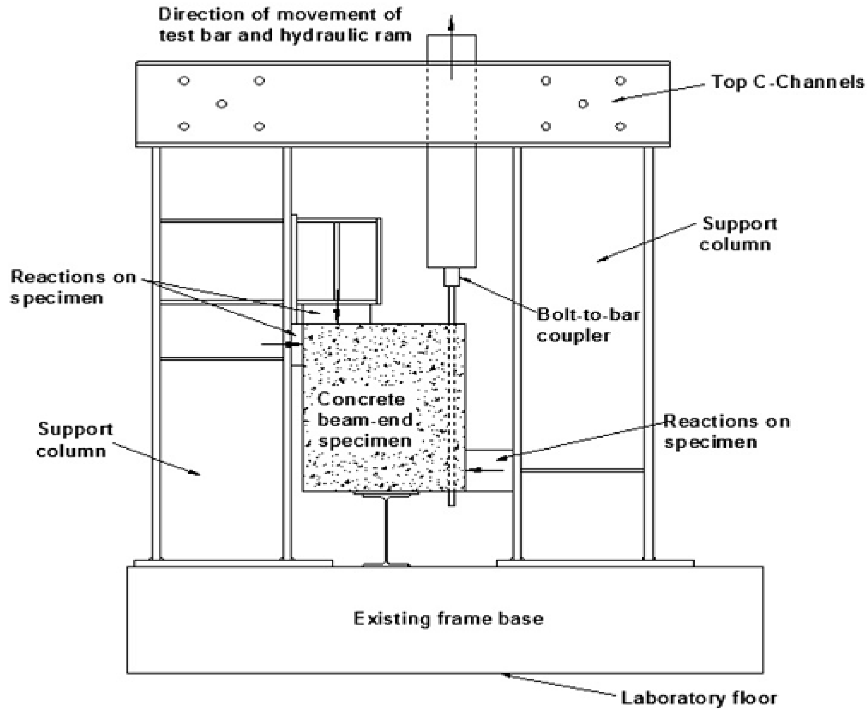

Figure 2.1: Schematic representation of bond test setup [17].

Pereira and Evangelista [19] set out a research to limit the disadvantages of using fine recycled concrete aggregate on the performance of concrete through the use of superplasticizer. They tested the workability, density and compressive strength of concrete mixes with and without superplasticizer for different ratios of replacement (0%, 10%, 30%, 50%, and 100%) of normal fine aggregate by recycled fine aggregate (RFA). They reported that it is possible to produce concrete with small percentages of RFA with acceptable quality for structural use by using efficient superplasticizer to contribute for high water demand of RFA.

Qasrawi and Marie [20] carried out experiments to test the effect of using recycled aggregate on the basic properties of normal concrete. Results of partial and full replacement of NA by RA showed that the compressive strength decreased by 5% to 25%

depending on the percentage of replacement. Also, the tensile strength decreased but by lower amount compared to the compressive strength. The authors reported that the use of RA has an adverse effect on the workability of concrete that can be easily retained by using superplasticizer (See Figures 2.2 through 2.4).

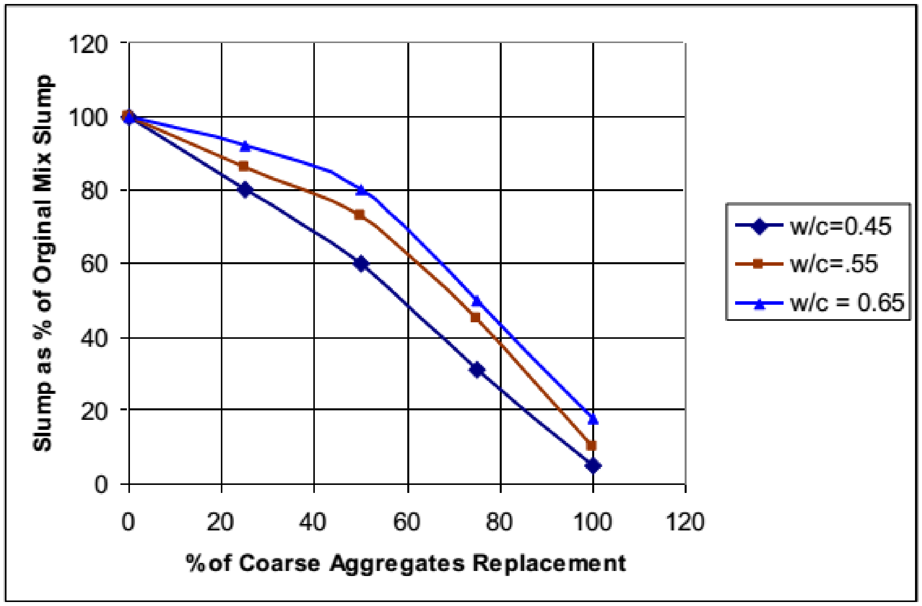

Figure 2.2: Relationship between concrete slump and percentage of replacement of RA [20].

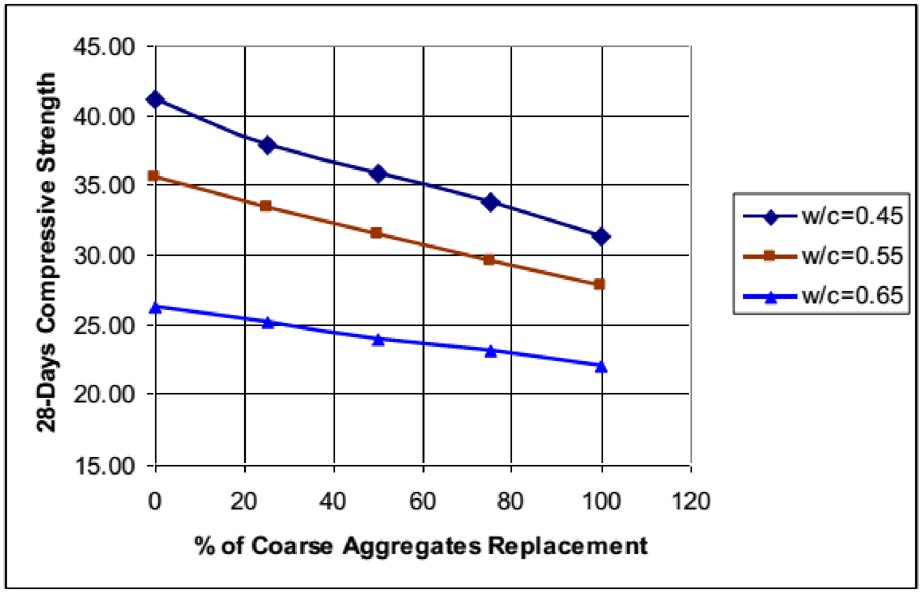

Figure 2.3: Relationship between compressive strength and percentage of replacement of RA [20].

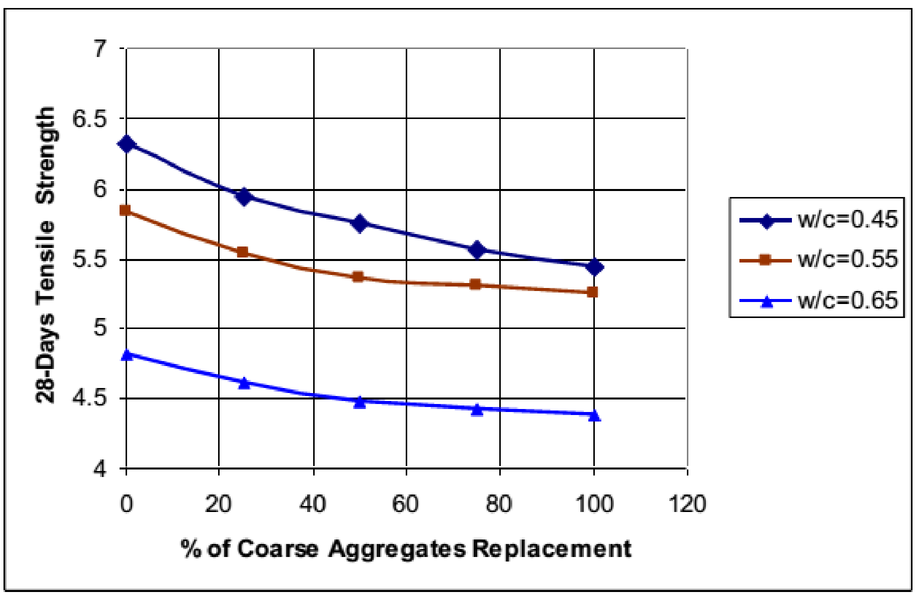

Figure 2.4: Relationship between tensile strength and percentage of replacement of RA [20].

Hassanean and Rashwan [11] designed mixes of concrete to study the influence of replacing certain ratios of normal aggregate by recycled concrete aggregate which came from the upper skeleton of building in Sohag/Egypt. The replacement ratio varied from 0 to 50% and they used two maximum nominal sizes of normal and recycled aggregate (20 and 40 mm). They reported that the bulk density and specific gravity of RA is slightly less than that of the NA while the water absorption is much higher and can reach up to 6.5 times that of NA. The compressive strength, splitting tensile strength, bond strength and flexural strength decreased with increasing RA ratio and due to the weakness of cohesion between the recycled aggregate and cement paste, the tensile strength of concrete is the most affected property of RAC.

Wagih and El-Karmoty [21] carried out experiments to study the effect of demolition concrete waste as aggregate for structural concrete. Tests were carried out for compressive strength, splitting tensile strength and elastic modulus with different cement contents (350, 400 and 450 kg/m^3). The results showed that RAC which contains concrete rubble as a partial replacement of natural aggregate possessed properties suitable for most structural applications in Egypt. It was reported that replacing 25% of NA with RA has no significant effect on concrete performance, while 50% replacement will cause reduction in the compressive strength from 7% to 13% and smaller amount of reduction in splitting and elastic modulus. On the other hand, full replacement of natural aggregates by RA led to higher reduction in workability and concrete strength, the reductions in tensile strength and elasticity modulus were up to 25% and 15%, respectively.

Butler and West [22] conducted a study to evaluate the effect of full replacement of NA with RA on the various mechanical properties of multiple concrete mixtures having equivalent compressive strength and slump (compressive strengths between 40 and 60 MPa and slumps between 75 and 125 mm). It was reported that the splitting tensile strength of RAC was statistically similar to NAC, especially for lower strength concrete.

The RAC with equivalent strength to NAC had modulus of elasticity values up to 19% lower than NAC. Fracture energy of RAC was 32% lower in comparison to the NA concrete specimens.

Sharma and Sharma [23] investigated the effects of RA extracted from construction and demolished wastes on fresh and mechanical properties of concrete in India. The investigation involved RA replacement percentages of 0%, 30%, 60% and 100%. The recycled aggregates were procured from M50 concrete cubes and used to replace aggregate in M25 concrete mix. Results showed that by increasing the replacement of aggregate, higher compressive and splitting tensile strength and pulse velocity values were obtained. However, the slump values decreased with an increase in the proportion of RA even with an increase of superplasticizer dosage.

Dilbas and Simsek [24] performed a study by using the demolished building rubble as a recycled aggregate in concrete mixes with and without silica fume (SF). Twelve concrete mixes in three groups were produced with a constant value of w/b (water to binder ratio) equal to 0.5 and fixed binder content of 350 kg/m^3. Physical and mechanical properties of concrete, such as compressive strength, modulus of elasticity, splitting tensile strength and water absorption, were determined. The authors proposed a 30% proportion of the replacement of RA as the optimum ratio, and they found that the addition of 5% SF to the concrete mix will improve the low properties of RAC by an amount between 5 to 10%.

Kim and Yun and other researchers conducted several studies to estimate the effect of RA on the bond strength between steel bars and concrete. Most of these results show obvious trend of bond strength reduction as the replacement ratio of RA was increased. The results show that for 100% replacement level of coarse RA, the bond strength between the RA concrete and the steel rebar decreased by 12% to 19% [20 - 21].

Silva and Brito [27] conducted a systematic research to investigate the effect of recycled aggregate on the tensile strength of concrete. The first important fact indicated that the relationship between compressive and tensile strength was unaffected by the use of RA regardless of the replacement quantity, quality or type. Also, there was a clear trend that the incorporation of RA leads to a decrease in the tensile strength of concrete. This decrease can be controlled by changing the crushing procedure to produce rounder RA with less old mortar adhering to its surface (better aggregate quality) which can improve the splitting tensile strength by up to 12% compared to mixes made with ordinary crushed RA. The use of proper mixing approach and using water compensation method during mixing to achieve saturated surface-dried state of RA was considered a good practice to achieve good concrete performance and compensate for the strength loss. Although the use of superplasticizer is an effective way to decrease the strength loss of RAC, its effectiveness will decrease with high replacement level of non-saturated RA that can absorb part of the mixing water with superplasticizer. The water compensation method helped in producing RAC with equivalent workability to that of the standard concrete and with minimum strength loss, regardless of the replacement level.

Figure 2.5, which was produced by Silva and Brito [27], shows that the different quality of RA affects the tensile properties of concrete. Concrete made with high quality aggregate (Class A) exhibited only 10% loss in splitting tensile strength when 100% replacement of coarse RA were used, which is considered marginal compared to 43% loss in splitting tensile strength when low quality aggregates (Class B) were used in the same percentage. The quality of RA also affected the flexural strength of RAC, where the loss in flexural strength increased from 11% to 31% when 100% of low quality RA was used instead of high quality RA.

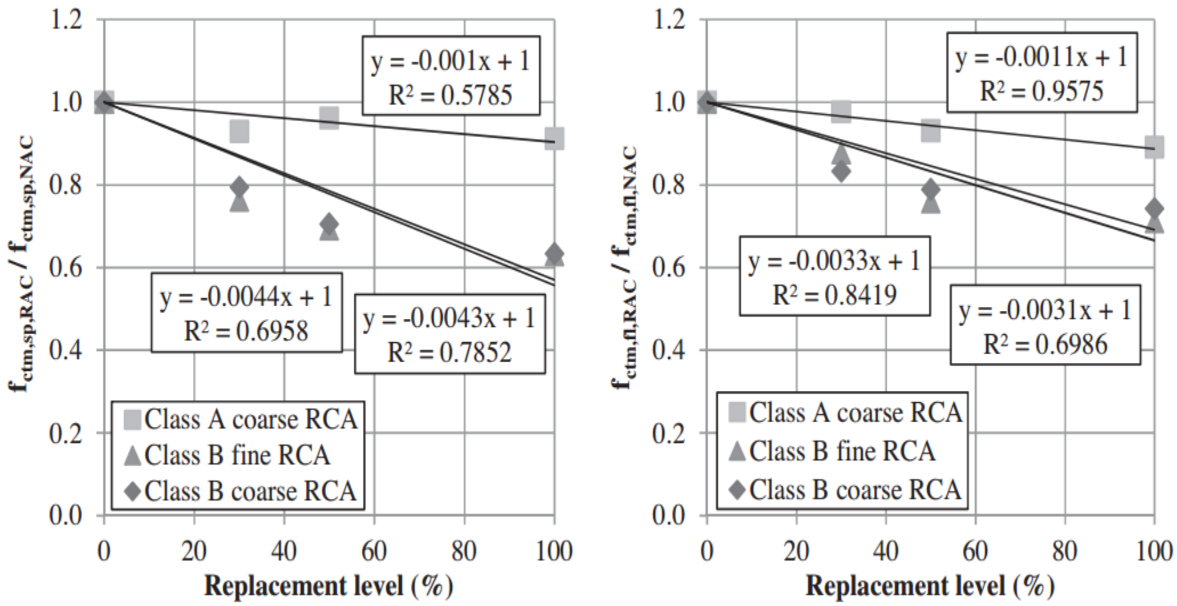

Figure 2.5: Relative splitting tensile (sp) and flexural (fl) strengths of RAC versus the replacement level of RA with different quality [27].

Bravo and Brito [13] performed a research to analyze the effect of RA of construction and demolition waste from different locations in Portugal on the mechanical properties of concrete. They concluded that RA, especially the fine recycled part, has a bad effect on most of the properties of concrete. They recorded a decrease in the compressive strength ranging from 17-34% and in splitting tensile between 20-32% in case of using coarse RA. While in the case of using fine RA, these values reached to 36%. Also, the full replacement of RA significantly affected the modulus of elasticity, the reduction reached to 47% in the case of course RA, and similar values were obtained in the case of fine RA. On the other hand, the abrasion resistance was the only property that was similar or marginally more in the RAC, but there was a decrease in the case when using fine RA [13]. Figures 2.6 through 2.9 depict the results obtained by Bravo and Brito [13].

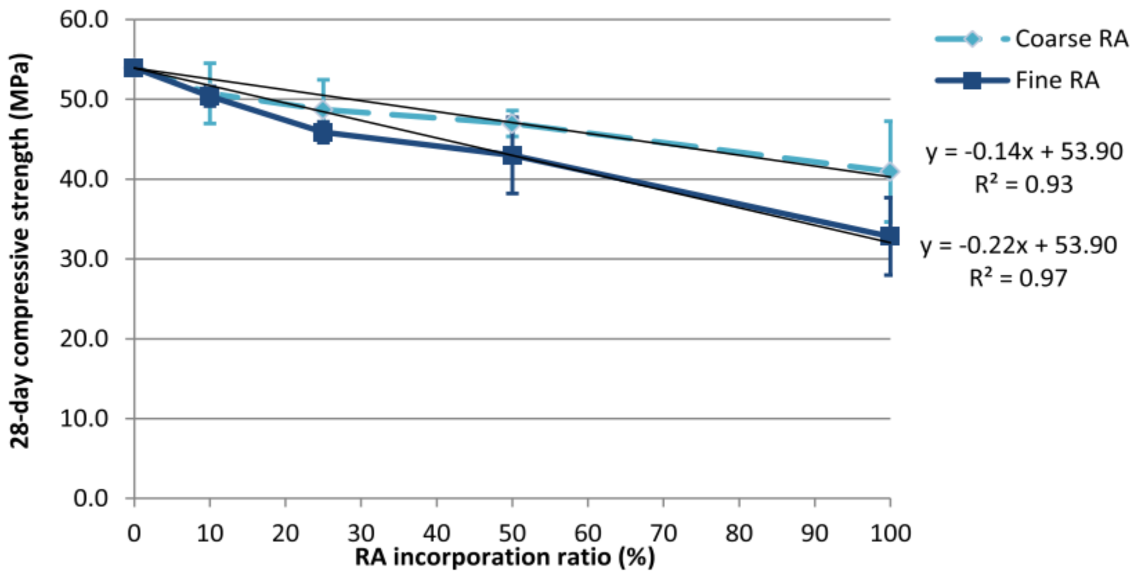

Figure 2.6: 28-day cube compressive strength of RA concrete versus aggregate replacement ratio [13].

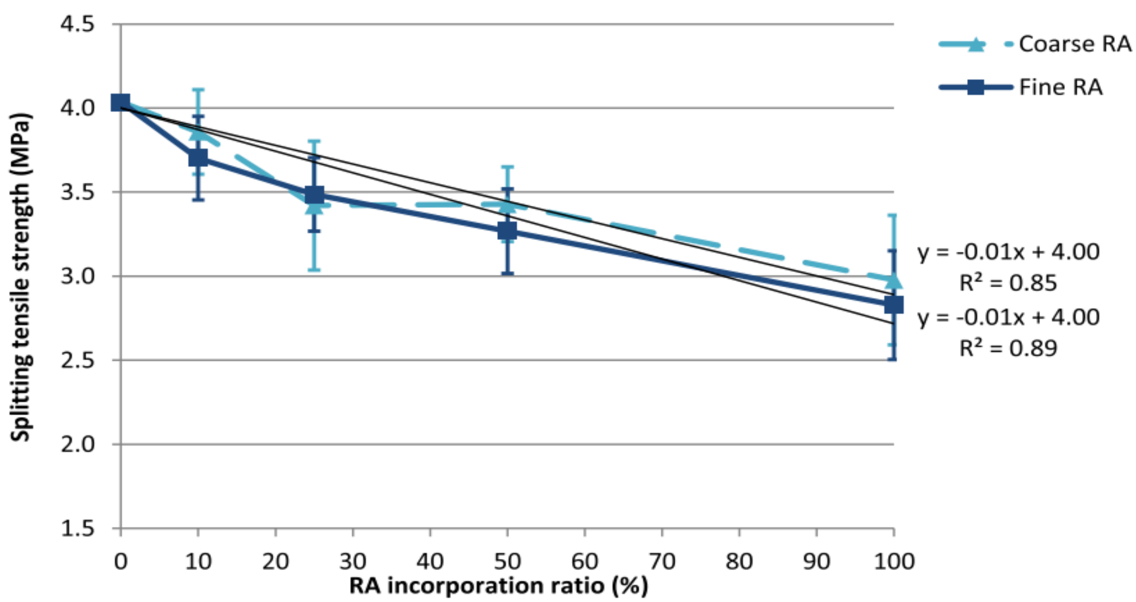

Figure 2.7: Splitting tensile strength of RA concrete versus aggregate replacement ratio [13].

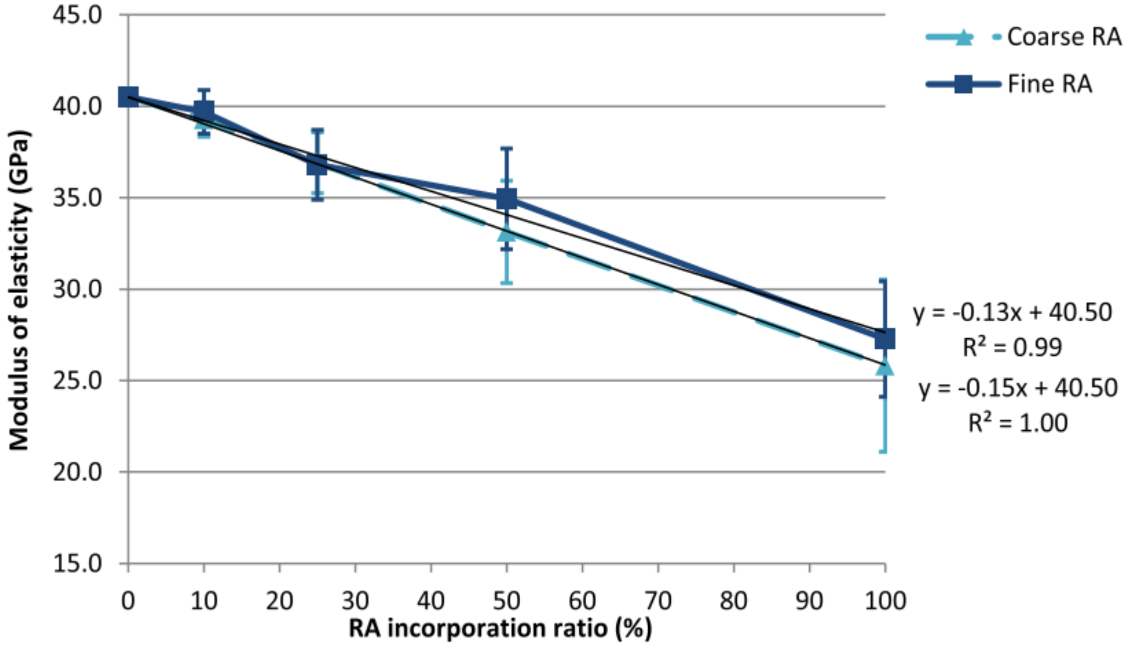

Figure 2.8: Modulus of elasticity of RA concrete versus aggregate replacement ratio [13].

