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Comparative Study between Recycled Fine and Coarse Aggregate Used in Roller Compacted Concrete Pavement

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ABSTRACT

To decrease the impact on the environment of building waste, the recycled aggregate may be used in various sustainable engineering applications, such as roller compacted concrete pavement (RCCP). This research examined how using recycled aggregate as a partial replacement for natural aggregate as coarse or fine affected the mechanical properties of roller-compacted concrete pavement. The recycled aggregate was crushed and sieved to coarse and fine aggregate before being used in the roller-compacted concrete pavement. Compressive strength, splitting tensile strength, and flexural strength were all evaluated after the samples were prepared at 28 and 90 days of curing. According to the study's findings, the partial replacement of coarse or fine aggregate with recycled aggregate by (10, 15 and 20%) by volume resulted in decreasing the mechanical properties and increasing the absorption and porosity of RCCP due to the contaminated cement paste on the surface of RCA when compared to the reference mix made with natural aggregate. Because the recycled aggregate contains un-hydrated cement particles, the results have improved after 90 days.

Keywords: Roller compacted concrete, Roller compacted concrete pavement, Fine recycled aggregate, Coarse recycled aggregate

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دراسة مقارنة بين الركام الناعم والخشن المعاد تدويره المستخدم في الخرسانة المرصوصة بالحدل

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قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

لتقليل التأثير على البيئة من نفايات البناء، يمكن استخدام ركام الخرسانة المعاد تدويره في العديد من التطبيقات الهندسية المستدامة مثل رصيف الخرسانة المرصوصة بالحدل (RCCP). تم دراسة تأثير استخدام الركام الخرساني المعاد تدويره كبديل جزئي عن الركام الطبيعي (خشن او ناعم) على الخواص الميكانيكية لـ RCCP تم سحق الركام الخرساني المعاد تدويره ونخله و اضافته إلى الركام الخشن والركام الناعم قبل استخدامه في RCCP. تم تقييم كلا" من مقاومة الانضغاط وقوة الشد للانقسام وقوة الانحناء بعد تحضير العينات في 28 و 90 يومًا من المعالجة. وفقًا لنتائج الدراسة ، أدى الاستبدال الجزئي للركام الخشن والناعم بالركام الخرساني المعاد تدويره بنسبة (10 ، 15 و 20٪) من حيث الحجم إلى تقليل الخواص الميكانيكية وزيادة الامتصاص والمسامية لـ RCCP بسبب عجينة الأسمنت الملوثة على سطح RCA بالمقارنة مع المزيج المرجعي المصنوع من الركام الطبيعي. نظرًا لأن الركام الخرساني المعاد تدويره يحتوي على جزيئات أسمنت غير رطبة ، فقد تحسنت النتائج بعد 90 يومًا.

الكلمات المفتاحية: الخرسانة المرصوصة بالحدل رصيف الخرسانة المرصوصة بالحدل، الركام المعاد تدويره الناعم، الركام المعاد تدويره الخشن