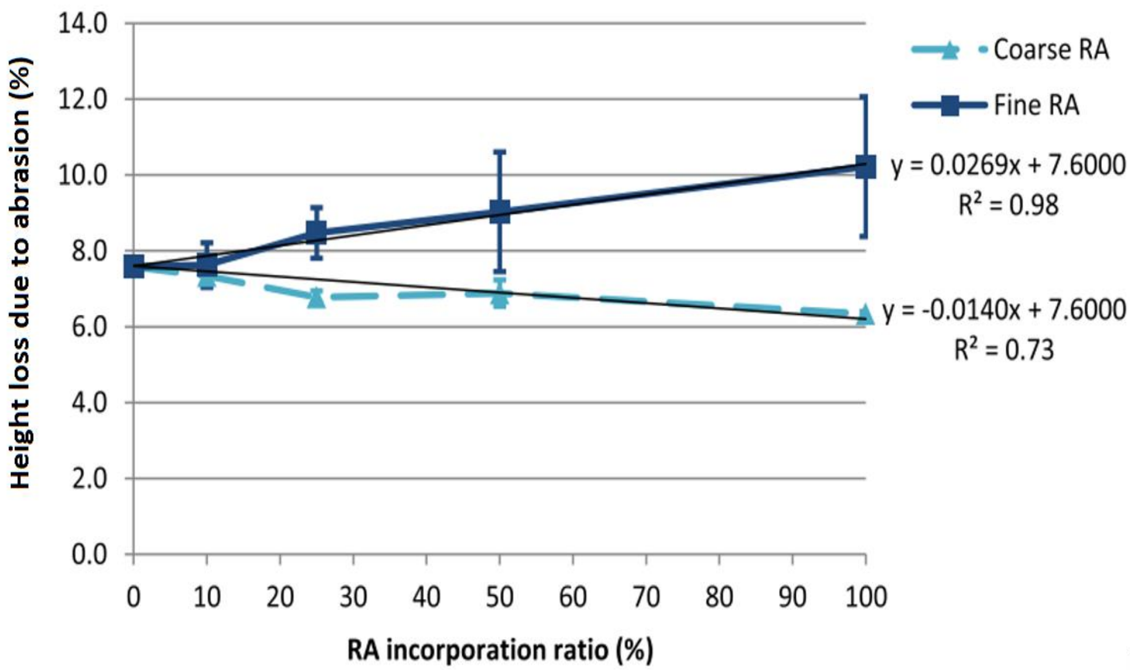

Figure 2.9: Abrasion resistance of RA concrete versus aggregate replacement ratio [13].

The effect of coarse RA on drying shrinkage and creep of concrete was investigated by Tam et al. [28]. They tested several RAC mixes with RA enter of 0%, 30%, and 100%. Drying shrinkage and creep were tested after 28 days of curing and after rewetting and unloading of specimens. It was reported that the drying shrinkage and creep increased by increasing the RA replacement level. Figures 2.10 and 2.11 show the creep strain and shrinkage percentage of RAC with different replacement levels of RA, respectively.

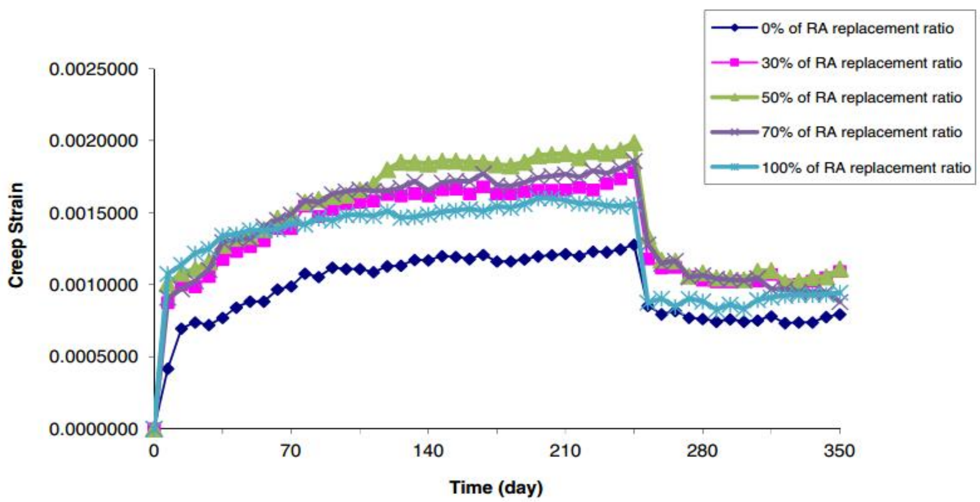

Figure 2.10: Creep strain of RAC with different RA replacement levels [28].

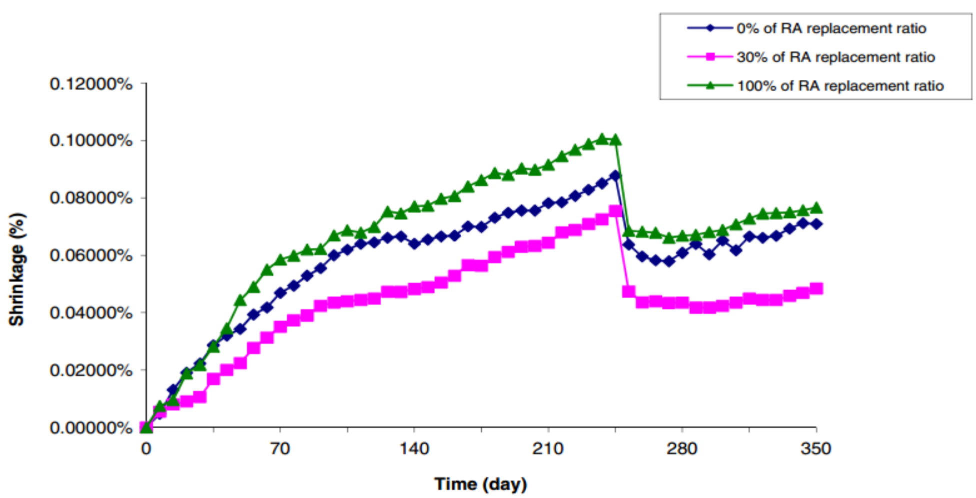

Figure 2.11: Drying shrinkage of RAC with different RA replacement levels [28].

Silva and Brito [29] have recently conducted a statistical analysis on data collected from 121 publications to establish a relationship between the compressive strength and modulus of elasticity of RAC. The collected data suggest that the modulus of elasticity decreased as the coarse RA replacement level increased, the effect of replacement level up to 30% have been considered minimal, while the 100% replacement level reduced the modulus of elasticity by 20% to 40%. Figure 2.12 shows the effect of increasing RA on the relative modulus of elasticity.

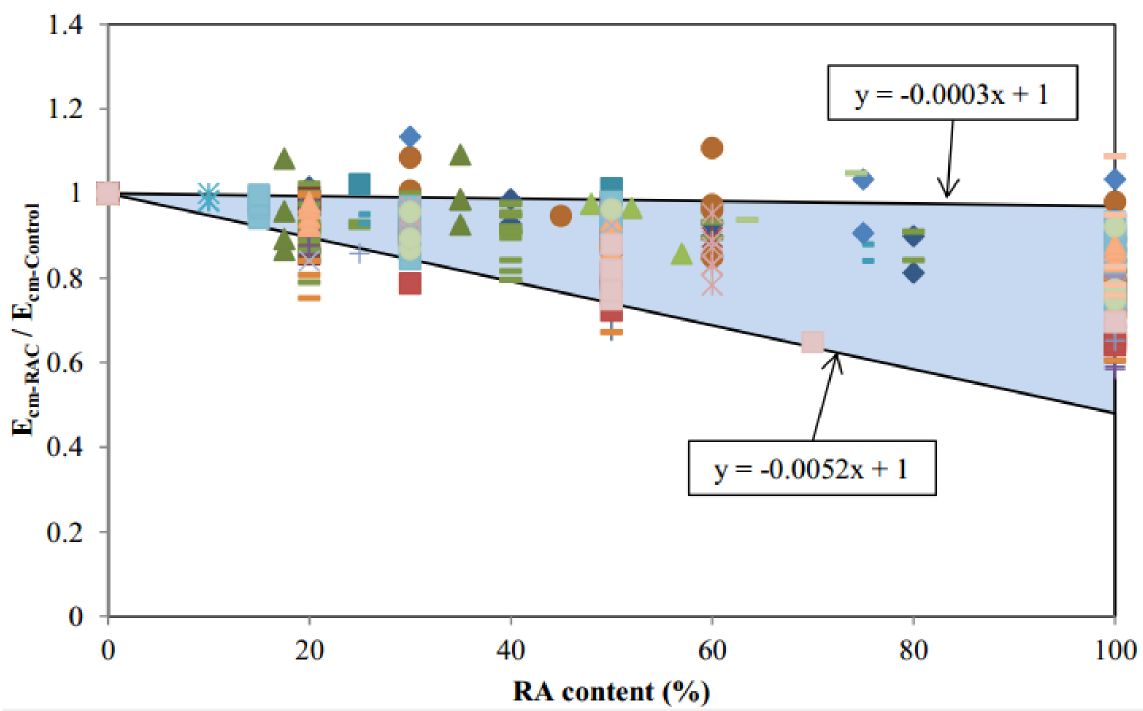

Figure 2.12: Relative modulus of elasticity relation with the RA content as established by Silva and Brito based on the literature data [29].

Silva and Brito [29] also tried to represent the relationship between the modulus of elasticity (E_{cm}) and the compressive strength (f_{cm}) of RAC with increasing replacement levels of RA. They represented literature data with respect to the standard curves of sandstone-aggregate concrete and basalt-aggregate concrete from the Eurocode (EN-

1992-1-1, 2008). The results, which are presented in Figures 2.13 and 2.14, show a great disparity for the modulus of elasticity of RAC, even though most of these values are above the proposed Eurocode curve for sandstone aggregates. This suggests that the modulus of elasticity of RAC will most probably comply with existing standards and specifications even with high RA replacement levels.

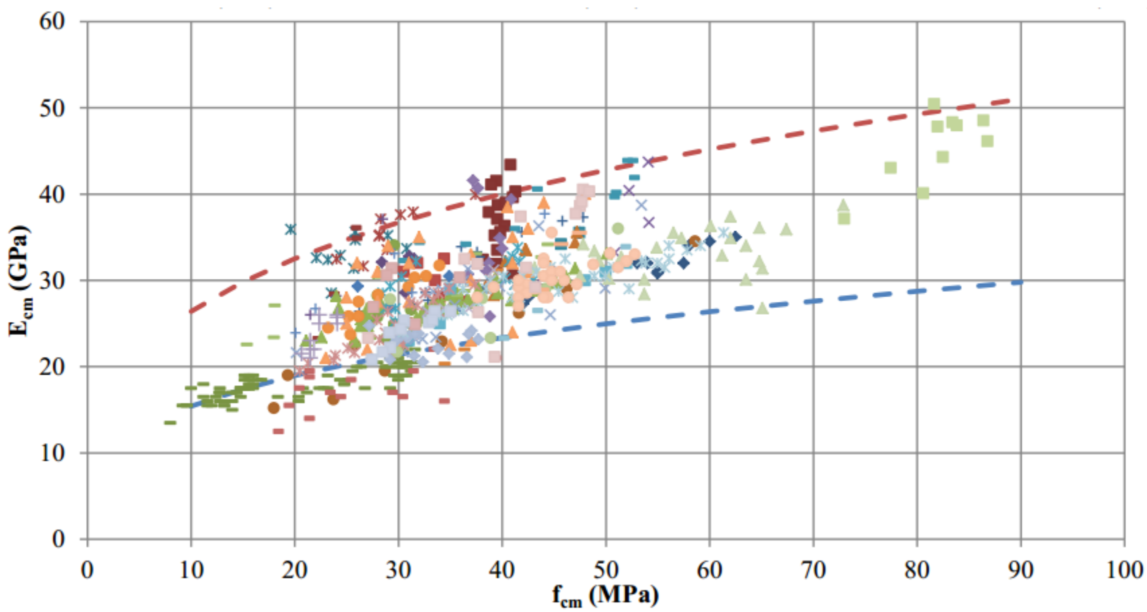

Figure 2.13: Modulus of elasticity (E_{cm}) versus compressive strength (f_{cm}) of RAC with respect to the Eurocode standard curves of sandstone and basalt aggregate concrete [29].

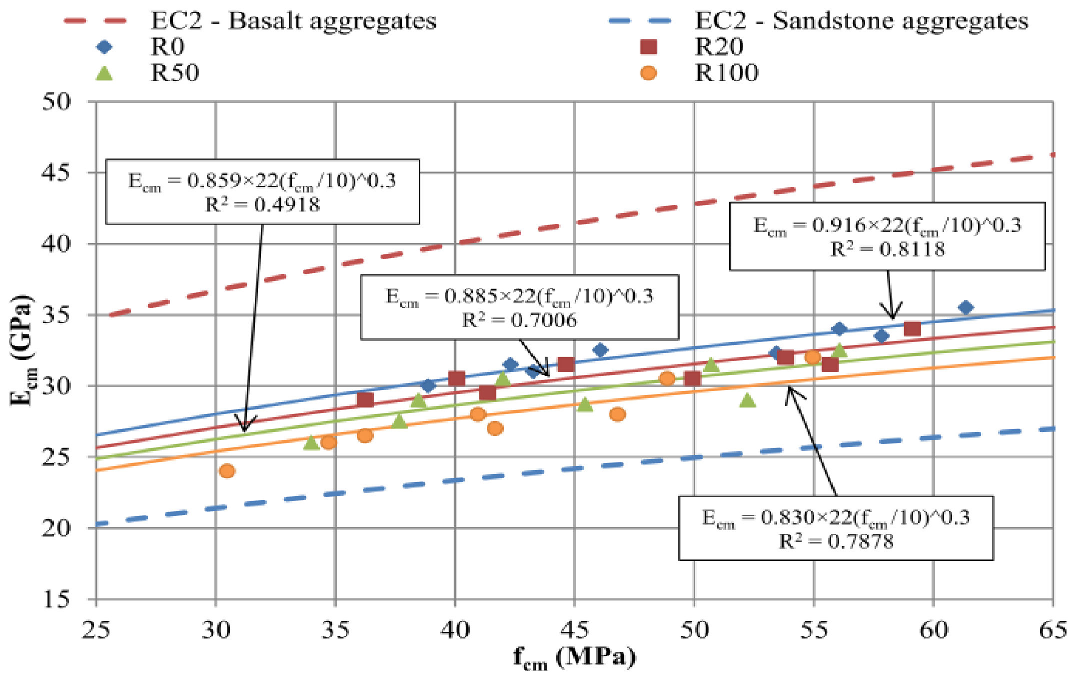

Figure 2.14: Modulus of elasticity (E_{cm}) versus compressive strength (f_{cm}) of RAC with different RA replacement levels, based on data from Kou et al. [30], reproduced by Silva and Brito [29].

Available experimental data on RAC show a wide variation in the results, sometimes even conflicting, as summarized in Table 2.2. The values presented in this table are the upper limits of all the analyzed research data. Unfortunately, there is a large scatter in the experimental data since the quality of demolished concrete that was used as recycled aggregates directly affects the quality of RAC. There is a general agreement that demolished concrete is usually a mix of concrete of different qualities from different dumping sites that most probably has a low to medium quality. However, it is possible to obtain low-to-medium strength concrete using coarse recycled aggregate regardless of the quality of the RA according to most of the published research. This is a very important point to consider for the practical applications and production conditions in the recycling plants.

Table 2.2: Summary of literature review on recycled aggregate concrete (RAC) compared to natural aggregate concrete (NAC).

Property	RAC compared to NAC	References
Compressive strength	Decreased up to 50%.	Katz [14], Qasrawi, Marie et al. [20], Alam et al. [31], Wagih, El-Karmoty et al. [21], Bravo, de Brito et al. [13].
Splitting and flexural tensile strength	Decreased from 10% to 30%.	Yang et al. [32], Qasrawi, Marie et al. [20], Alam et al. [31], Butler, West et al. [22], Wagih, El-Karmoty et al. [21] , Bravo, de Brito et al. [13].
Modulus of elasticity	Decreased from 15% to 45%	Yang et al [32], Butler, West et al. [22], Wagih, El-Karmoty et al. [21].
Drying shrinkage	Increased by up to 50%	Domingo-Cabo et al. [33].
Creep	Increased by up to 50%	Domingo-Cabo et al. [33].
Bond Strength of Steel and Concrete	Decreased by up to 19%	Butler, West et al. [17], Hassanean, Rashwan et al. [11].
Abrasion resistance	Small change in case of coarse RA	Bravo, de Brito et al. [13].

Though some work has been conducted to evaluate the RAC, there is a need to assess the properties of concrete with the local RA.

CHAPTER 3

EXPERMENTAL WORK

3.1 INTRODUCTION

The experimental work conducted during this study is explained and discussed in this chapter. This chapter also presents the properties of the concrete materials and mixtures proportions, in addition to a brief explanation for the tests which were conducted in this study to determine the mechanical properties of concrete, according to ASTM standards.

3.2 MATERIALS

The following materials were used to prepare the concrete mixes:

a) Type I cement.

This is the normal ordinary Portland cement according to ASTM C 150 with a specific gravity of 3.15.

b) Fine aggregate (dune sand).

Dune sand is vastly available in eastern Saudi Arabia. It has a specific gravity of about 2.56 and water absorption about 0.5%.

c) Natural coarse aggregate (crushed limestone).

The natural crushed limestone used in this study was brought from a local quarry in the Eastern Province of the Kingdom. The limestone aggregates had a specific gravity of 2.60 and water absorption of about 1.23%. The coarse aggregates were graded into four different sizes as given in Table 3.1.

Table 3.1: Grading of the coarse aggregate used in this study.

Sieve size	% retained
1/2" (12.5 mm)	45
3/8" (9.5 mm)	15
3/16" (4.75 mm)	30
3/32" (2.36 mm)	10

d) Recycled coarse aggregate from local damping site.

In this study, the demolished concrete which was used as, was collected from Al-Khobar city. The place that the demolished concrete was taken from Al-Khobar is near the intersection between King Khaled Street and the 20th Street. Only the concrete wastes were taken by removing any non-concrete material. Then, this concrete was crushed into small pieces and sieved into four different sizes with the same grading as the natural coarse aggregate, see Table 3.1. The water absorption and specific gravity of the recycled aggregate were determined according to ASTM C 127 and summarized in Table 3.2.

Table 3.2: Specific gravity and water absorption of the RA

Specimen #		1	2	3	Avg.
Weight (gram)	SSD	1064.3	1057.6	1059.7	---
	Submerged	605.3	593.2	600.3	---
	Oven Dry	967.7	967.7	964.2	---
Absorption %		9.98	9.29	9.90	9.73
Bulk S.G.		2.11	2.08	2.10	2.10
Bulk SSD S.G.		2.32	2.28	2.31	2.30
Apparent S.G.		2.67	2.58	2.65	2.63

e) Super Plasticizer (SP)

Suitable dosages of SP (Glenium 51®) were utilized to obtain the desired workability (i.e., a slump of 75 to 100 mm); the dosages were between 0.15% to 0.2% by weight of cement.

3.3 CONCRETE MIX PROPORTIONS

Three series of concrete mixtures were prepared. The concrete mixtures in these three series were proportioned to produce low strength, medium and high strength concrete. Various proportions of RA and NA were used to prepare these concrete mixes. Tables 3.3 and 3.4 summarize the proportions in each concrete mixture.

All the concrete mixtures were designed for a workability of 75 to 100 mm slump. The mixture proportions were designed based on the absolute volume method. After selection of the cement content and w/c ratio for each mix, the proportions of NA and RA were calculated.

The total water of each mixture was corrected based on the water compensation method to achieve saturated surface-dried state of RA. The water compensation method mainly depends on the initial water content and the effective absorption of the RA during the mixing period. An additional amount of water was added to the initial water content to compensate for the water absorbed by the RA, this additional amount depends on the quantity of RA and its effective absorption, and it should not contribute as an excess water in the mix [34].

Table 3.3: Mix proportions for low, medium and high strength concrete mixtures.

Concrete strength	Cement content, kg	w/c ratio	Coarse/Fine aggregate ratio	Proportions of RAC
Low strength	300	0.5	2	0, 20, 40, 60 and 100%
Medium strength	350	0.45	2	0, 20, 40, 60 and 100%
High strength	400	0.40	2	0, 20, 40, 60 and 100%

Table 3.4: Details of concrete mixtures components.

Mix #	Description of mix	Cement (kg)	Water (kg)	NA (kg)	RA (kg)	FA (kg)
RC 1-1	Low strength concrete, cement content 300 kg/m^3, 0.5 w/c ratio, 0% Recycled aggregate	22.20	13.16	90.94	0.00	55.74
RC 1-2	Low strength concrete, cement content 300 kg/m^3, 0.5 w/c ratio, 20% Recycled aggregate	22.20	14.53	71.58	17.90	54.84
RC 1-3	Low strength concrete, cement content 300 kg/m^3, 0.5 w/c ratio, 40% Recycled aggregate	22.20	15.85	52.84	35.23	53.97
RC 1-4	Low strength concrete, cement content 300 kg/m^3, 0.5 w/c ratio, 60% Recycled aggregate	17.13	34.68	52.01	53.13	17.13
RC 1-6	Low strength concrete, cement content 300 kg/m^3, 0.5 w/c ratio, 100% Recycled aggregate	22.20	19.58	0.00	84.07	51.53
RC 2-1	Medium strength concrete, cement content 350 kg/m^3, 0.45 w/c ratio, 0% Recycled aggregate	25.90	13.65	88.12	0.00	54.01
RC 2-2	Medium strength concrete, cement content 350 kg/m^3, 0.45 w/c ratio, 20% Recycled aggregate	25.90	14.98	69.37	17.34	53.14
RC 2-3	Medium strength concrete, cement content 350 kg/m^3, 0.45 w/c ratio, 40% Recycled aggregate	25.90	16.26	51.20	34.13	52.30
RC 2-4	Medium strength concrete, cement content 350 kg/m^3, 0.45 w/c ratio, 60% Recycled aggregate	25.90	17.50	33.60	50.40	51.49
RC 2-6	Medium strength concrete, cement content 350 kg/m^3, 0.45 w/c ratio, 100% Recycled aggregate	25.90	19.87	0.00	81.47	49.93
RC 3-1	High strength concrete, cement content 400 kg/m^3, 0.4 w/c ratio, 0% Recycled aggregate	29.60	13.79	85.91	0.00	52.65
RC 3-2	High strength concrete, cement content 400 kg/m^3, 0.4 w/c ratio, 20% Recycled aggregate	29.60	15.08	67.62	16.91	51.81
RC 3-3	High strength concrete, cement content 400 kg/m^3, 0.4 w/c ratio, 40% Recycled aggregate	29.60	16.33	49.92	33.28	50.99
RC 3-4	High strength concrete, cement content 400 kg/m^3, 0.4 w/c ratio, 60% Recycled aggregate	29.60	17.54	32.76	49.14	50.19
RC 3-6	High strength concrete, cement content 400 kg/m^3, 0.4 w/c ratio, 100% Recycled aggregate	29.60	19.85	0.00	79.42	48.68

3.4 TESTS

The prepared RAC specimens were tested to determine the following mechanical properties:

a) Compressive strength,

b) Modulus of elasticity,

c) Split tensile strength,

d) Flexural strength,

e) Bond strength,

f) Abrasion resistance, and

g) Drying shrinkage.

The details of the specimen size, test duration, and test methods are shown in Table 3.5, Figure 3.1 shows a set of RAC specimens.

Table 3.5: Details of specimens' sizes and test methods and durations.

Property	Test Standard	Specimen shape	Test duration
Compressive Strength	ASTM C 39	100×100×100 mm Cubes	3, 7, 28, 56 and 90 days.
Modulus of Elasticity	ASTM C 469	75 mm diameter and 150 mm height Cylinder	After 28 days of water curing.
Splitting Tensile Strength	ASTM C 496	75 mm diameter and 150 mm height Cylinder	After 28 days of water curing.
Flexural Strength	ASTM C 78	40×40×160 mm Prism	After 28 days of water curing.
Bond Strength	Similar to ASTM C 234	150×150 ×150 mm Cubes	After 28 days of water curing.
Abrasion Resistance	Similar to ASTM C 779	50×50×50 mm Cubes	After 28 days of water curing.
Drying Shrinkage	ASTM C 157	50×50×280 mm Prism	3, 7, 14, 28, 56 and 90 days after 28 days of water curing.

Figure 3.1: Test specimens of concrete mix RC 2-2 after casting and demolding.

3.4.1 Compressive Strength

The compressive strength of RAC and NAC specimens was determined on 100-mm cube specimens according to ASTM C 39 after 3, 7, 28, 56 and 90 days of curing in water. Three cubes were tested at each age and the average compressive strength was reported.

An automatic hydraulic type compression testing machine (MATEST) shown in Figure 3.2 was used to apply load at a rate between 0.15 to 0.35 MPa/s until failure.

Figure 3.2: Hydraulic type compression strength testing machine.

3.4.2 Modulus of Elasticity

For measurement of modulus of elasticity, cylindrical specimens 75 mm in diameter and 150 mm high were used. The test was conducted according to ASTM C 469 after 28 days of water curing. Sulphur capping was used to achieve smoothness of the top surface of the cylinders, then a load cell was used to apply a constant rate of loading. Cylindrical frame that contains two linear variable displacement transducers (LVDTs), as shown in Figure 3.3 was fixed on the specimens to record the strain in the specimens during the test. The load and linear deformations were recorded by using a digital data logger. Three specimens were tested to represent each mix and the average modulus of elasticity was reported.

Figure 3.3: Modulus of elasticity test setup showing the sulfur capping on the top of the specimen and LVDTs.

The modulus of elasticity was calculated according to ASTM C 469 equation by using the load and deformation data recorded during the test:

$$E = \frac{S_2 - S_1}{\epsilon_2 - 0.000050}$$

Where:

E = Chord modulus of elasticity, MPa,

S_2 = Stress corresponding to 40 % of ultimate load, MPa,

S_1 = Stress corresponding to a longitudinal strain, ϵ_1, of 50 millionths, MPa,

ϵ_2= Longitudinal strain produced by stress S_2.

3.4.3 Splitting Tensile Strength

Splitting tensile strength is an indirect way to estimate the tensile strength of concrete specimens. It is easier to conduct split tensile strength test and it also gives a good approximation of concrete tensile strength. The test was conducted according to ASTM C 496 using concrete cylinders of 75 mm diameter and 150 mm high. An automatic compression testing machine was used to conduct the test, as shown in Figure 3.4. Loading was applied at a constant rate until the specimen failed by splitting. Three specimens were tested to represent each mix and the average splitting tensile strength was reported.

Figure 3.4: Splitting Tensile test setup and samples after testing.

The splitting tensile strength was calculated according to the ASTM C 496 equation:

$$T = \frac{2P}{\pi l d}$$

Where:

T = Splitting tensile strength, MPa,

P = Maximum applied load, N,

l = Length, mm,

d = Diameter, mm.

3.4.4 Flexural Strength

The most common parameter used to represent the flexural strength of concrete is the modulus of rupture. To obtain the modulus of rupture of the NAC and RAC, a four-point flexural loading test was conducted on prism specimens of 40×40×160 mm according to ASTM C 78, see Figure 3.5. During the tests, the load-deflection data was recorded using a digital data logger.

Figure 3.5: Flexural strength test setup.

The modulus of rupture was calculated according to ASTM C 78 equation:

$$R = \frac{PL}{bd^2}$$

Where:

R = Modulus of rupture, MPa,

P = Maximum applied load, N,

L = Span length, mm,

b = Average width of specimen, mm,

d = Average depth of specimen, mm.

3.4.5 Bond Strength

For measurement of the bond strength, cube specimens of 150×150×150 mm were used, with 12 mm diameter steel rebar embedded in the center of each cube. Two plastic sleeves, 50-mm long, were inserted at the beginning and at the end of the embedded steel bar to provide free movement of the rebar within this region, thus the bonded distance for each rebar with the concrete was limited to 50 mm in the middle of the cube, as shown in Figure 3.6.

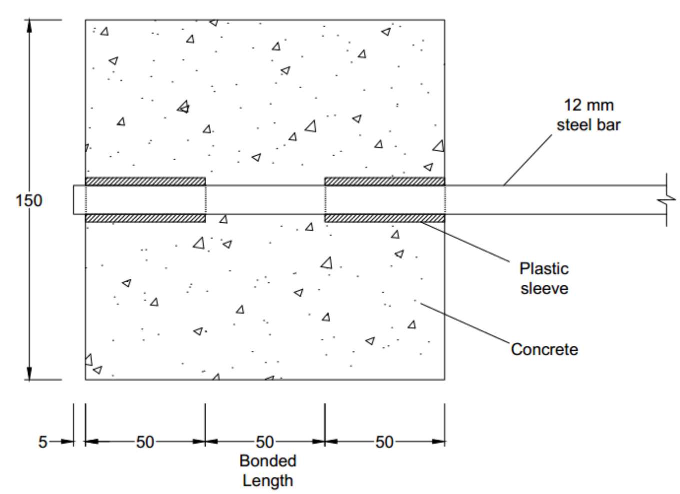

Figure 3.6: schematic diagram of the bond strength specimen.

The pull-out test was conducted after 28 days of water curing using a universal testing machine. The concrete cube was restrained in a steel frame, as shown in Figure 3.7. Three LVDTs were used to record the bar slip during the test, one at the bottom end of the rebar (the free end slip of the bar), and two were fixed at the loaded end of the bar, as shown in Figure 3.7. A digital data logger was used to record the pullout load that was applied at a constant rate until the beginning of bar slippage.

Three specimens were tested to represent each mix and the average peak load was found for each mixture. The bond strength was determined by dividing the peak load by the bonded area of the steel bar.

Figure 3.7: Test setup of the pull out test (Left), the two LVDTs fixed at the loaded end of the steel bar during the pull out test (Right).

Figure 3.8: Bond strength samples after failure due to steel bars slippage.

3.4.6 Abrasion Resistance

Abrasion resistance of concrete can be used as an indication of the quality acceptance of the concrete and its surface exposed to wear. This test has been conducted in order to evaluate the effect of RCA on the abrasion resistance of concrete, the test being based on the concept of ASTM C 779 test. In ASTM C 779, a steel disk in conjunction with abrasive grit abrade the concrete specimens (square tiles). During the current test, the steel disks were replaced by an abrasion paper and 50×50×50 mm cubic concrete specimens were tested instead of the concrete tiles, see Figure 3.9. The average height of the cubes was measured in addition to the cube’s weight before and after abrading of the specimens. Figure 3.9 shows a set of specimens used for evaluating the abrasion resistance. Three specimens were tested for each mixture, each specimen abraded for five minutes, then the average loss of height and weight of the specimens were calculated.

Figure 3.9: Abrasion resistance test specimens.

3.4.7 Drying Shrinkage

The loss of capillary water from the freshly hardened concrete when it is exposed to weather conditions causes contraction of hardened concrete. This contraction is called the drying shrinkage. Drying shrinkage may cause tensile stresses that may lead to cracking of the element before being subjected to any restrictions [34].

The drying shrinkage was determined according to ASTM C 157, where three prism specimens of 50 mm square cross section and 280 mm long were tested for each concrete mixture. The test was conducted using shrinkage-measuring machine consisting of a LVDT fitted into designated steel stand and connected to a data logger, as shown in Figure 3.10.

At age of 28 days, the specimens were removed from water dried into the saturated surface dry (SSD) condition, then the drying shrinkage was monitored after 3, 7, 14, 28, 56 and 90 days.

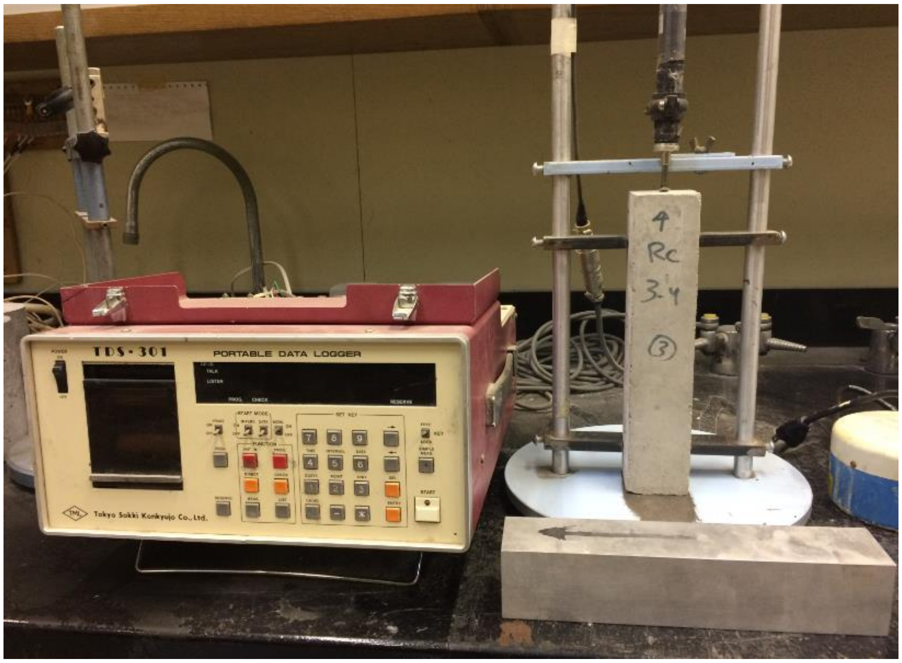

Figure 3.10: Test setup for measuring drying shrinkage.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter discusses the results obtained from the experimental program stated in the previous chapter. The mixture description, components and labels were described in Table 3.4 along with the RA replacement level for each RAC.

4.2 COMPRESSIVE STRENGTH

The average compressive strength results of the RAC specimens after 3, 7, 28, 56, 90 days are numerically presented in Table 4.1 and plotted in Figures 4.1 through 4.4. Based on these data, the effect of RA content and duration of curing and the effect of cement content and w/c ratio on the compressive strength of RAC are discussed below.

For each category of RAC mixture, the compressive strength increases with an increase in the duration of curing and it decreases with an increase in the RA replacement level, as shown in Figures 4.1 through 4.3. However, the trend of increasing compressive strength of RAC is similar to that of the conventional concrete, where the compressive strength of all the three concrete mixture series at 7 days is about 70% to 75% of the 28-day compressive strength, and it is almost 107% to 112% at 56 and 90 days, respectively. The results in Table 4.1 also show that the incorporation of RA did not affect the compressive strength gain over time. This means that the percentage of compressive strength reduction at 28 days, due to the incorporation of RA as a replacement of NA, is almost the same as the percentage reduction at 7 days and at later stages, such as 56 days and 90 days. This is clear in Figures 4.1 through 4.3 that show that the gap between the compressive strength curves are almost constant over time. Figure 4.4 compares the compressive strength of all the mixtures.

Table 4.1: Average compressive strength of the investigated RAC.

Mix Type	Mix Label	Cement Content, kg/m^3	w/c Ratio	RA Replacement Level, %	Average Compressive Strength, MPa					Reduction in the 28-day strength, %.
					3 days	7 days	28 days	56 days	90 days	
Low-strength RAC	RC 1-1	300	0.5	0	25.6	27.6	35.6	38.5	39.9	0.0
	RC 1-2	300	0.5	20	21.5	23.8	31.2	33.8	34.4	12.4
	RC 1-3	300	0.5	40	20.2	22.5	29.1	30.3	31.8	18.3
	RC 1-4	300	0.5	60	19.5	21.0	27.5	28.8	30.1	22.8
	RC 1-6	300	0.5	100	13.9	17.2	21.8	23.9	24.8	38.8
Medium-strength RAC	RC 2-1	350	0.45	0	30.0	32.3	40.3	42.4	44.5	0.0
	RC 2-2	350	0.45	20	26.3	28.1	36.1	37.8	39.2	10.4
	RC 2-3	350	0.45	40	24.6	26.3	34.2	36.4	37.6	15.1
	RC 2-4	350	0.45	60	20.2	23.4	30.8	32.5	33.7	23.6
	RC 2-6	350	0.45	100	18.7	20.2	26.1	27.3	28.3	35.2
High-strength RAC	RC 3-1	400	0.4	0	34.4	36.1	45.2	48.5	50.4	0.0
	RC 3-2	400	0.4	20	31.6	33.6	42.8	45.4	47.6	5.3
	RC 3-3	400	0.4	40	27.0	30.1	38.5	41.3	42.6	14.8
	RC 3-4	400	0.4	60	23.8	25.1	32.2	34.8	35.9	28.8
	RC 3-6	400	0.4	100	20.1	22.0	27.1	30.1	30.8	40.0

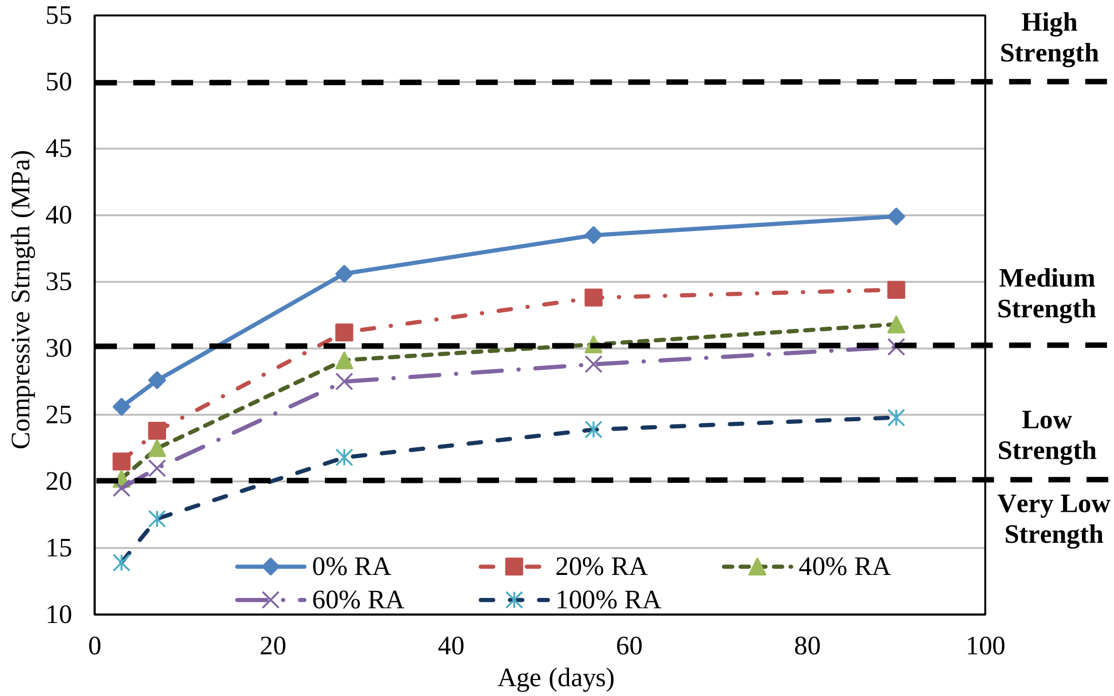

Figure 4.1: Compressive Strength of Low Strength Concrete Mixtures.

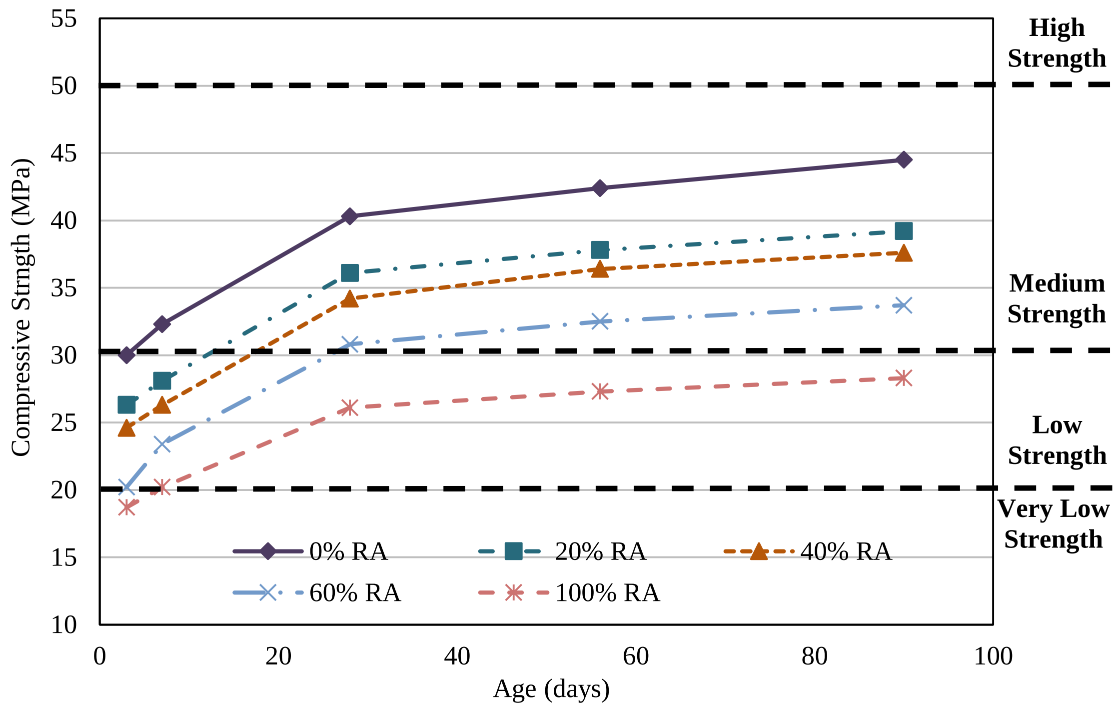

Figure 4.2: Compressive Strength of Medium Strength Concrete Mixtures.

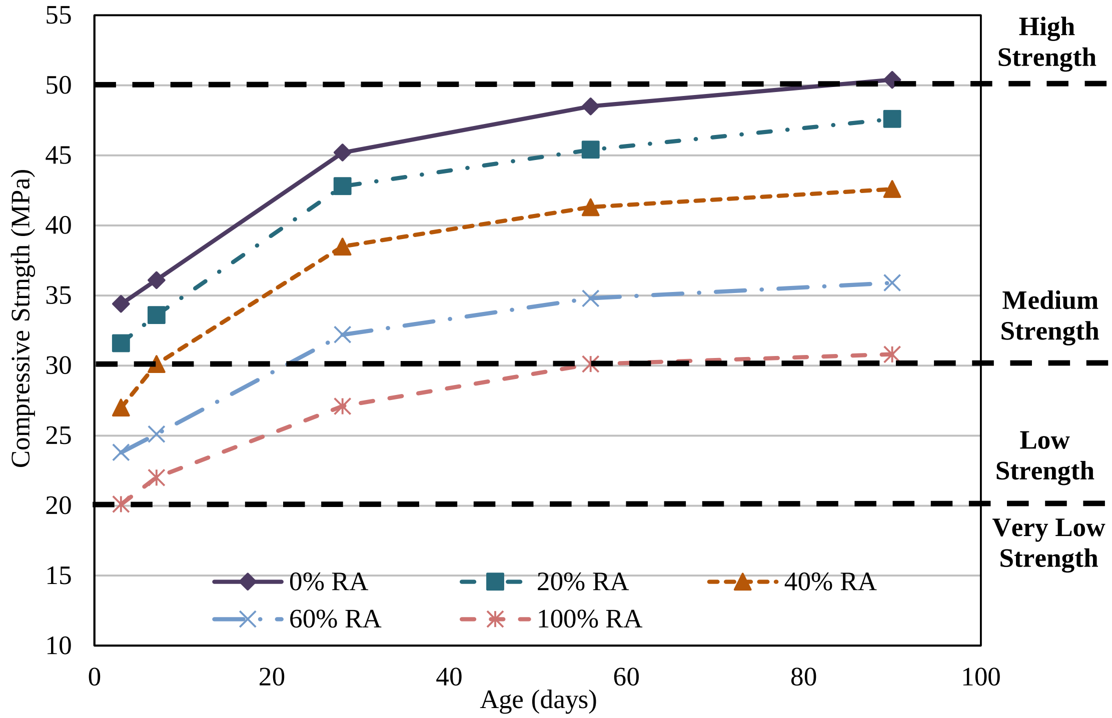

Figure 4.3: Compressive Strength of High Strength Concrete Mixtures.

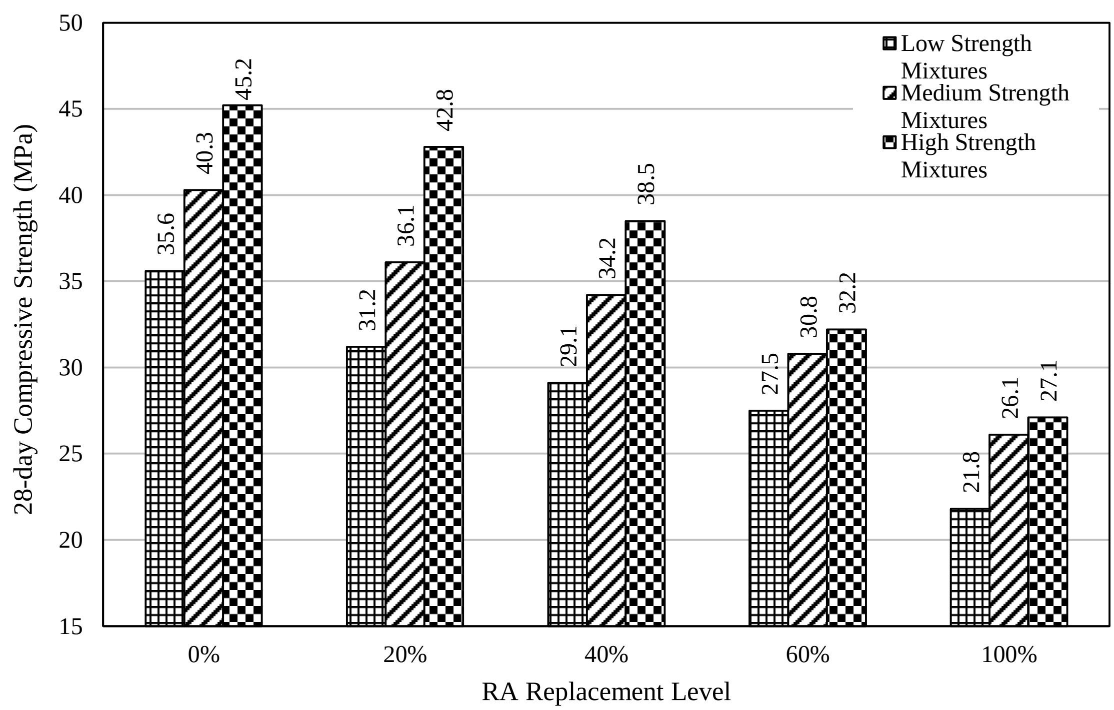

Figure 4.4: 28-day compressive strength for all concrete mixtures.