1. INTRODUCTION

Many types of pavement can benefit from the speed and economy of roller compacted concrete (RCC) construction. RCC is typically used for low-speed, heavy-load pavements because of its rough surface. Commercial areas and local roads and highways have seen a rise in their use of it in recent years. A large vibrating steel drum and rubber-tired rollers compact roller-compacted concrete pavement (RCCP) into its final form. Roller-compacted concrete pavement includes the same essential parts as conventional concrete, such as well-graded aggregates, cement materials, and water, but it has different mix proportions **(ACI327R-14; Abu-Khashaba et al., 2014)**. Compared to normal concrete, RCCP contains a more significant percentage of fine aggregates, allowing for tighter packaging and compaction of the concrete. Fresh RCCP is rougher than typical zero-slump conventional concrete, with a rigid enough consistency to stay steady under vibratory rollers yet moist enough to properly mix and spread paste without segregation. Roller-compacted concrete pavements (RCCPs) are rigid and long-lived. Aside from parking and storage, RCCPs are an excellent choice for streets and highways, intermodal terminals, port facilities, and military installations. They have all these properties and are quick and inexpensive to build on. RCC may also be utilized as a base material in composite systems. Recent years have seen a steady rise in the usage of RCC in both public and private sector applications **(Ashtankar and Chore, 2014; Salih and Abed, 2016; Ali et al., 2022).** At the end of its useful life, construction and demolition waste (CDW) can cause significant environmental damage. Recycling and reusing this waste in producing new building materials may help civil construction projects use less energy and reduce carbon emissions**.** This industry is estimated to utilize 40% of all primary energy, and CDW contributes 50% of all industry waste **(Behera et al., 2014).** RCA means recycled concrete aggregate and is described as concrete made using recycled aggregates or a combination of recycled and natural aggregates. Waste/demolished concrete is crushed to produce recycled aggregates, which can be fine or coarse **(Chakradhara Rao et al., 2011).** According to (**de Vries, 1996)**, RCA is now the main priority in building projects in many parts of the world. In 1994, the Netherlands utilized 78,000 tons of RCA, and since 1991, Germany has been attempting to achieve a recycling rate of 40 % for its building and demolition materials. **(Van Acker, 1998).** Environmentally and economically, recycling aggregate (RA) is better than natural aggregate (NA). There is no need to create any new mining locations, which will significantly reduce the negative effects on the environment as well as the amount of energy and gasoline used by transporting (for the same hauling distance, RCA is less energy efficient than NA when the unit weight of RA is lower than NA). RA and NA have different specific gravities. **(Mack et al., 2018).** Using coarse RA from Hong Kong C&D rubble decreases greenhouse gas emissions by 65% and saves up to 58 % in energy usage, according to research by **(Hossain et al., 2016).** Existing concrete is crushed to make RA, which is then utilized as an aggregate in new construction. The RA manufacturing process should be improved to increase the amount and quality of usable RA. Several elements contribute to RA performance, including the original concrete's quality and the presence of impurities **(Noguchi et al., 2015).** It has been shown that using (RA) in concrete can improve its compressive and flexural strength when more cement (up to 34 kg/m^3) is added to its mix, as revealed in a study by **(Beltrán et al., 2014).** A survey by (**Etxeberria et al., 2007)** found that raising the cement content, reducing the water-to-cement ratio, and modifying the additive-to-aggregate ratio enhanced concrete's compressive and tensile strengths by 25 percent and 50 percent weight-based replacement levels. The increased mortar and impurity content of fine recycled aggregate (FRA) compared to coarse recycled aggregate (CRA) was the primary reason for the worry about utilizing FRA in the concrete mixture. The angular shapes, the rough surface, and the strong absorption of small RCA particles are all related to the adhesion and loss of mortars. **(Evangelista et al., 2015)**. Many contaminants were found in the fine recycled aggregate (FRA), which may reduce the strength of concrete (**Smith, 2010).** In the investigation by **(Evangelista et al., 2015),** lower fractions of FRA (125–500 m) have a high paste content, whereas more significant fractions (1–4 mm) of FRA have significant fractures at the paste-aggregate ITZ. The surface of FRA is both rougher and more porous (which may contribute to a greater surface area), promoting interlocking the connection between the aggregate and the paste, which results in a higher compressive strength than utilizing natural fine aggregate **(Neno et al., 2014; Topçu and Bilir, 2010)**. According to much research, recycled aggregate RA concrete develops its strength faster than natural aggregate (NA) concrete as age increases (e.g., 28 days). This is because RA particles have non-hydrated cement residue attached to their surface, which reacts with water to speed up the strength development process **(Poon et al., 2004; Evangelista and de Brito, 2007; Gesoglu et al., 2015; Kurad et al., 2017)**. The concrete prepared with recycled aggregate has less compressive strength because the mix contains two different interface transition zones (ITZs). The ITZ represents the cement paste-aggregate bond, often weaker than the cement paste or the hydrated aggregate. Concrete that contains natural aggregate has an ITZ between the aggregate and mortar, but concrete that contains recycled aggregate (RA) has an ITZ between the natural aggregate and old paste and the new paste in the mix **(Etxeberria et al., 2007; Tam et al., 2005; Kou et al.,2011; Kong et al., 2010; Lihua et al., 2017; Abbas, 2022)**. As a result, the concrete containing RA has a lower compressive strength since it uses a more significant amount of water to obtain the desired workability **(Kurda et al., 2017)**. The lower-density mortar **(Kurda et al., 2017)** is a factor used to reduce the compressive strength of concrete containing recycled aggregate (RA). **(Katz, 2003)** found that the flexural strength of concrete produced using RCA is around 10% lower than that of conventional concrete (CC). When saturated recycled aggregate was utilized in the concrete mixture, the flexural strength of the mix, including RCA, decreased significantly **(Poon et al., 2004; Kou et al., 2011).** According to an investigation by **(Limbachiya et al., 2000; Beltrán et al., 2014),** RA does not considerably impact concrete's flexural strength. According to (**Katz, 2003)**, the tensile strength of RA concrete was about 6% lower than that of conventional concrete. The tensile strength of concrete replacement with recycled aggregates (RA) can be decreased by up to 10% when coarse recycled aggregates replace only natural coarse aggregate. The tensile strength was lowered by 10%–20% when natural coarse and fine were replaced with RA**. (Hansen, 1986; Etxeberria et al., 2007).**