It is well known that the concrete technology development and the production of ultra-high-strength concrete have led to different definitions of high-strength concrete. Nowadays, several classifications of concrete strength level are defined all over the world, some of these classifications (such as the classifications in North America) define the high strength concrete as a concrete having 28-day compressive strength more than 41 MPa [35]. ACI has different classification which will be considered in this research to classify the concrete according to the compressive strength, where the concrete with compressive strength above 50 MPa is defined as a high-strength concrete, concrete with compressive strength from 30 to 50 MPa is defined as medium-strength concrete, concrete with compressive strength from 20 to 30 MPa is defined as low-strength concrete, and concrete with compressive strength of less than 20 MPa is defined as very-low-strength concrete [36].

Based on this classification, and refereeing to Table 4.1, it is clear that the proposed low-strength concrete mixtures (with cement content of 300 kg/m^3) were located in the medium-strength category of 28-day strength before the incorporation of RCA. When 40% or more of NA was replaced by RA; the 28-day compressive strength was reduced from 36 to 29 MPa, which means that this mixture series was dropped into low-strength concrete category.

The proposed medium and high strength concrete mixtures (with cement content of 350 and 400 kg/m3) were also located within the medium-strength category of 28-day strength. Where 60% or more of NA was replaced by RA; the medium strength mixture series dropped into the low strength category level of concrete strength, where the 28-day compressive strength decreased from 40 to 30 MPa, and the high strength mixture series dropped into the low strength category when full replacement of RA was used, where the 28-day compressive strength decreased from 45 to 32 MPa in this case.

The conjoint effect of high cement content and low w/c ratio results in an increase in of the compressive strength of RAC regardless of the RA replacement levels. The incorporation of RA lead to a reduction in the compressive strength for all concrete mixtures, this reduction was minor when the replacement levels was up to 40%, and this can be generalized for the three concrete categories at different ages. Beyond this limit of RA replacement, the reduction in compressive strength becomes higher. It is clear from the data in Table 4.1 and Figure 4.4 that by decreasing the w/c ratio and increasing the cement content of concrete mixtures, the compressive strength of RAC can be increase.

The data in Table 4.1 and Figure 4.5 show that the 28-day compressive strength reduction is in the range of 15% to 18% when 40% of RA was used, while this reduction reached to 23% to 28% when the RA replacement level was increased to 60%, and it reached to 40% reduction when full replacement of RA was used. These values are considered high compared to the previous literature results which reported that the full replacement of NA by RA resulted in a compressive strength reduction of about 30% to 35% in most cases, and in a few cases this value reached to 50% reduction or slightly exceeded this limit [13, 14, 20, 21]. This is a good indication that the quality of RA which was used in this research was poor, which can also be inferred through the low specific gravity and the very high water absorption of the utilized RA, as shown in Chapter 3.

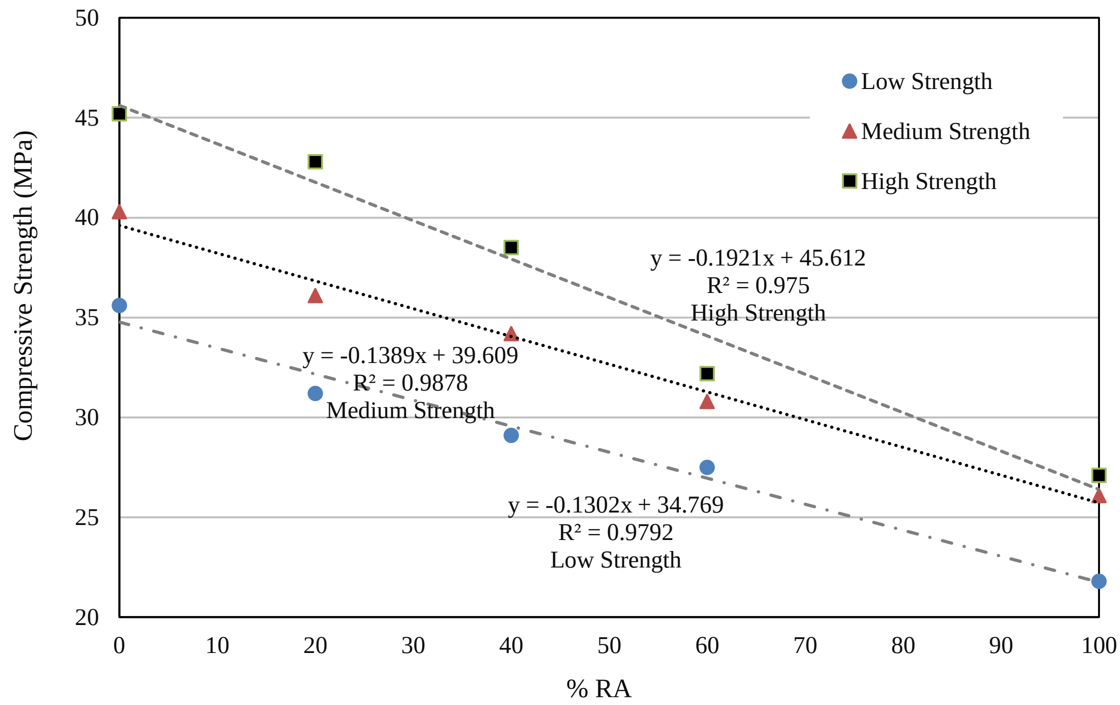

Figure 4.5: Effect of RA replacement level on the compressive strength of RAC concrete.

It is clear from the data in Figure 4.5 that the relationship between compressive strength reduction and RA replacement level is almost linear. The data in Figure 4.6 show that the reduction in the relative compressive strength of RAC (fc'-RAC/fc'-control) can be expressed by the following linear equation:

$$y = -0.0039x + 1 \qquad (R^2 = 0.9673) \qquad (1)$$

Where: y is the relative compressive strength (fc'-RAC/fc'-control), x is the level of RA replacement, and R^2 is the coefficient of determination.

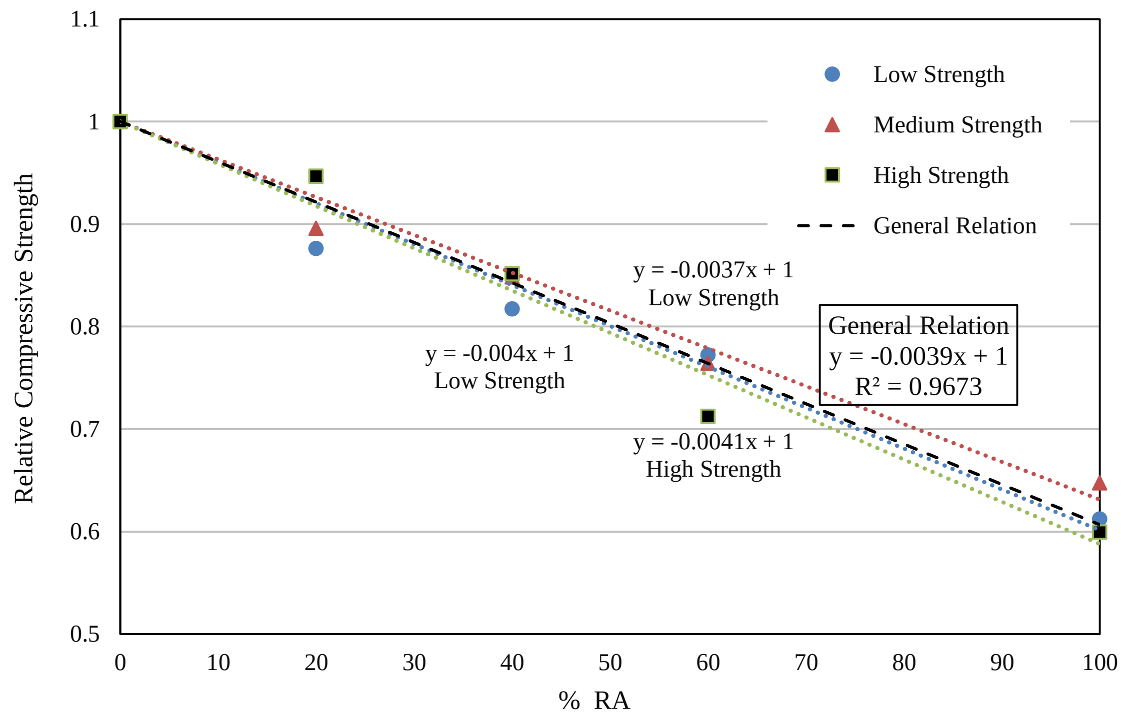

Figure 4.6: Influence of increasing RA replacement level on the relative compressive strength.

Figures 4.7 and 4.8 show that the relationship between the reduction in compressive strength and the RA replacement level is almost linear, and it can be represented by one of two equations:

$$y = 0.3932x \qquad (R^2 = 0.9673) \qquad (2)$$

Where: y is the % of 28-day compressive strength reduction, x is the level of RA replacement, and R^2 is the coefficient of determination.

Or by:

$$y = 0.1589x \qquad (R^2 = 0.9342) \qquad (3)$$

Where: y is the 28-day compressive strength reduction, x is the level of RA replacement, and R^2 is the coefficient of determination.

Due to their high R^2 values, these derived models can be reliably used to predict the compressive strength for any given concrete category with varying local RA content.

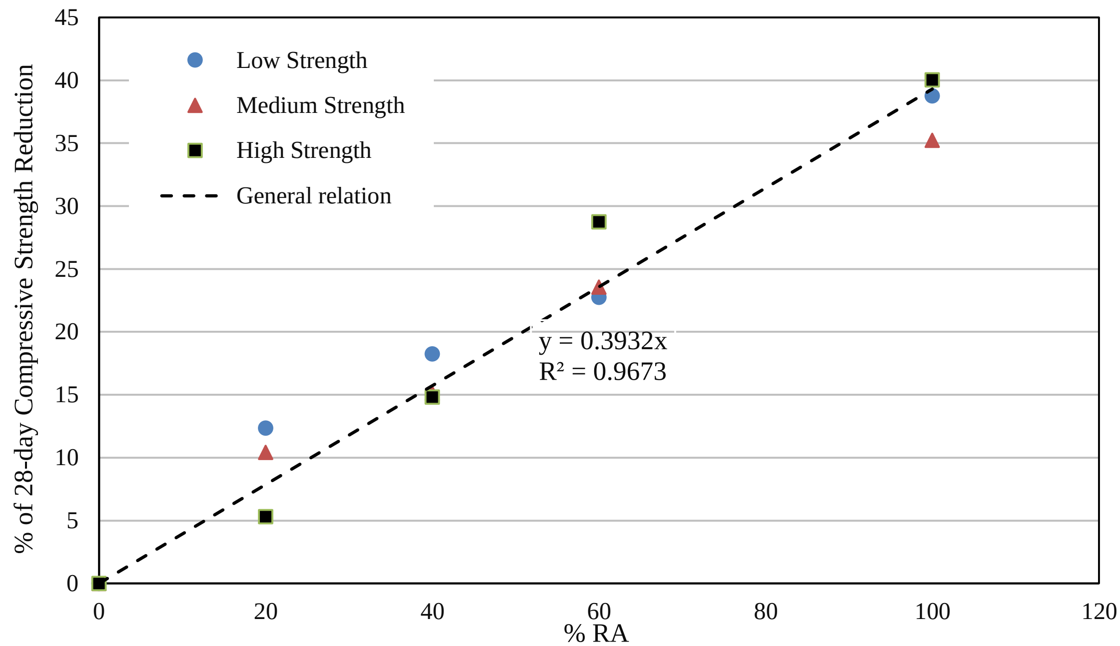

Figure 4.7: Relationship between RA replacement level and the % of 28-day compressive strength reduction.

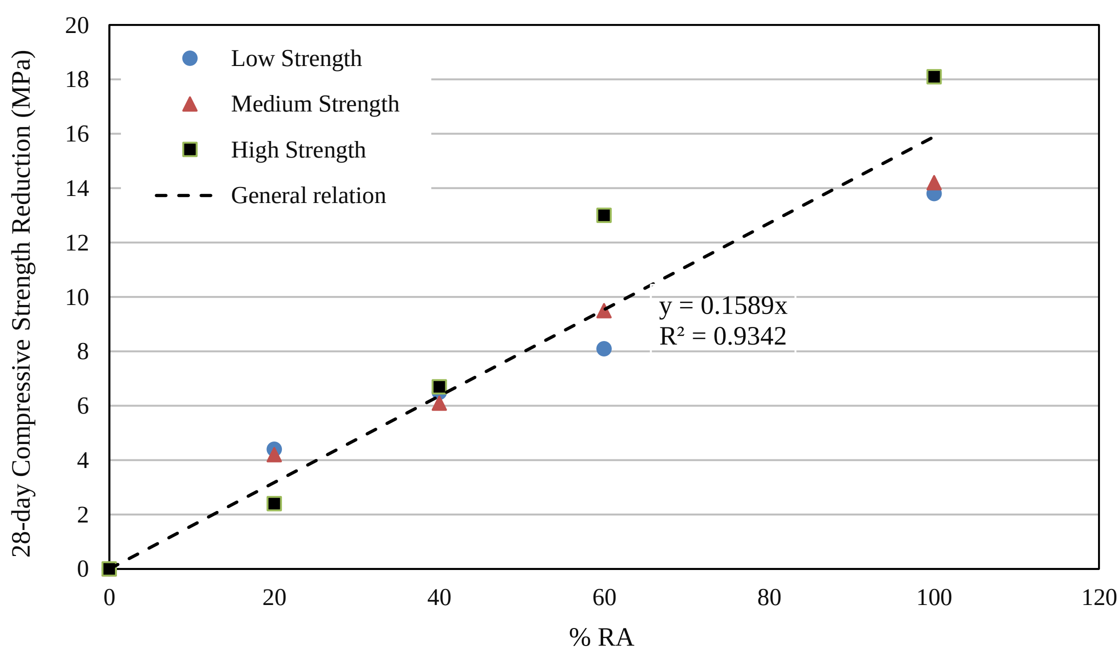

Figure 4.8: Relationship between RA replacement level and the amount of 28-day compressive strength reduction.

The results of the RAC reported in this study show high reduction in the compressive strength compared to the previous results of concrete with RA from CDW. The compressive strength reduction reached to 40% in case of full aggregate replacement with RA, but this value didn't exceed 18% in case of 40% RA replacement (which means reduction of no more than 7 MPa of the 28-day compressive strength of the conventional strength concrete). This value can be considered acceptable compared to the amount of saving and the other benefits of using the RA.

It is expected that the reduction in compressive strength of RAC is mainly due to the RA composition and stiffness, and due to the increase of effective water cement ratio which was used to compensate for the high water absorption of the RA. The water absorbed by the RA is expected to increase the porosity of concrete and decrease the bond between the RA and the new cement paste which in turn will lead to a decrease in the concrete strength.

Another potential interpretation of the compressive strength reduction in the RAC is associated with the micro-cracks in the RA. When the old concrete fails, micro-cracks usually extend through a high-porosity matrix band close to the aggregate, which is referred to as interfacial transition zone (ITZ). The mortar attachment on the RA surface is likely to contain part of the old ITZ with micro-cracks that merges with the new ITZ between the RA and the new cement paste (matrix), forming an extended weak band between the cement paste and RA, which will subsequently decrease the concrete strength [37].

On the other hand, when the strength of the new paste is superior to the old paste in the recycled aggregate, the failure occurs through the recycled aggregates (the recycled aggregate being the weakest point). This is most likely to happen in the concrete mixtures with low w/c ratio and high cement content. Visual observation of concrete specimens after failure indicated both the interfacial bond failure as well as the RA failure.

4.3 MODULUS OF ELASTICITY

The deformation of a concrete specimen under a given state of stress is highly influenced by its modulus of elasticity. High modulus of elasticity means that the concrete will exhibit less deformation compared to the one with a low modulus of elasticity under the same stress, even if they have the same compressive strength. The modulus of elasticity varies with the compressive strength of concrete, but it is also influenced by the properties of the constituent materials, and as such the composition of RA and its stiffness could have a great influence on the modulus of elasticity of RAC [38].

Table 4.2 summarizes the results of modulus of elasticity of the RAC specimens along with the reduction (in percent) associated with each replacement level of RA. It is clear from the data in Table 4.2 and Figure 4.9 that the reduction in the modulus of elasticity is proportional to the quantity of RA in RAC. The reduction in the modulus of elasticity was almost 14% to 16% when 40% RA is used while this reduction reached to 26% to 30% as the RA replacement level was increased to 60%, and it reached to 42% when full replacement of RA was used. The modulus of elasticity curve of the high strength mixtures is higher than the curves of the medium and low strength mixtures, which indicates that the compressive strength effect on the modulus of elasticity is still valid for RAC, but with different relationships as will be discussed later.

Table 4.2: Average modulus of elasticity of RAC.

RA Replacement Level, %	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Modulus of Elasticity (GPa)	Reduction due to RA, %	Modulus of Elasticity (GPa)	Reduction due to RA, %	Modulus of Elasticity (GPa)	Reduction due to RA, %
0	32.85	0.0	34.40	0.0	36.52	0.0
20	29.76	9.4	31.90	7.3	34.82	4.6
40	27.61	16.0	29.50	14.2	31.63	13.4
60	23.40	28.8	25.46	26.0	25.53	30.1
100	19.11	41.8	20.20	41.3	22.03	39.7

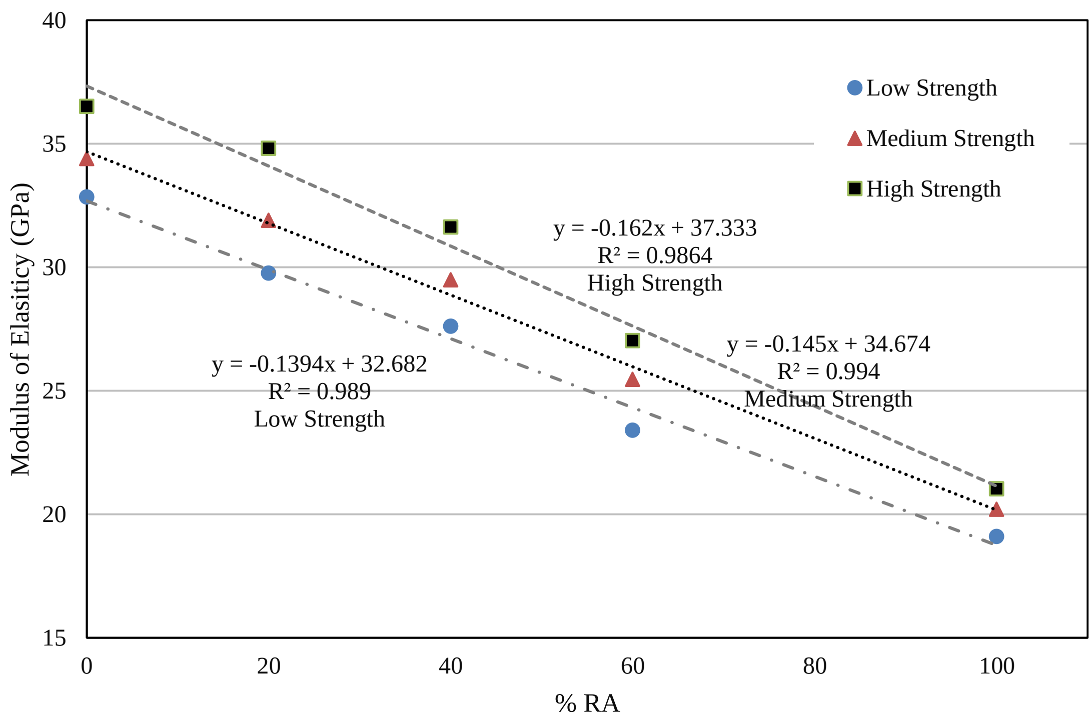

Figure 4.9: Influence of increasing RA replacement level on the modulus of elasticity of RAC.

It is clear from these results that the reduction in the modulus of elasticity of RAC is even more than the reduction in the compressive strength. The main reason for this reduction in the modulus of elasticity of RAC could be ascribed to the poor RA quality, which includes both of the low aggregate stiffness, due to its low density, and the high water absorption of aggregate, which was compensated for by increasing the effective w/c ratio in the mixtures. These factors influenced the modulus of elasticity of RAC in a similar way to the compressive strength.

The data in Figure 4.10 show that the reduction in the relative modulus of elasticity ($E_{RAC}/E_{control}$) of RAC can be expressed by the following equation:

$$y = -0.0042x + 1 \qquad (R^2 = 0.9851) \qquad (4)$$

Where: y is the relative modulus of elasticity, x is the level of RA replacement, and R^2 is the coefficient of determination.

The relative modulus of elasticity which reached to almost 0.58, for all the three concrete mixture series, when full replacement of RA was used, can be expressed by a general equation as sown in Figure 4.10, and this equation is independent of cement content and w/c ratio of the concrete mixtures.

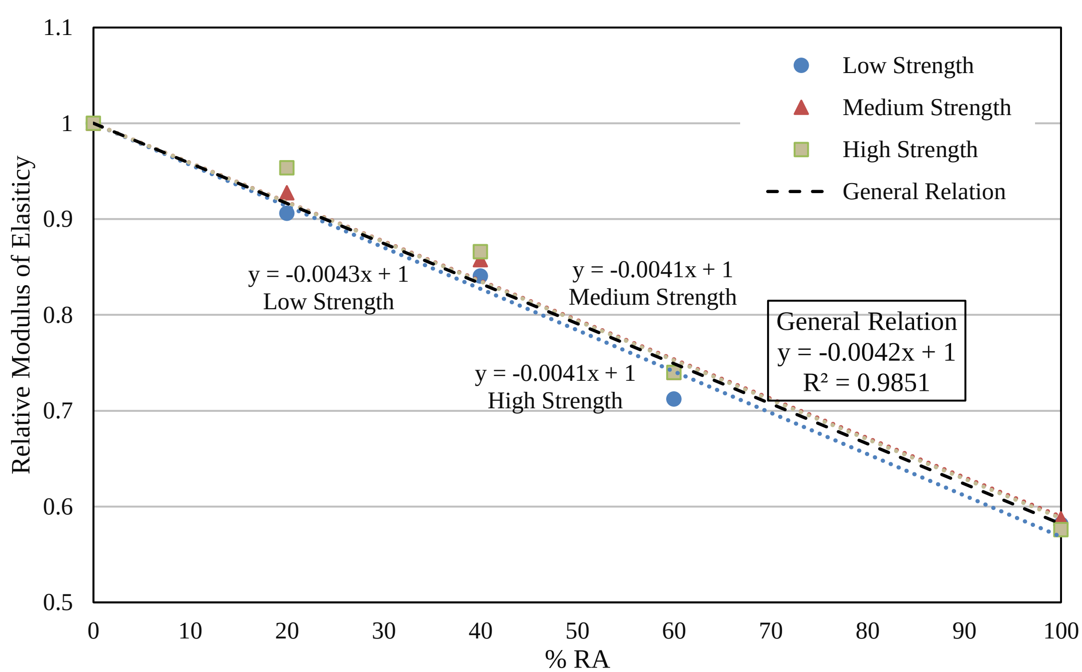

Figure 4.10: Influence of increasing the RA replacement level on the relative modulus of elasticity of RAC.

Figure 4.11 presents the relationship between the modulus of elasticity and the compressive strength of concrete with different types of aggregates according to Eurocode-02 (EC2) [39] and ACI 318-08 [36]. This figure also shows that most of the modulus of elasticity results for the RAC are above the proposed EC2 curve for sandstone aggregate concrete and almost similar to limestone aggregate. This means that the RAC will generally have elastic modulus which follows within the acceptable limits of the existing standards even when high level of RA replacement is used.

Figure 4.12 presents the relationship between the modulus of elasticity and the compressive strength of the three RAC mixtures. It can be observed that the different cement contents and w/c ratios for the three mixtures caused some changes in the relationship between the modulus of elasticity and compressive strength. These relationships are somewhat different from the proposed relationships between the modulus of elasticity and compressive strength of concrete which were proposed by EC2 [39] (Equation 5 below) and ACI 318 [36] (Equation 6 below) but they are still confined within the proposed curves of basalt aggregate concrete and sandstone aggregate concrete which were mentioned in EC2 [39].

EC2 equation for limestone aggregate concrete [39]:

$$E = 0.9 \times 22(fc'/10)^{0.3} \tag{5}$$

ACI 318 equation for normal strength concrete [36]:

$$E = 4.734 \times fc'^{0.5} \tag{6}$$

Where: E is the modulus of elasticity (GPa), and fc' is the compressive strength (MPa).

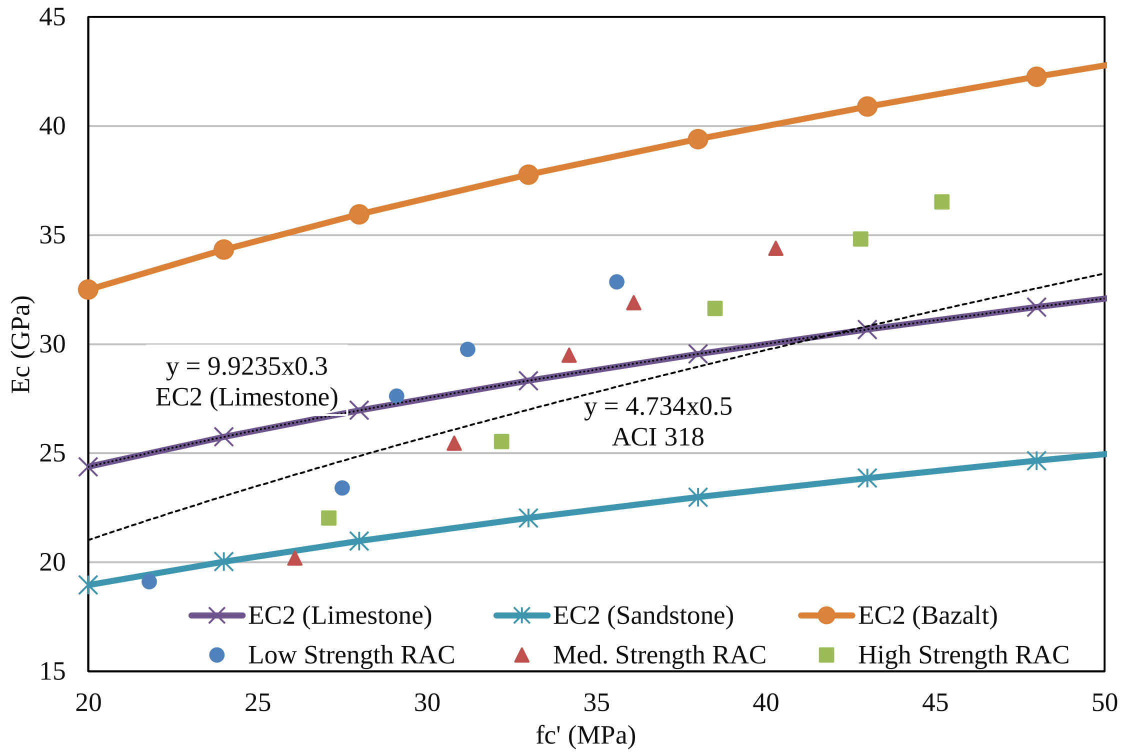

Figure 4.11: Relationship between modulus of elasticity and compressive strength of concrete with different types of aggregates.

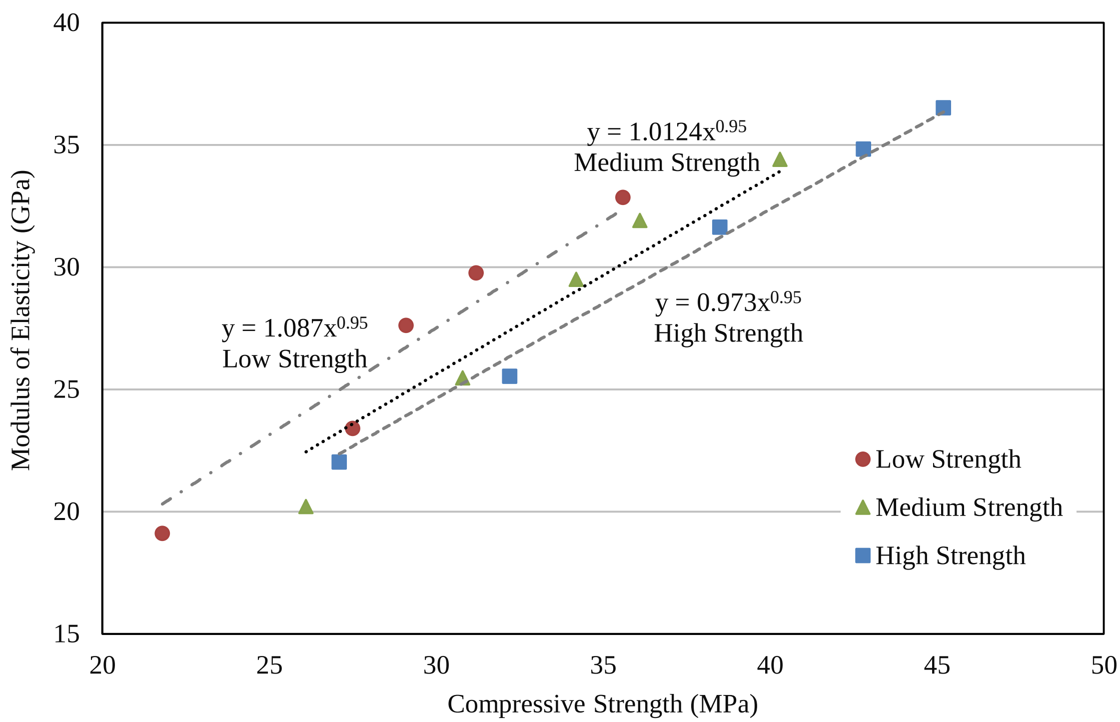

Figure 4.12: Relationship between modulus of elasticity and compressive strength of the three RAC mixtures.

Several authors presented mathematical formulations to correlate compressive strength and modulus of elasticity of concretes with coarse recycled aggregates. The equations proposed by those authors are presented in Table 4.3. It is clear that these relationships are different from each other, and also different from the relationships that were derived in this study. This is mainly because the relationship between modulus of elasticity and compressive strength depends on the aggregate type as well, and not only on the w/c ratio and cement content of concrete mixtures. It is also a good indication that previous relationships which were derived concrete with different types of aggregates and different RA quality are not suitable for the local RAC.

A variation in the models proposed in this study can be noted. This is probably due to the quality of RA used. As expected, none of the proposed relationships were close to the ACI 318 relationship (Equation 6).

Table 4.3: Equations correlating RAC compressive strength with modulus of elasticity.

Author	Equation
Low Strength RAC (Current study)	$E = 1.087 \times fc'^{0.95}$
Medium Strength RAC (Current study)	$E = 1.0124 \times fc'^{0.95}$
High Strength RAC (Current study)	$E = 0.973 \times fc'^{0.95}$
Radonjanin et al. [40]	$E = 11.48 \times fc'^{0.2084}$
Corinaldesi [41]	$E = 8.2 \times fc'^{1/3}$
Bezerra et al. [42]	$E = 2.58 \times fc'^{0.63}$
Lovato [43]	$E = 5.74 \times fc'^{0.5} - 13.39$
Ravindrarajah et al. [44]	$E = 3.48 \times fc'^{0.5} + 13.1$
Mellmann et al. [45]	$E = 0.378 \times fc' + 8.243$

4.4 SPLITTING TENSILE STRENGTH

As mentioned earlier, the splitting tensile strength is an indirect method to estimate the tensile strength of concrete. Table 4.4 summarizes the results of this strength of RAC specimens along with the reduction percentage associated with each replacement level of RA. It is clear from the data in Table 4.4 and Figure 4.13 that the relationship between the splitting tensile strength reduction and RA replacement level is linear as evidenced by the high values of R^2 for the three types of mixtures.

The reduction in the splitting tensile strength is almost 14% to 17% when 40% of RA was used while this reduction reached to 23% to 28% when the RA replacement level was increased to 60%, and it reached to 37% when full replacement of RA was used. These values are very similar to the values of compressive strength reduction, which means that the poor RA quality and the increase of effective w/c ratio affected the splitting tensile strength of concrete in a similar way to that noted in the compressive strength. Similar to the modulus of elasticity, the splitting tensile strength curve of the high strength concrete is higher than the curves of the medium and low strength mixtures, which indicates that the compressive strength effect on the splitting tensile strength is still valid for RAC.

Table 4.4: Average splitting tensile strength of RAC.

RA Replacement Level, %	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Splitting Tensile (MPa)	Reduction due to RA, %	Splitting Tensile (MPa)	Reduction due to RA, %	Splitting Tensile (MPa)	Reduction due to RA, %
0	2.67	0.0	2.84	0.0	3.13	0.0
20	2.43	9.0	2.56	9.8	2.98	4.7
40	2.29	14.3	2.35	17.4	2.66	15.0
60	2.07	22.7	2.11	25.8	2.25	28.2
100	1.75	34.4	1.87	34.3	1.98	36.7

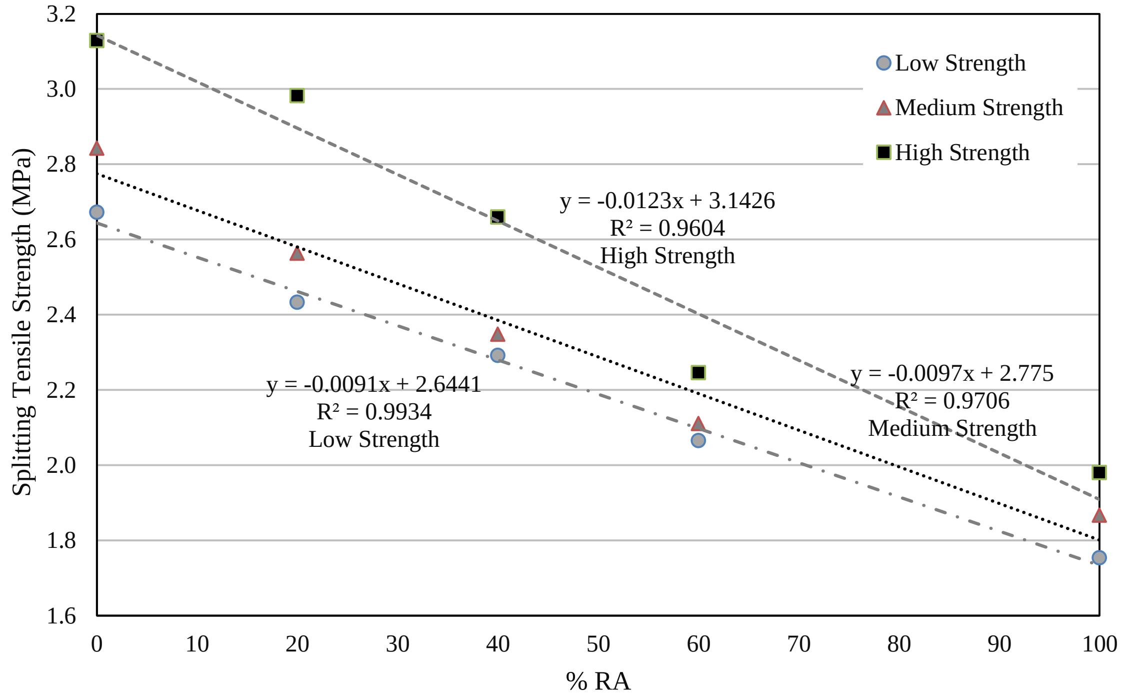

Figure 4.13: Influence of increasing RA replacement level on the splitting tensile strength of RAC.

The data in Figure 4.14 show that the reduction in the relative splitting tensile strength ($fst_{RAC}/fst_{control}$) of RAC can be expressed by the following equation.

$$y = -0.0037x + 1 \qquad (R^2 = 0.964) \qquad (7)$$

Where: y is the relative splitting tensile strength, x is the level of RA replacement, and R^2 is the coefficient of determination.

The relative splitting tensile strength which reached to almost 0.63, for all the three concrete mixture series, when full replacement of RA was used, can be expressed by a general equation as sown in Figure 4.14, and this equation is independent of cement content and w/c ratio of concrete.

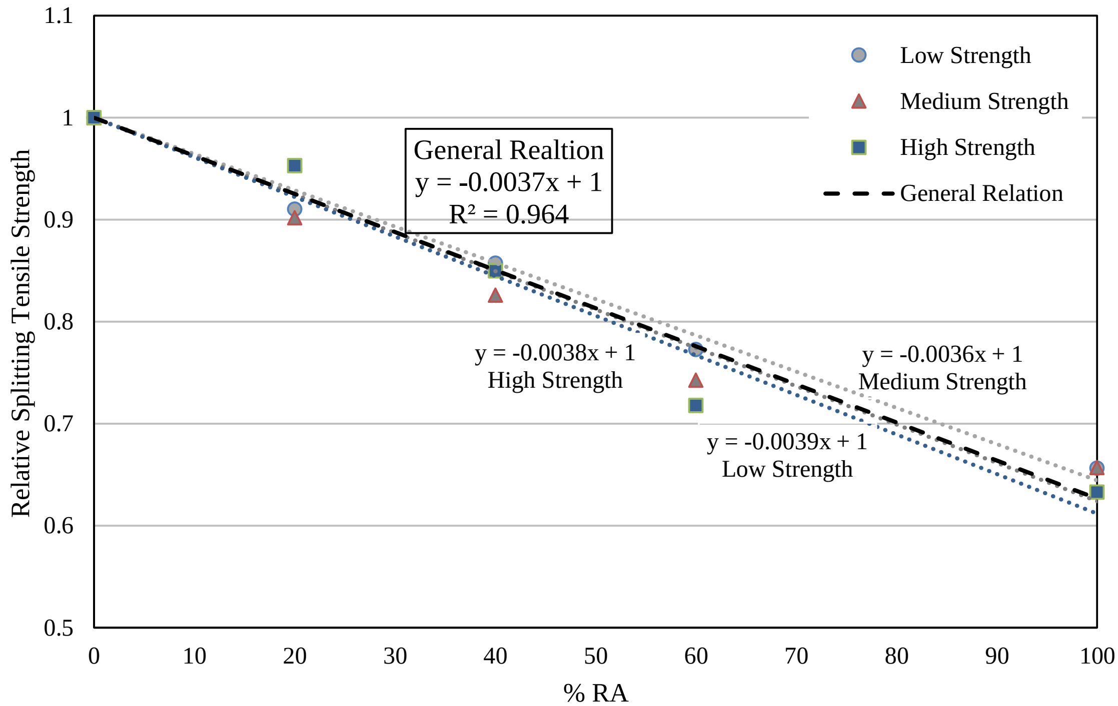

Figure 4.14: Influence of increasing RA replacement level on the relative splitting tensile strength of RAC.

Figure 4.15 presents the relationship between the splitting tensile strength and compressive strength for the three RAC mixtures. It can be observed that the different cement contents and w/c ratios for the three mixtures did not considerably change the relationship between the splitting tensile and compressive strength (where the three graphs are close to each other). These relationships, which are close to each other, are lower than the proposed relationships between the splitting tensile and compressive strength of concrete which were proposed by the ACI 318 [36] and Gaedicke [46] for limestone aggregate concrete.

ACI 318 equation for normal strength concrete [36]:

$$f_{st} = 0.56 \times fc'^{0.5} \qquad (8)$$

Gaedicke [46] equation for limestone aggregate concrete:

$$f_{st} = 0.203 \times fc'^{0.811} \tag{9}$$

Where: f_{st} is the splitting tensile strength (MPa), and fc' is the compressive strength (MPa).

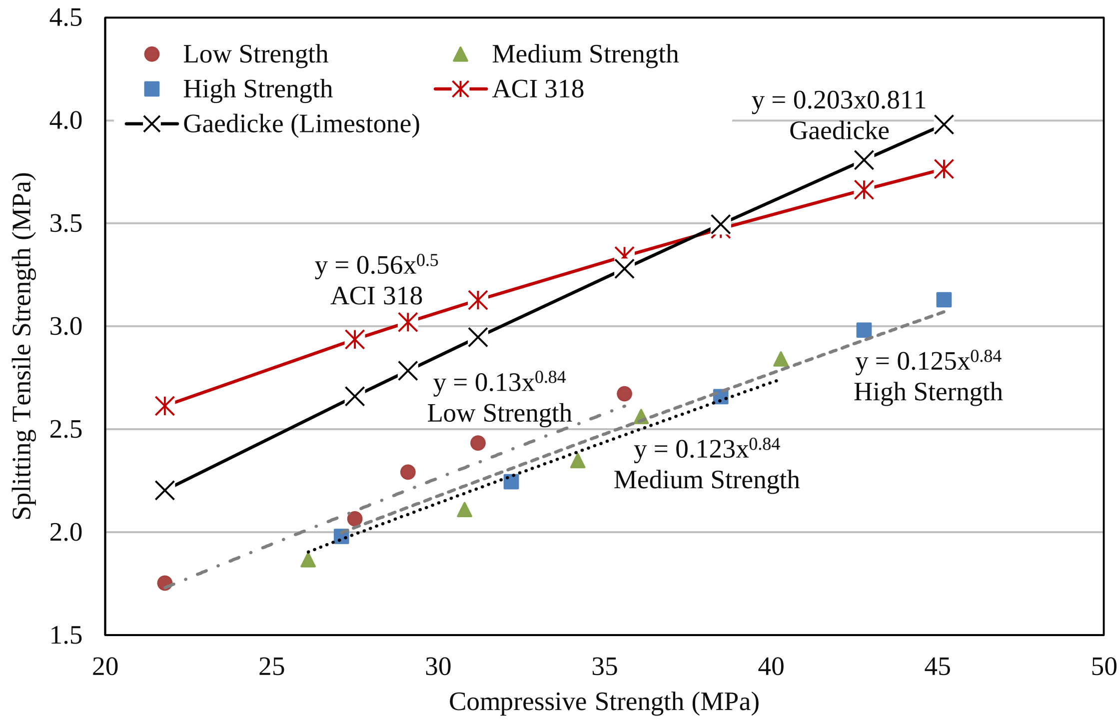

Figure 4.15: Relationship between splitting tensile strength and compressive strength of the three RAC mixtures.

Dilbas et al. [47] proposed another correlation to correlate compressive strength and splitting tensile strength of concretes with coarse recycled aggregates. The model proposed by Dilbas and the three models proposed by utilizing the data developed in this study for the RAC are shown in Table 4.5.

Table 4.5: Equations correlating RAC compressive strength with splitting tensile strength.

Author	Equation
Low Strength RAC (Current study)	$f_{st} = 0.13 \times fc'^{0.84}$
Medium Strength RAC (Current study)	$f_{st} = 0.123 \times fc'^{0.84}$
High Strength RAC (Current study)	$f_{st} = 0.125 \times fc'^{0.84}$
Dilbas et al. [47]	$f_{st} = 0.07 \times fc' - 0.19$

As expected none of the reported relationships were close to the ACI 318 relationship, or the equation proposed by Gaedicke [46] for the limestone aggregate concrete (Equations 8 and 9). It is clear, from these different models, that the relationship between the compressive strength and splitting tensile strength of concrete depends on the type and quality of aggregates. This is why the previous relationships which were proposed by the ACI and the previous studies are not applicable for the local RAC, and it is therefore required to derive relationships that represent the RAC produced utilizing the local aggregates.

4.5 FLEXURAL STRENGTH

Flexural strength is another indirect means to estimate the tensile strength of concrete. It is often represented by the modulus of rupture. Table 4.6 summarizes the results of modulus of rupture of the RAC specimens along with the percentage reduction associated with each replacement level of RA. It is clear from Table 4.6 and Figure 4.16 that the reduction in the modulus of rupture is linearly proportional to the RA replacement level.

The reduction in the modulus of rupture is almost 16% to 20% when 40% RA were used while this reduction reached to 28% when the RA replacement level was increased to 60%, and it reached to 33% when full replacement of RA was used. These values are close, but also have some discrepancies, to the values of reduction in the splitting tensile strength. These discrepancies are probably because of the small size of the specimens (160×50×50 mm prism) compared to the maximum coarse aggregate size (19 mm) in the mixtures, which could result into some segregation and non-homogeneous concrete when the specimens were poured. The modulus of rupture was mainly affected by the same factors that influenced the splitting tensile strength of concrete.

Table 4.6: Average modulus of rupture of RAC.

RA Replacement Level, %	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Modulus of Rupture (MPa)	Reduction due to RA, %	Modulus of Rupture (MPa)	Reduction due to RA, %	Modulus of Rupture (MPa)	Reduction due to RA, %
0	4.11	0.0	4.70	0.0	5.90	0.0
20	3.62	11.7	4.19	10.8	5.25	11.1
40	3.33	19.0	3.94	16.1	4.70	20.4
60	3.20	22.1	3.75	20.1	4.25	28.1
100	2.92	28.8	3.50	25.4	3.98	32.7

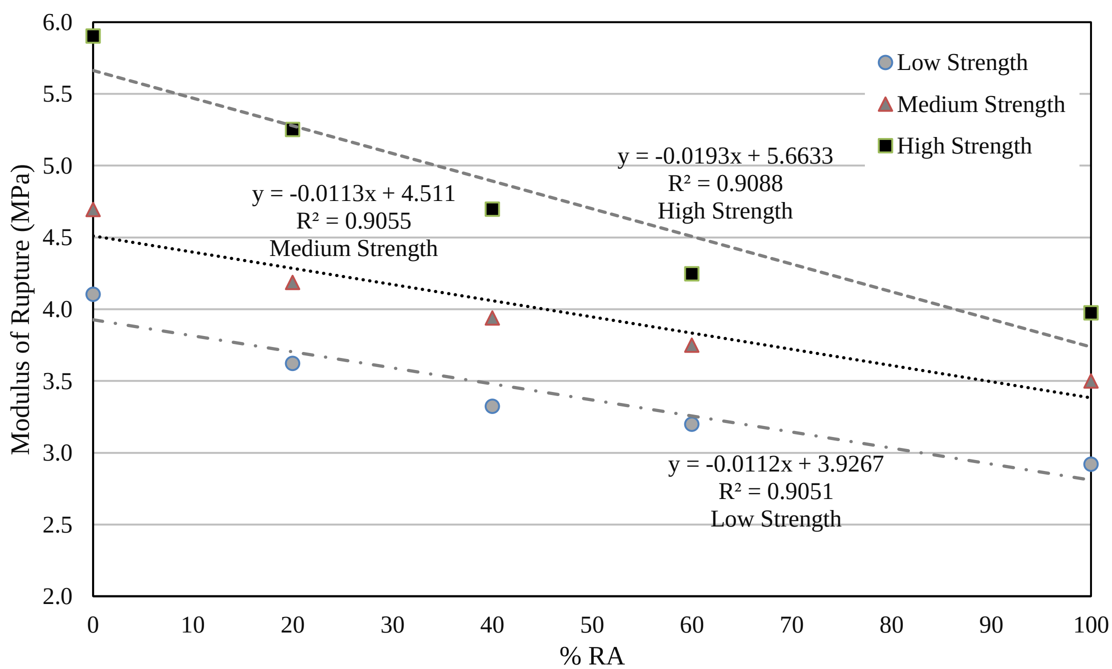

Figure 4.16: Influence of increasing RA replacement level on the flexural strength of RAC.

The data in Figure 4.17 show that the reduction in the relative flexural strength ($fr_{RAC}/fr_{control}$) of RAC can be expressed by the following equation:

$$y = -0.0034x + 1 \qquad (R^2 = 0.8102) \qquad (10)$$

Where: y is the relative flexural strength, x is the level of RA replacement, and R^2 is the coefficient of determination.

The relative modulus of rupture was in the range of 0.62 and 0.72, for all the three concrete mixtures series, when full replacement of RA was used, can be expressed by a general equation as shown in Figure 4.17, and this equation is independent of cement content and w/c ratio of the concrete mixtures.

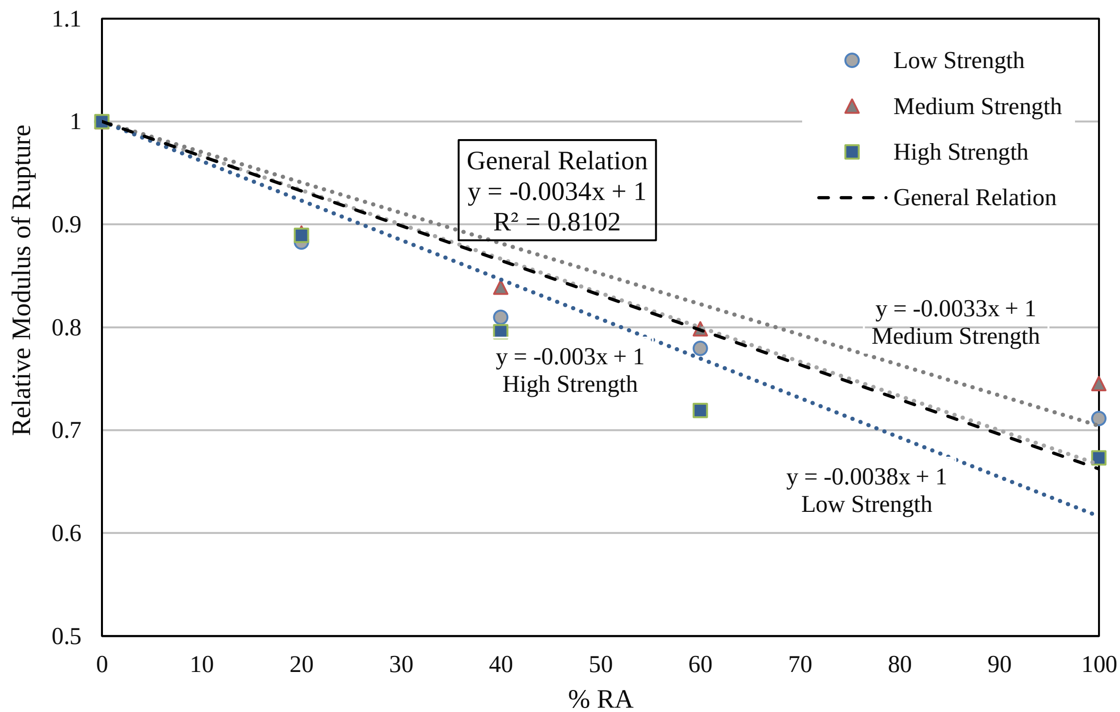

Figure 4.17: Influence of increasing RA replacement level on the relative reduction in the flexural strength of RAC.

Figure 4.18 presents the relationship between the modulus of rupture and compressive strength for the three RAC mixtures. It can be observed that the different cement contents and w/c ratios for the three mixtures caused some changes in the relationship between the modulus of rupture and compressive strength. These relationships, which are not close to each other, are slightly more than the proposed relationships between the modulus of rupture and compressive strength of conventional concrete which were proposed by the ACI 318 [36] and Garber [48].

ACI 318 equation for normal strength concrete [36]:

$$f_r = 0.62 \times fc'^{0.5} \tag{11}$$

Garber [48] equation for limestone aggregate concrete:

$$f_r = 0.393 \times fc'^{0.667} \tag{12}$$

Where: f_r is the modulus of rupture (MPa), and fc' is the compressive strength (MPa).

The flexural test has been conducted by a screw type testing machine. During the test, there were some difficulties and faults in controlling the loading rate in that machine. This could be the reason for the high values of the modulus of rapture compared to the values in the literature and in ACI 318 [36], and this could be also another reason for the discrepancies in the results which were described above.

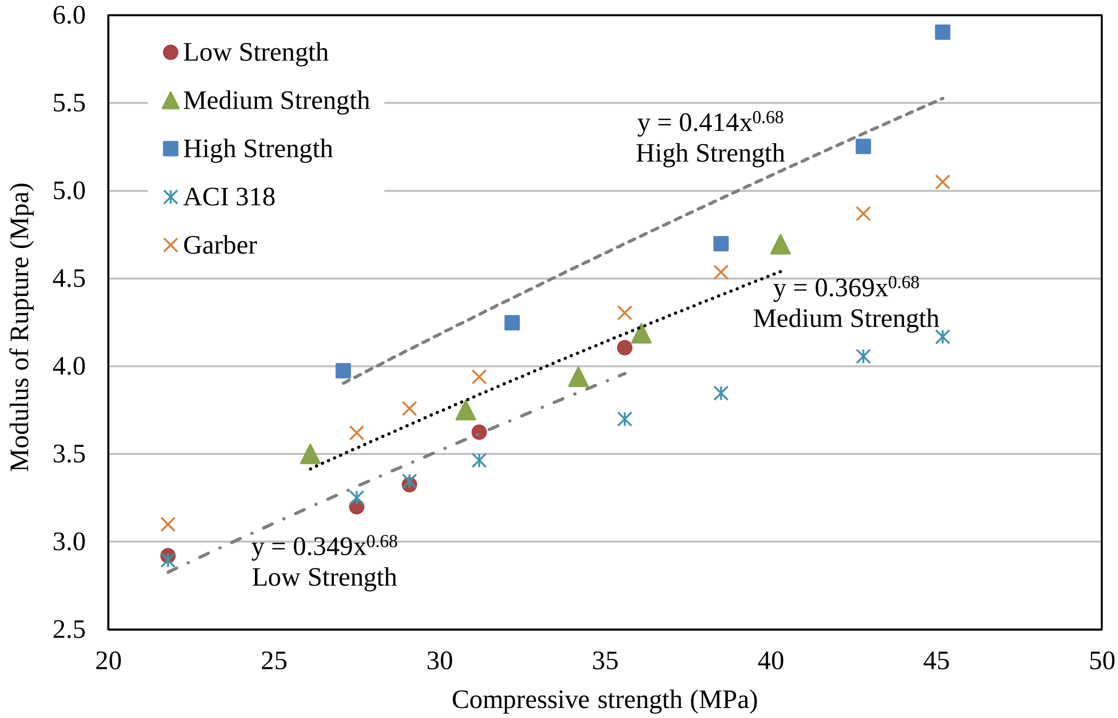

Figure 4.18: Relationship between modulus of rupture and compressive strength of the three RAC mixtures.

The three models developed from the data of this study for the RAC are shown in Table 4.7. As expected, none of these relationships were close to the ACI 318 relationship, or the equation proposed by Garber [48] for the limestone aggregate concrete (Equations 11 and 12). It is clear, from these different models, that similar to the modulus of elasticity and splitting tensile strength, the relationship between flexural strength and compressive strength also depends on the aggregate type and quality, and it is not suitable to use the previous derived equations for the local RAs.

Table 4.7: Equations correlating RAC compressive strength with modulus of rupture.

Author	Equation
Low Strength RAC (Current study)	$f_r = 0.349 \times fc'^{0.68}$
Medium Strength RAC (Current study)	$f_r = 0.369 \times fc'^{0.68}$
High Strength RAC (Current study)	$f_r = 0.414 \times fc'^{0.68}$

4.6 BOND STRENGTH

Table 4.8 summarizes the bond strength of the RAC along with the reduction associated with each replacement level of RA. It is clear from the data in Table 4.8 and Figure 4.19 that the relationship between the reduction in the bond strength and RA replacement level is linear with high R^2 values.

It can be easily noted that there is a great disparity between the bond strength results of the low strength concrete mixtures and the medium and high strength concrete mixtures, where the recorded bond strength for the low strength mixtures are much lower than the results of the other two mixtures. There are two probable reasons for this disparity in the bond strength results: (1) The inaccurate control of loading rate in the same screw type testing machine which was described in in Section 4.6, and (2) There is a possibility that misalignment of the bonded steel bars occurred during casting or during testing, which means that some of the steel bars were tilted and were not pulled out from the concrete in perfect normal angle. This misalignment could be the principle reason of results disparity.

The reduction in the bond strength ranged between 10% to 21% when 40% of RA was used while this reduction ranged between 16% to 28% when the RA replacement level was increased to 60%, and it reached to 51% when full replacement of RA was used. The bond behavior of RAC is somewhat similar to the behavior of splitting tensile strength because the splitting tensile highly affects the concrete bearing strength at the interfacial zone between the concrete and the ribs of the steel bars. It is also believed that the shape of the RA increases the segregation during compaction of concrete which, in turn, affects the bond strength between the RAC and the steel bars [25].

Table 4.8: Average bond strength of RAC.

RA Replacement Level, %	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Bond Strength (MPa)	Reduction in Bond Strength, %	Bond Strength (MPa)	Reduction in Bond Strength, %	Bond Strength (MPa)	Reduction in Bond Strength, %
0	14.84	0.0	23.08	0.0	24.59	0.0
20	13.77	7.2	21.60	6.4	22.35	9.1
40	13.29	10.5	18.20	21.2	21.23	13.6
60	12.39	16.5	15.72	31.9	18.62	24.3
100	7.80	47.4	11.20	51.5	12.01	51.1

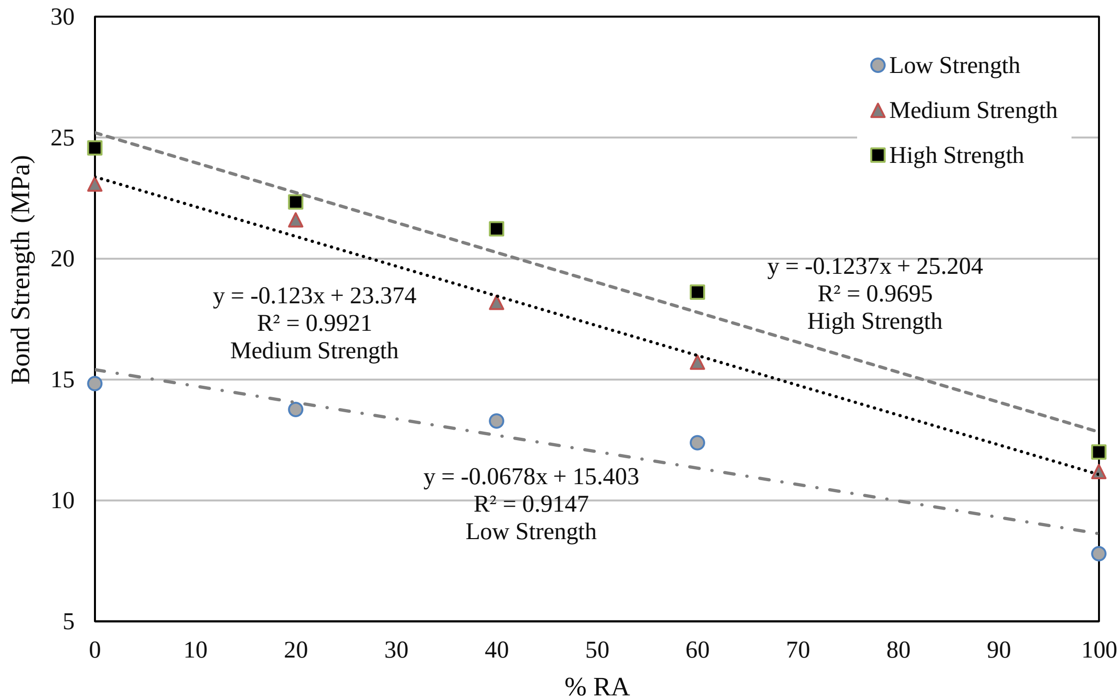

Figure 4.19: Influence of increasing RA replacement level on the bond strength of RAC.

Similar to the other mechanical properties, the bond strength curve of the high strength concrete mixtures is more than the curves of the medium and low strength concrete mixtures, which indicates that the compressive strength effect on the bond strength between concrete and steel is still valid for RAC.

The data in Figure 4.20 show that the decrease in the relative bond strength ($fb_{RAC}/fb_{control}$) of RAC can be expressed by the following equation.

$$y = -0.0046x + 1 \qquad (R^2 = 0.9326) \qquad (13)$$

Where: y is the relative bond strength, x is the level of RA replacement, and R^2 is the coefficient of determination.

The relative bond strength relationships for three mixtures series are not close to each other like the previous reported mechanical properties. They reached to an amount between 0.48 and 0.6, for all the three concrete mixtures series, when full replacement of RA was used. The relationship between the relative bond strength and the RA replacement level is expressed by a general equation as shown in Figure 4.20.

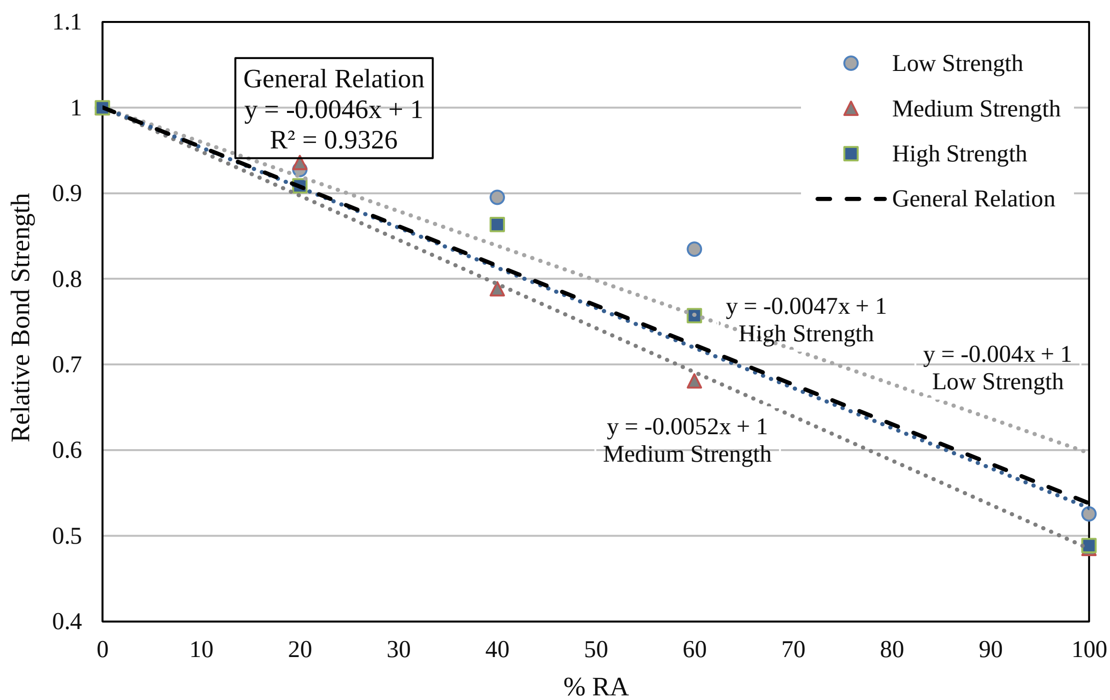

Figure 4.20: Influence of increasing RA replacement level on the relative bond strength of RAC.

Figure 4.21 presents the relationship between the bond strength and compressive strength for the three RAC mixtures. It can be observed that the different cement contents and w/c ratios for the three mixtures caused some changes in the relationship between the bond strength and compressive strength. The relationships for the low, medium and high strength concrete mixtures are confined between the following upper and lower limits which were developed based on the 95% confidence interval statistics conducted on all recorded data.

Bond strength vs. compressive strength upper limit:

$$f_b = 0.14 \times fc'^{1.4} \tag{14}$$

Bond strength vs. compressive strength lower limit:

$$f_b = 0.10 \times fc'^{1.4} \tag{15}$$

Where: f_b is the bond strength (MPa), and fc' is the compressive strength (MPa).

The three relationships between bond strength and compressive strength of the three RAC series are shown in Table 4.9

Table 4.9: Equations correlating RAC compressive strength with bond strength.

Concrete	Equation
Low Strength RAC (Current study)	$f_b = 0.11 \times fc'^{1.4}$
Medium Strength RAC (Current study)	$f_b = 0.132 \times fc'^{1.4}$
High Strength RAC (Current study)	$f_b = 0.123 \times fc'^{1.4}$

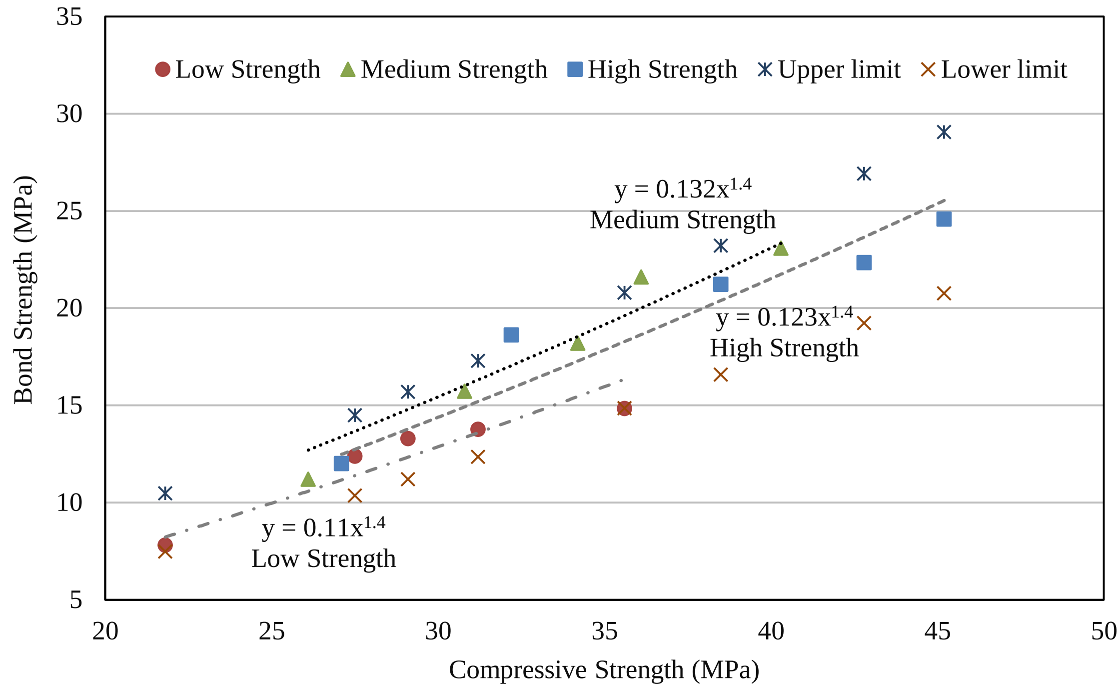

Figure 4.21: The relationships between bond strength and compressive strength of the three RAC mixtures series.

4.7 ABRASION RESISTANCE

Abrasion resistance test was conducted to evaluate the effect of RA on the abrasion resistance of concrete. The mass loss and height loss of the cubic concrete specimens were recorded before and after abrading of the specimens by the sand papers. The results of height loss and mass loss percentage are summarized in Table 4.10 and Table 4.11 along with the % of increase of the abrasion resistance associated with each replacement level of RA.

The data in Table 4.10 and Table 4.11 show that the effect of RA incorporation on the height and mass loss of concrete by abrasion is small. For the low strength mixtures, the percentage of height loss changed from 1.38% to 1.42% when full RA replacement were used, while for the medium strength and high strength mixtures these values changed between 0.8% and 0.84%, and between 0.49 and% 0.51%, respectively.

Table 4.10: Average abrasion results of RA by height.

RA Replacement Level	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Height Loss %	% Increase	Height Loss %	% Increase	Height Loss %	% Increase
0	1.38	0.00	0.80	0.00	0.49	0.00
20	1.39	0.51	0.81	1.14	0.49	0.82
40	1.39	0.87	0.82	2.64	0.50	2.06
60	1.41	1.81	0.83	3.76	0.50	3.09
100	1.42	3.12	0.84	5.13	0.51	4.53

Table 4.11: Average abrasion results of RA by mass.

RA Replacement Level	Low Strength Mix		Medium Strength Mix		High Strength Mix	
	Mass Loss %	% Increase	Mass Loss %	% Increase	Mass Loss %	% Increase
0	1.38	0.00	0.78	0.00	0.48	0.00
20	1.38	0.32	0.79	1.22	0.49	0.90
40	1.39	0.83	0.80	2.89	0.49	2.15
60	1.40	1.92	0.81	3.92	0.50	2.98
100	1.42	3.23	0.82	5.45	0.50	4.44

It was expected that the high porosity of RA would result into a better bond between the cement paste and the RA which in turn will lead to enhancement of the abrasion resistance of the RAC. However, this enhancement of the bond between the RA and the cement paste is also expected to be opposed by the increase in the effective w/c ratio which would decrease the bond. In addition, the incorporation of RA increases the amount of cement matrix in the concrete, which is more easily abraded than the grains of natural aggregates, and this is another factor that may reduce the abrasion resistance of RAC.

It seems that all these different factors together lead into small or negligible decrease of the abrasion resistance of RAC as can be seen in Figure 4.22 through Figure 4.24. The percentage increase in the height loss and mass loss by abrasion ranged between 3% to 6% when full replacement of RA was used. It can also be noticed that the abrasion percentage is higher for the proposed low strength mixtures which contains less cement content and higher w/c ratio, as a result of the higher porosity and the higher amount of cement matrix in this concrete category.

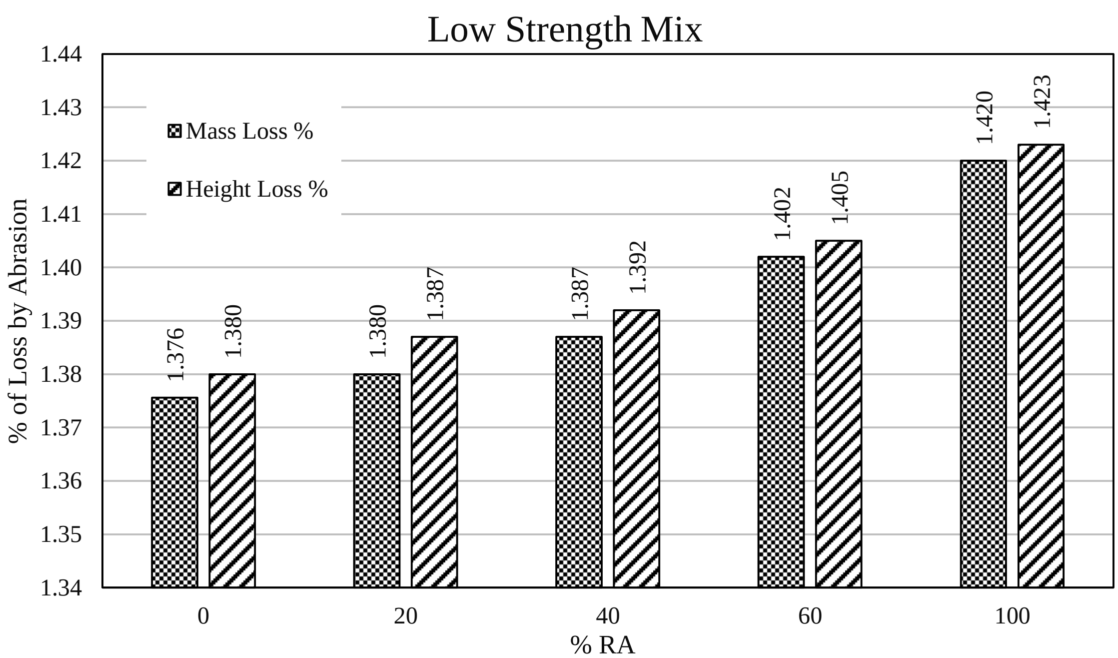

Figure 4.22: Mass loss and height loss by abrasion in low strength concrete mixtures.

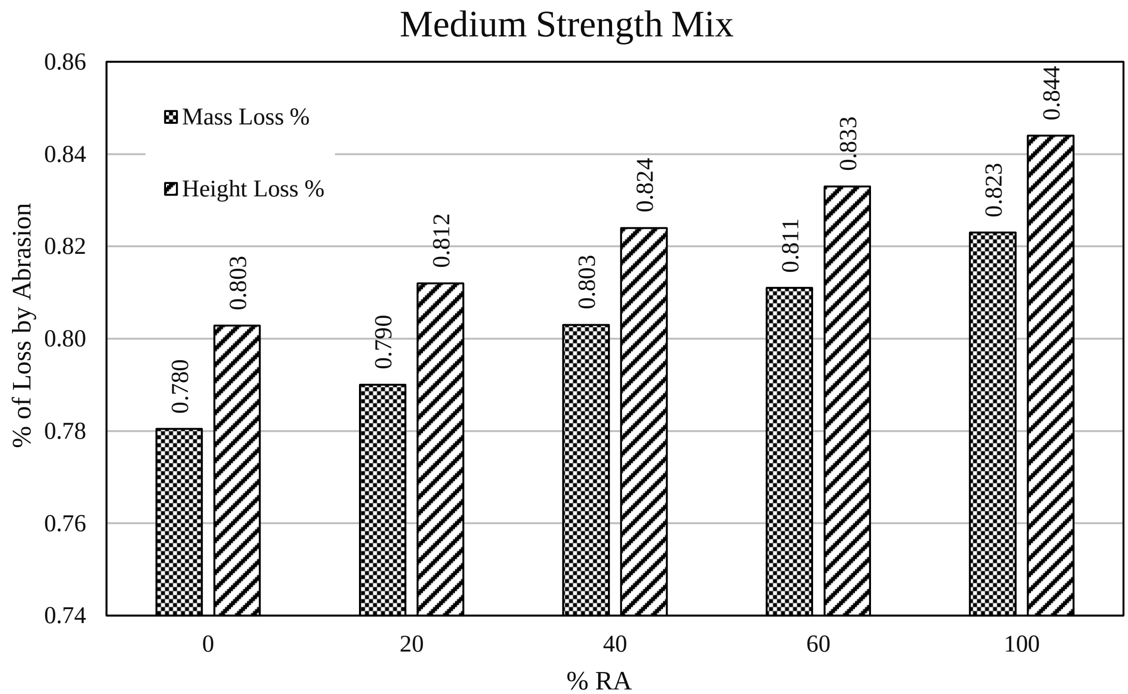

Figure 4.23: Mass loss and height loss by abrasion in medium strength concrete mixtures.

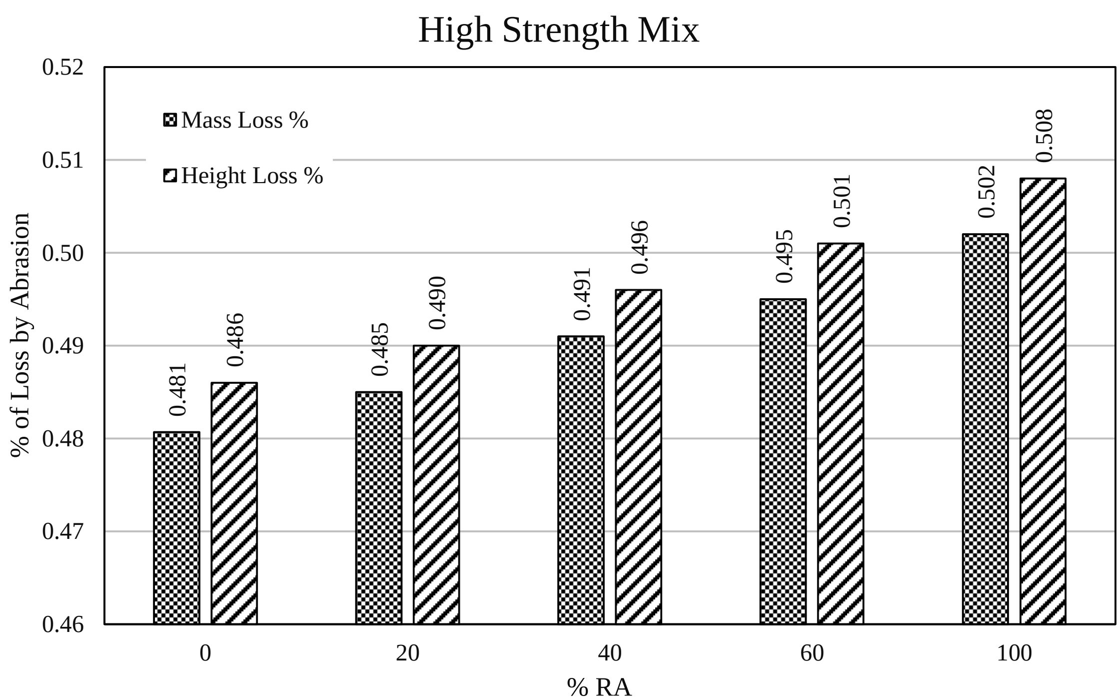

Figure 4.24: Mass loss and height loss by abrasion in high strength concrete mixtures

Although the incorporation of RA caused minor or negligible change in the abrasion resistance of concrete, but it is still clear from the data in Figures 4.25 and 4.26 that the relationship between the increase in abrasion resistance and RA replacement level is linear with high R^2 values. The relationships between the RA replacement level and the relative height and mass loss for three mixtures series are not close to each other like the previous reported mechanical properties. They reached to an amount between 1.03 and 1.05 %, for all the three concrete mixtures series, when full replacement of RA was used. The relationship between the relative mass loss and the RA replacement level is expressed by several equations shown in Figures 4.25 and 4.26.

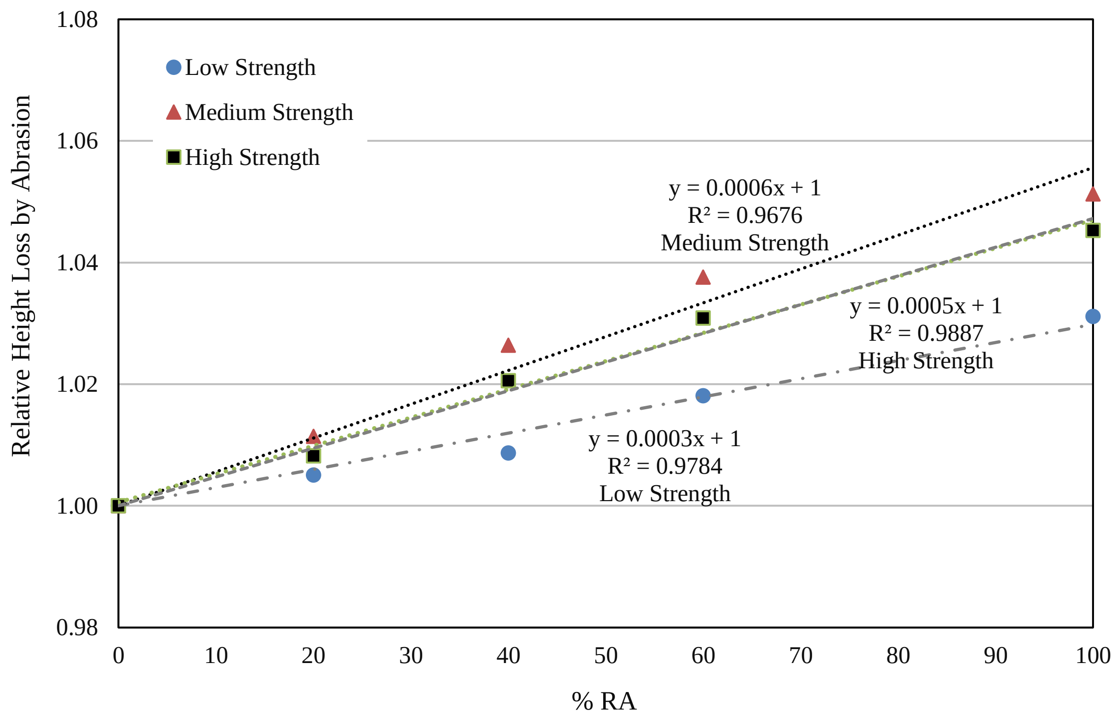

Figure 4.25: Relationships between the RA replacement level and the relative height loss by abrasion.

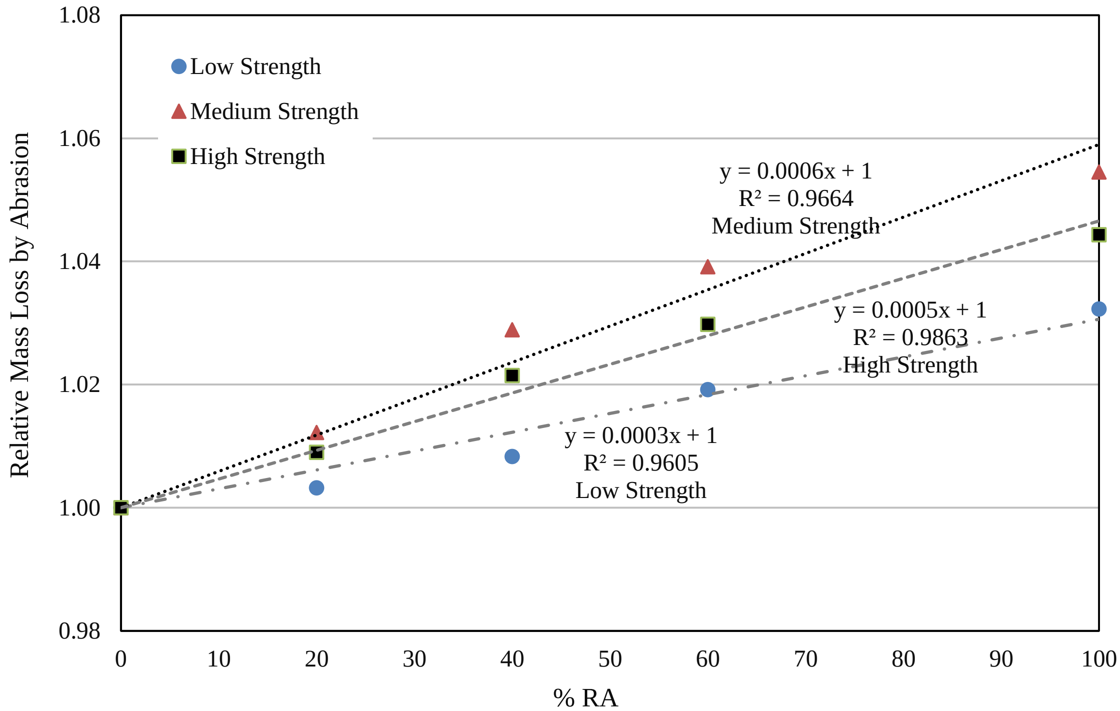

Figure 4.26: Relationships between the RA replacement level and the % of mass loss by abrasion.

4.8 DRYING SHRINKAGE

The loss of capillary water of the hardened concrete leads to its drying shrinkage. This shrinkage generates tensile stresses in the concrete which may lead to cracking if there is restraint to its movement of concrete.

Literature review on RAC reported a considerable increase of drying shrinkage of concrete as the incorporation level of RA increased. It was reported that the high water absorption of RA would aggravate both drying shrinkage and creep of concrete. Different limits of concrete free shrinkage have been set by different agencies to ensure high cracking resistance of concrete, most of these limits were around 500 microstrain at the age of 28 days [49]. The ACI limit of drying shrinkage is 500 microstrain at the age of 7 days, this limit will be considered in this research as the threshold limit for the drying shrinkage of structural concrete.

Tables 4.12 through 4.14 summarize the drying shrinkage of the three RAC mixtures during the first 90 days following the water curing period of the specimens. These results are also represented graphically in Figures 4.27 through 4.29.

Table 4.12: Drying shrinkage of the low strength RAC.

Duration (days)	Drying Shrinkage (Microstrain)				
	RC 1-1	RC 1-2	RC 1-3	RC 1-4	RC 1-6
7	257	310	464	498	559
14	300	411	599	670	713
28	329	484	611	791	845
56	357	496	625	806	861
90	385	536	653	891	875

Table 4.13: Drying shrinkage of the medium strength RAC.

Duration (days)	Drying Shrinkage (Microstrain)				
	RC 2-1	RC 2-2	RC 2-3	RC 2-4	RC 2-6
7	115	188	329	373	419
14	188	286	417	500	495
28	237	383	501	561	627
56	283	428	571	692	733
90	295	450	655	719	778

Table 4.14: Drying shrinkage of the high strength RAC.

Duration (days)	Drying Shrinkage (Microstrain)				
	RC 3-1	RC 3-2	RC 3-3	RC 3-4	RC 3-6
7	78	168	189	303	234
14	144	261	311	413	420
28	224	354	433	554	606
56	263	413	486	617	730
90	286	444	527	644	744

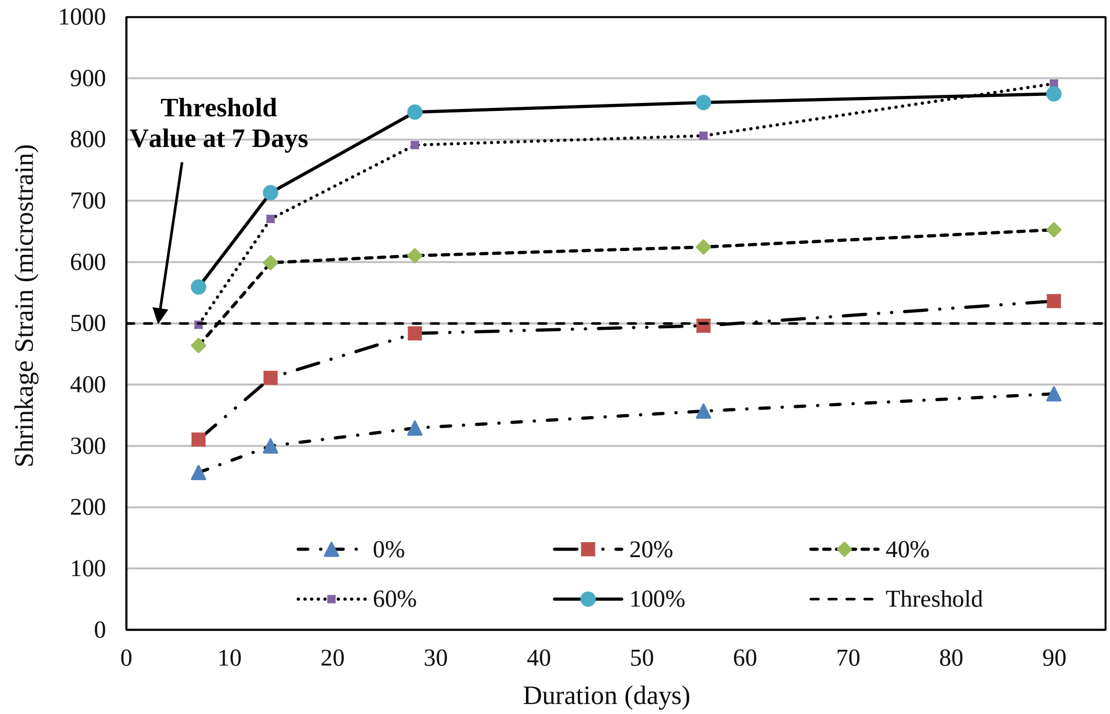

Figure 4.27: Drying shrinkage strain in Low Strength Mixtures.

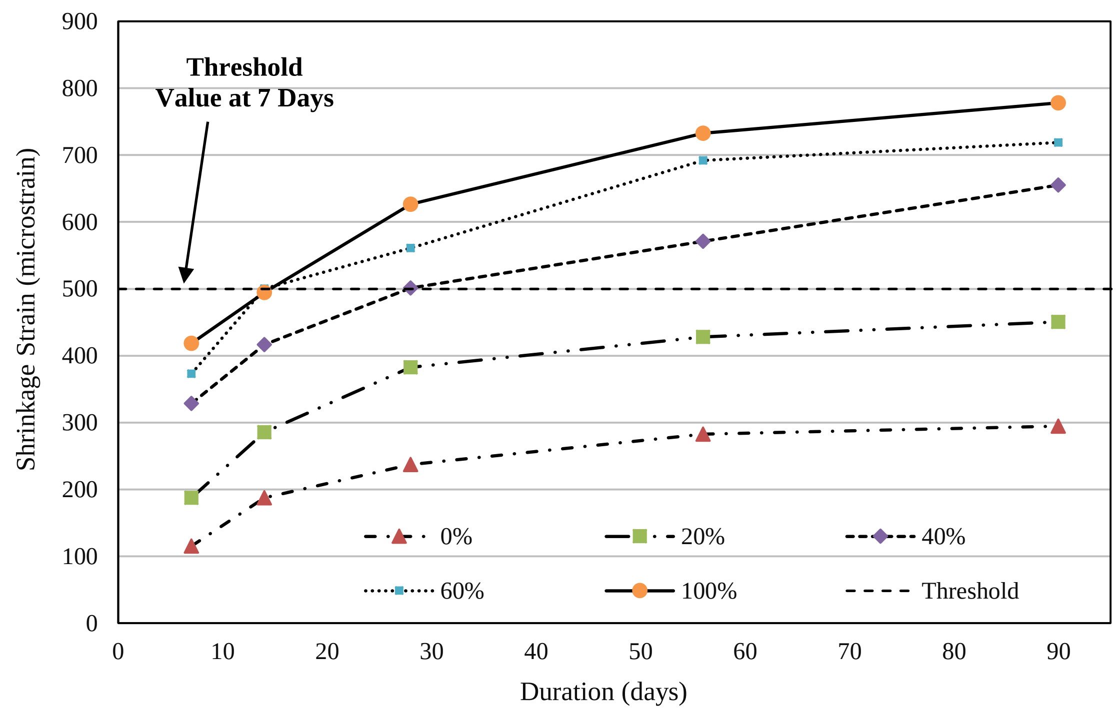

Figure 4.28: Drying shrinkage strain in Medium Strength Mixtures.

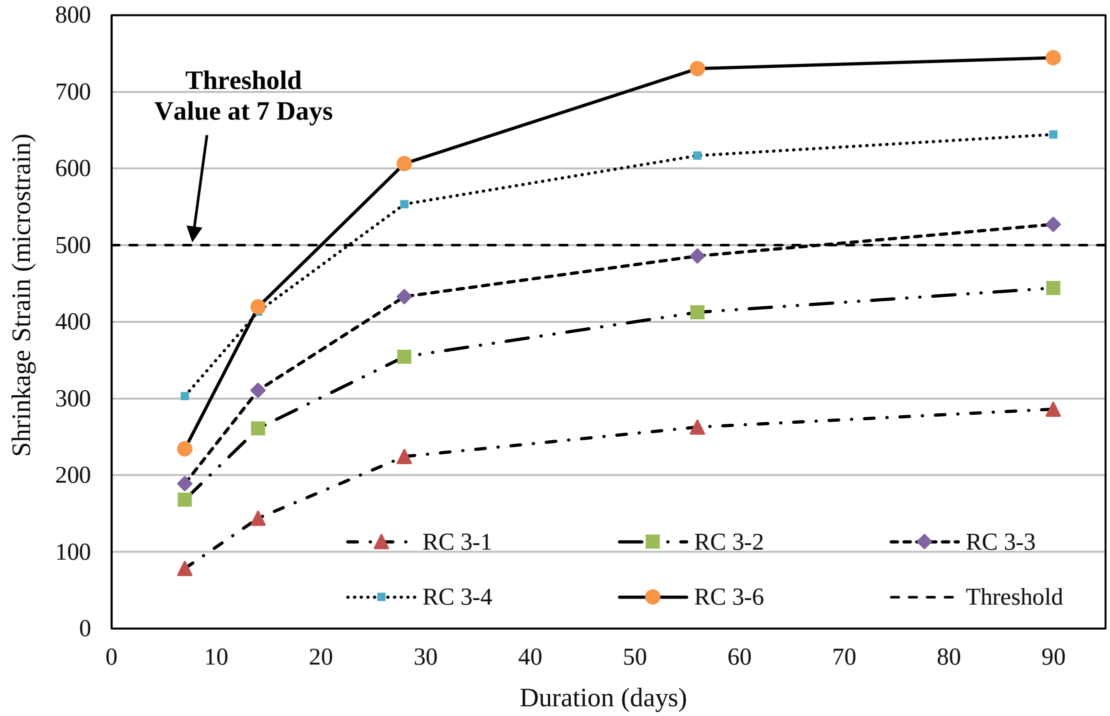

Figure 4.29: Drying shrinkage strain in High Strength Mixtures.

It is clear from the drying shrinkage results that increasing the RA dosage leads to considerable increase in drying shrinkage from the early stages after the specimen's removal from water. It is also clear that the low strength concrete mixtures (which contains the lowest cement content and the highest w/c ratio) exhibited the highest values of drying shrinkage, while the lowest values were recorded for the high strength concrete mixtures. Similar results were reported in the literature.

Before the incorporation of RA, the drying shrinkage values of the three concrete mixtures series were below the threshold shrinkage limit at of 500 microstrain. The drying shrinkage for the three mixtures was less than the 500 microns, these values being 385, 295 and 286 microstrain for the low, medium and high strength concrete, respectively, after 90 days.

The incorporation of 60% or more of RA caused the drying shrinkage of the low strength concrete mixture to exceed the threshold shrinkage limit at 7 days. The same incorporation level caused an increase of drying shrinkage for the medium and high strength concrete mixtures but they did not exceed the threshold limit. This means that 40% replacement level will not cause the RAC to exceed the drying shrinkage threshold limit, even for the concrete mixtures with high w/c ratio, but beyond this limit thee will be a need to decrease the w/c ratio and increase the cement content to prevent that.

4.9 SCANNING ELECTRON MICROSCOPY

Previous studies which examined the properties of RAC predicted several reasons for the decrease in the compressive strength and other mechanical properties of concrete with RA.

To evaluate the micro-structure and the bond between the RA and the cement paste, some samples were analyzed using scanning electron microscopy (SEM) and backscattered electron image (BEI) techniques. These tests were conducted on the remnant of the specimens after finishing all other tests. Different concrete specimens were broken into small pieces and a gold coating was applied. The scanned pictures were examined to visualize the interfacial transition zone between the coarse aggregate (NA or RA) and the mortar, to display the effect of RAC on the transition zone, as shown in Figures 4.30 – 4.34.

Figure 4.30 and Figure 4.31 show the SEM of concrete mix RC 2-2 (Medium strength mixture). Figure 4.30 shows that the interfacial zone between the NA and the new mortar has no cracks and it is difficult to distinguish the boundary of the interfacial zone because of the overlap between mortar and NA. In Figure 4.31 it is easy to distinguish between the boundary of the interfacial zone because of the obvious crack that extended along the zone between the RA and the new mortar. But at the same time it can be noticed that the microstructure of the new mortar and the RA are close to each other compared to the microstructure of the NA, this is mainly because the RA consists of old cement paste matrix which is more or less similar to the new concrete mortar in the RAC.

Figure 4.32 presents SEM and BEI pictures of the same specimen of concrete mix RC 1-4 (Low strength mixture). It is easy to observe the crack between the RA and the concrete mortar in these pictures, and effect of the high w/c ratio on the microstructure of the new mortar which contains several voids compared to the mortar of the medium strength mix.

Figure 4.33 and Figure 4.34 present SEM and BEI pictures of the high strength concrete mixtures (RC 3-4 and RC 3-4). The cracks in the interfacial zones between the RA and the concrete mortar are also clear in these pictures and it is easy to distinguish the interfacial zone for these specimens.

SEM and BEI photos show that the interfacial zone between the RA and mortar is weak and has obvious cracks, compared to the interfacial zones between NA and mortar which is dense and has no cracks. These SEM pictures of the concrete specimens proved that the bond between the RA and the cement paste was weaker than that between the NA and the cement paste, which gave rise to a weak interfacial transition zone. This would have contributed to the decline in the compressive strength and other mechanical properties of RAC.

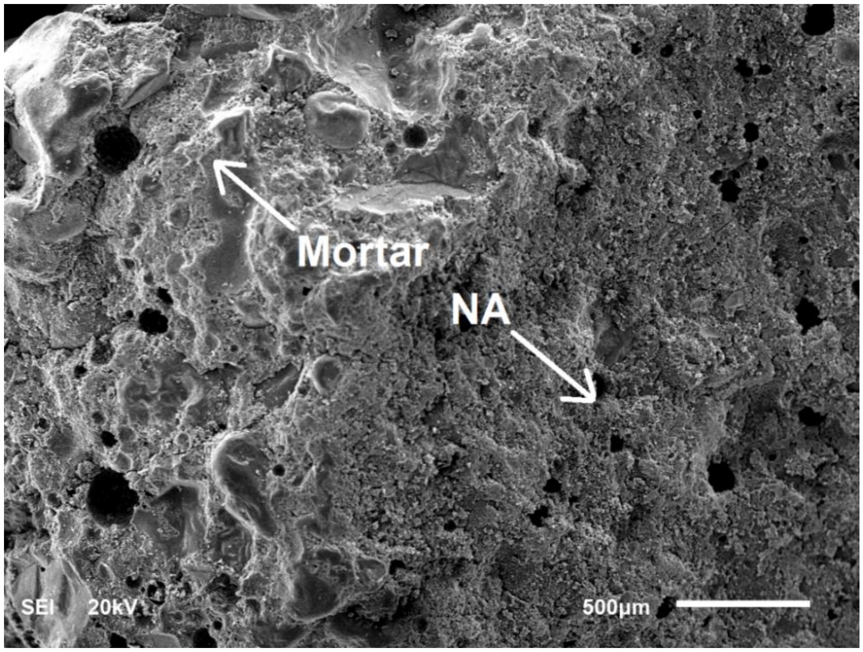

Figure 4.30: SEM picture between the mortar and the NA of concrete mix RC 2-2.

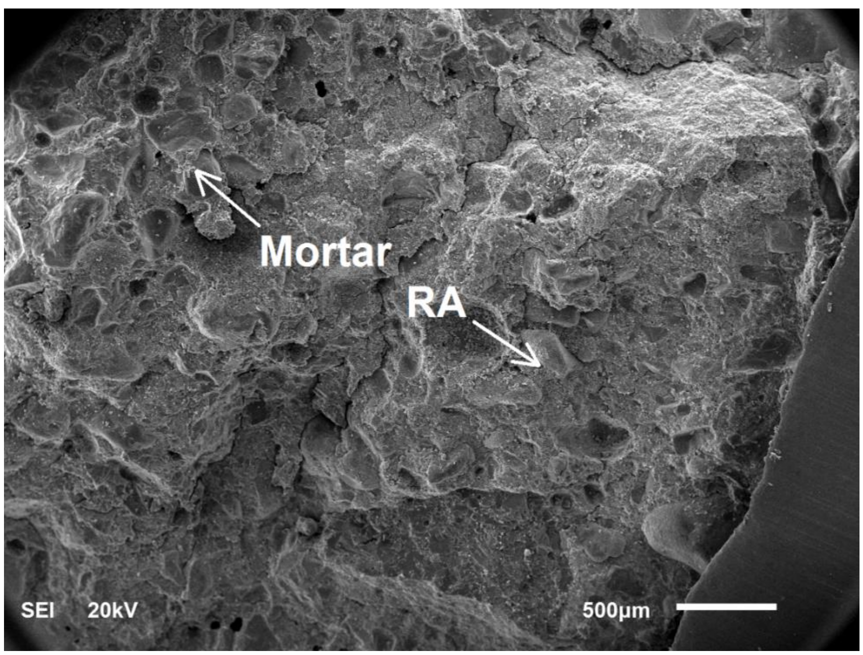

Figure 4.31: SEM picture between the mortar and the RA of concrete mix RC 2-3.

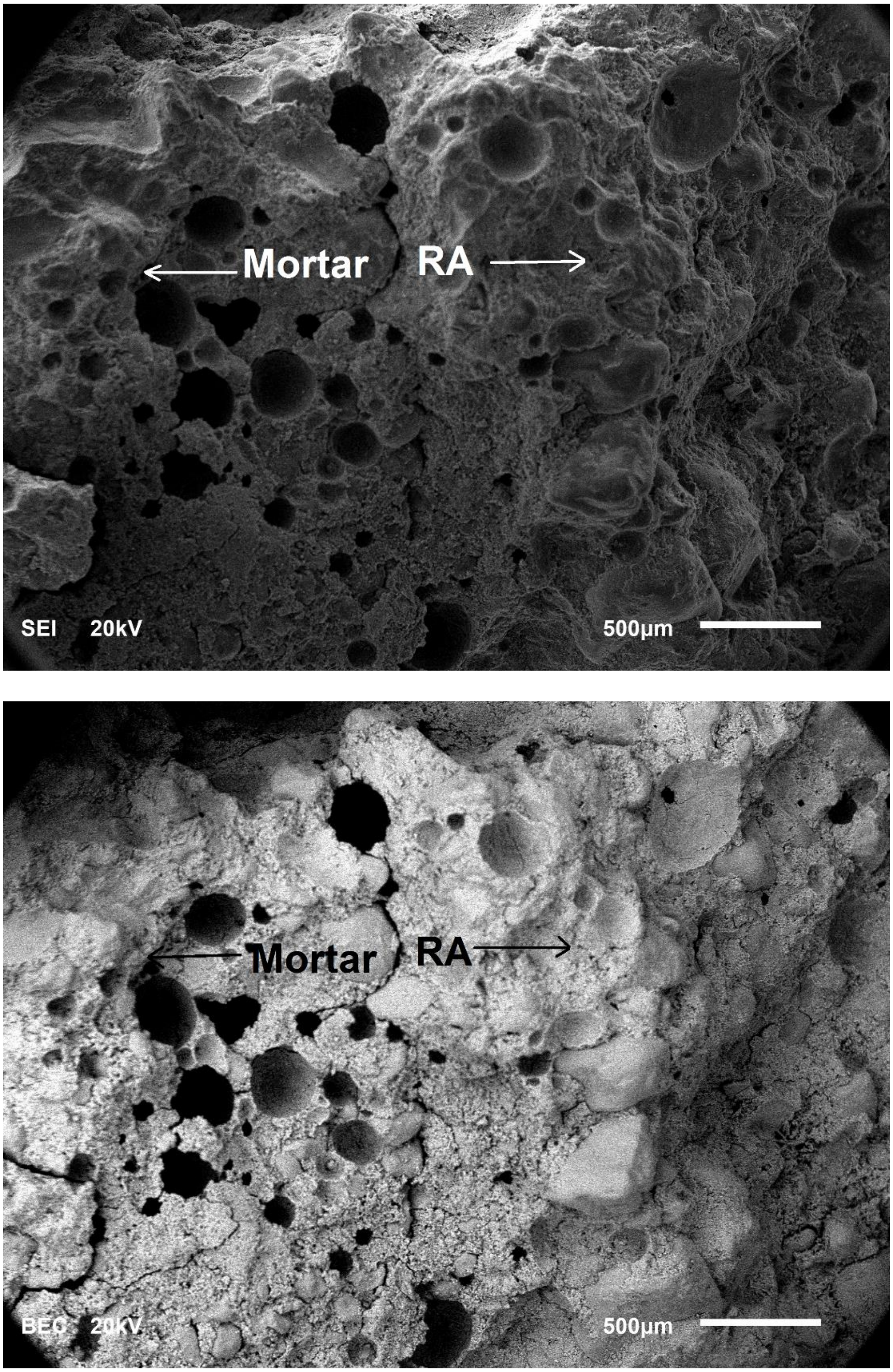

Figure 4.32: SEM and BEI pictures between the mortar and the RA of concrete mix RC 1-4.

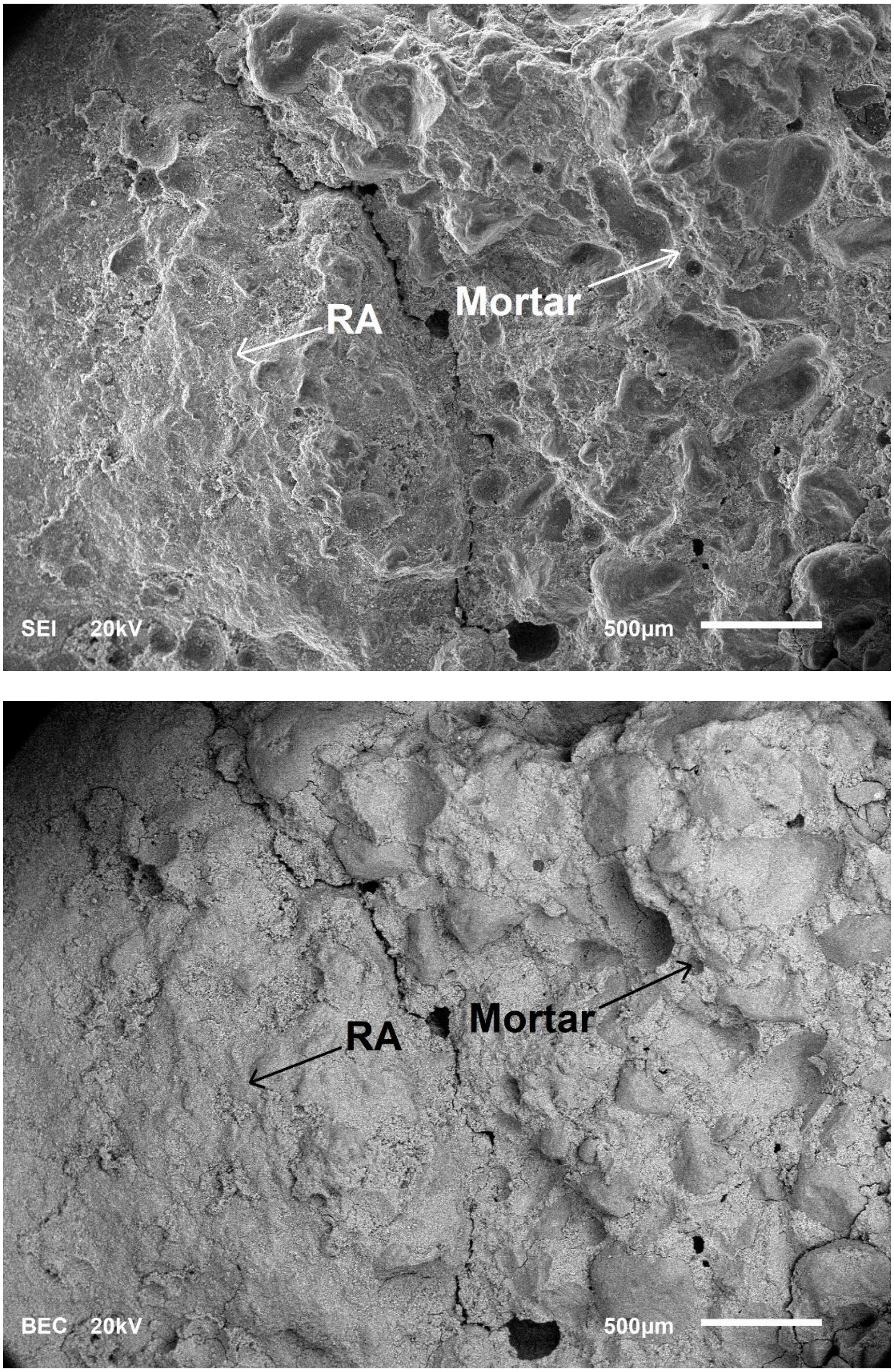

Figure 4.33: SEM and BEI pictures between the mortar and the RA of concrete mix RC 3-4.

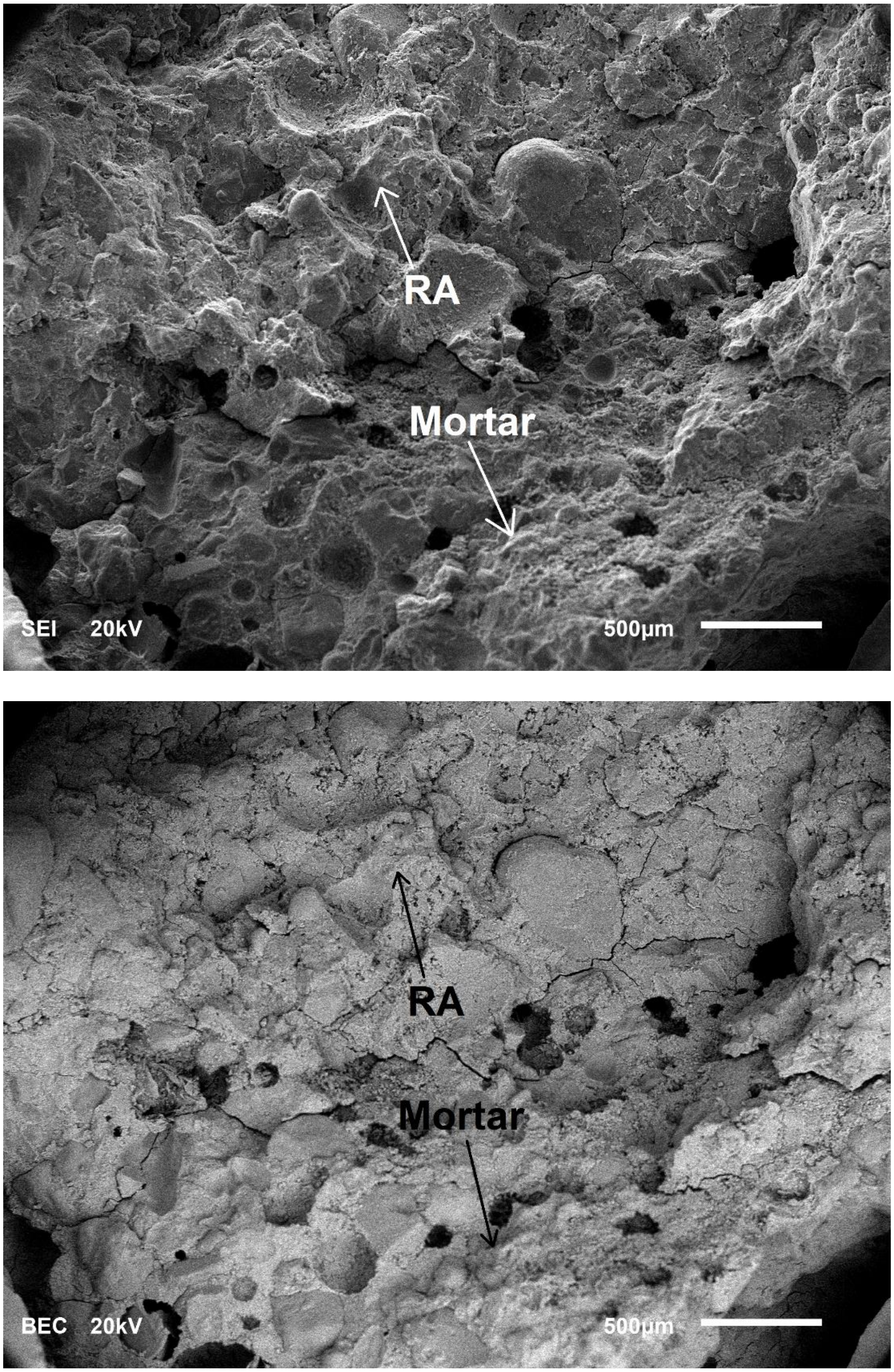

Figure 4.34: SEM and BEI pictures between the mortar and the RA of concrete mix RC 3-6.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The principal objective of this study was to assess the possibility of using local recycled aggregates in the production of concrete, mainly by the evaluation of the mechanical properties of RAC. The following conclusions could be drawn based on the experimental data obtained in this study:

(i) The mechanical properties of hardened concrete decreased by the incorporation of RA. Most of the mechanical properties of RAC decreased in a linear manner with increasing RA content.

(ii) The deterioration in the mechanical properties of RAC was mainly attributed to the poor quality of the RA compared to the virgin NA, and to the increase of the effective water cement ratio which was used to compensate for the high water absorption of the RA. The water absorbed by the RA is expected to increase the porosity of concrete and to decease the bond between the RA and the cement paste.

(iii) The relationship between the reduction in compressive strength and RA replacement level was almost linear. The percentage reduction in the 28-day compressive strength was about 15% to 18% when 40% RA was used while this reduction increased to 40% when full replacement of RA was used.

(iv) The incorporation of RA did not affect the compressive strength gain over time, which means that certain replacement level of RA caused similar amount of compressive strength reduction at different ages of concrete. For example, the 7-day compressive strength of the three concrete mixture series is almost about 70% to 75% of the 28-day compressive strength for all RA replacement levels.

(v) The reduction in the modulus of elasticity of RAC was almost linearly proportional to the RA replacement level. The modulus of elasticity reduction was about 14% to 16% when 40% of RA was used and it reached to 42% when full replacement of RA was used. The poor quality of RA, especially the low aggregate stiffness due to its low density, beside the increase of effective w/c ratio highly affected the modulus of elasticity of RAC concrete.

(vi) The reduction in the splitting tensile strength of RAC was almost linearly proportional to the RA replacement level. The reduction in the splitting tensile strength was about 14% to 17% when 40% of RA was used and it reached to 37% when full replacement of RA was used. The splitting tensile strength was mainly affected by the same factors that influenced the compressive strength.

(vii) The reduction in the modulus of rupture of RAC was almost linearly proportional to the RA replacement level. The modulus of rupture reduction was about 16% to 20% when 40% of RA was used and it reached to 33% when full replacement of RA was used. The reduction in the modulus of rupture was mainly affected by the same factors that influenced the splitting tensile strength, with some discrepancies due to the small specimens' size compared to the maximum coarse aggregate size in the mixtures.

(viii) The reduction in the bond strength of RAC was almost linearly proportional to the RA replacement level. The reduction in the modulus of rupture was about 10% to 21% when 40% RA was used and it reached to 51% when full replacement of RA was used. The bond strength behavior of RAC was similar to the behavior of splitting tensile strength, this is because the splitting tensile strength highly affects the concrete bearing strength at the interfacial zone between the concrete and the rib of the of the steel bar.

(ix) The incorporation of RA in concrete resulted into small or negligible decrease of the abrasion resistance of RAC, the mass loss by abrasion increased by 3% to 6% when full replacement of RA was used. The abrasion loss was higher in the concrete mixtures with low cement content and high w/c ratio.

(x) Increasing the RA dosage resulted into considerable increase in drying shrinkage. The low strength concrete mixtures (which had low cement content 300 kg/m^3) and high w/c ratio) exhibited the highest values of drying shrinkage, while the lowest values were recorded for the high strength concrete mixtures (which had high cement content (400kg/m^3) and low w/c ratio).

(xi) A RA replacement level of more than 60% didn’t increase the drying shrinkage beyond the threshold limit of 500 microstrain for the concrete mixtures with low w/c ratio (0.4 or 0.45). For the concrete mixtures with high w/c ratio (0.5) and low cement content (i.e., low strength mixtures), the threshold limit of drying shrinkage was exceeded due to the incorporation of 60% RA, but the shrinkage of specimens with 40% RA was within the allowable limit.

(xii) The SEM of the concrete specimens proved that the bond between the RA and the cement paste was weaker than that between the NA and the cement paste, which in its turn led to a decrease in the compressive strength and other mechanical properties of RAC.

5.2 RECOMMENDATIONS

The recommended quantity of RA to be used in RAC in Saudi Arabia is as follows:

- The quantity of RA should not exceed 20% for the low strength concrete mixtures (with high w/c ratio), otherwise, the drying shrinkage of concrete will exceed the threshold limit of 500 microstrain and it may result in concrete cracking.
- For the proposed medium and high strength concrete mixtures, the quantity of RA should not exceed 40%, otherwise, the drying shrinkage of concrete may exceed the threshold limit of 500 microstrain.
- The incorporation of 40% of RA will cause reduction in compressive strength and other mechanical properties by an amount not exceeding 20%. This means a reduction of not more than 7 MPa of the 28-day compressive strength of the normal strength concrete and another acceptable amounts of reduction in modulus of elasticity, modulus of rupture, splitting tensile and bond strength. This is why the 40% RA replacement level can be considered as the optimum replacement level when the concrete mixtures contain medium to high cement content and low w/c ratio (i.e., medium and high strength concrete mixtures described in this study).

- The increasing of the RA replacement level will affect the modulus of elasticity and, therefore, it should be controlled and limited since the modulus of elasticity is important in designing structures for the serviceability limit state. It is possible to compensate for the stiffness loss in any concrete structural element by increasing its height or depth, and so the influence of modulus of elasticity on the structure deformation could be controlled.

5.3 RECOMMENDATIONS FOR FURTHER STUDIES

- The scope of this study was restricted to only one source of RA. A complimentary study should be conduct with different sources of RA, and it should investigate the effect of different compositions and characteristics of the local RA on the mechanical properties of the RAC using the optimum replacement level of RA.
- The effects of supplementary cementing materials and other concrete admixtures, such as silica fume and fly ash, on the properties of RAC should be investigated.
- In this study, the water compensation method was used to compensate for the water absorbed by the RA to produce RAC with minimum strength loss and equivalent workability to the control concrete. The incorporation of superplasticizer is another way of offsetting the workability and strength loss with increasing the RA replacement level. A combination between the two methods could be the optimum way to achieve better mechanical properties and workability of RAC. This approach still needs further investigation.

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Vitae

Name : Abdulrahman Hasan Izzat Zaben

Nationality : Jordanian

Date of Birth :2/10/1988

Email :Azaben123@gmail.com

Educational Qualification

Name of Institution	Degree	Passing Year	CGPA
King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia	M.Sc. Civil Engineering (Structures)	January 2017	**3.56/ 4.0**
The University of Edinburgh, Edinburgh, United Kingdom	M.Sc. Structural and Fire Safety Engineering	September 2016	**74/100**
Birzeit University, Ramallah, Palestine	Bachelor Degree in Civil Engineering.	June 2011	**85/100**

Professional Experience

Employer: Birzeit University – Ramallah – Palestine.

Period: September 2011 - January 2013

Position: University Teaching Assistant

Enrolled Projects

- Mechanical Properties of Green Recycled Aggregate Concrete Using Construction and Demolition Waste in Saudi Arabia.
- Retrofitting of exterior Beam-Column joints using CFRP
- Utilizing of Ultra-high performance concrete with fibers in hollow core structures.