This study investigates the mechanical proprieties of Roller Compacted Concrete Pavement (RCCP) mixes suitable for road paving with feasible cost and better engineering properties by employing recycled concrete aggregate (coarse and fine). The recycled concrete aggregate was obtained from waste materials available in Iraq and crushed in various sizes. The maximum size of recycled coarse aggregate is 19 mm, and recycled fine aggregate is passed through sieve No.4 (4.75mm). The RCCP mixes were differently prepared by replacing natural aggregate with recycled concrete aggregate. The replacement percent of course or fine recycled aggregate was (10%, 15%, and 20%) by volume of natural aggregate. Materials had proportioned according to ASTM D1557-12, as indicated in American Concrete Institute Committees; ACI 327R. 84 cylindrical samples with dimensions of (15×30) cm and prism samples of (10x10x50) cm were prepared and cast in steel molds by vibrating hammer and tamping plate. After 28 and 90 days of normal curing, the samples were brought from the water tank for the different tests.

2. EXPERIMENTAL WORK

2.1. Materials Properties

2.1.1 Natural Aggregate

A natural aggregate (fine and coarse) was sieved according to **(ASTM C136M-19),** and materials were finer than 75m (No.200) according to **(ASTM C117-17).** The fine and coarse aggregate grading adapted to the **(ASTM C33/C33M-18, 2018)** are shown in **Figs. 1 and 2.** The natural aggregate (fine and coarse) properties are given in **Table 1.**

Table 1. Natural aggregate properties

Test	Coarse aggregate	Fine aggregate	**ASTM C33/C33M-18, 2018** limits
Bulk specific Gravity	2.64	2.55	--
Absorption of water (%)	0.67	1.75	--
SO_3 (%)	0.04	0.231	--
Abrasion by Los Angeles Test (%)	18	--	50% max.

Fractured aggregates (%)	90	--	--

A grading limit for mixed aggregate used in RCCP is recommended by **(ACI 327R-14, 2014),** as shown in **Fig. 3.**

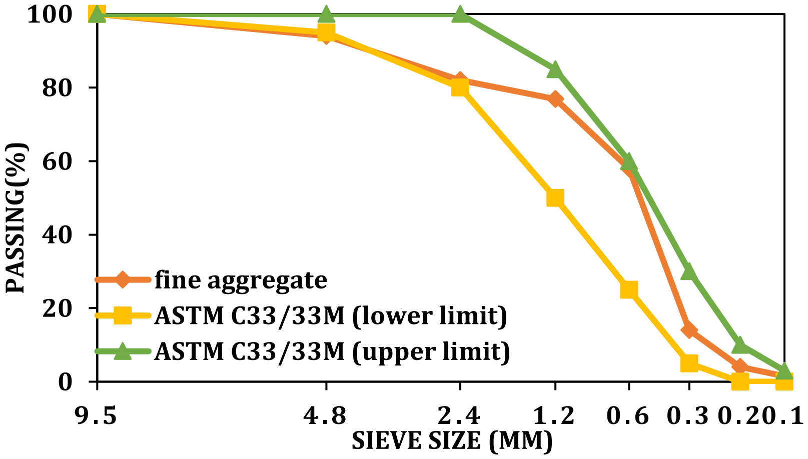

Figure 1. Gradation of natural fine aggregates and ASTM C33 limits

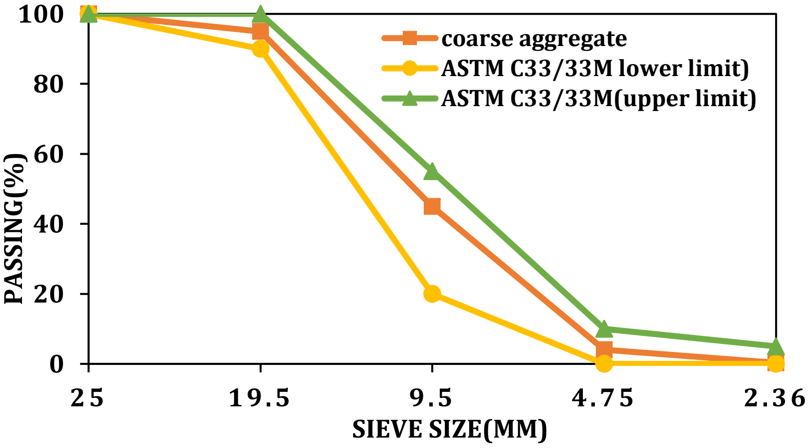

Figure 2. Gradation of natural coarse aggregates and ASTM C33 limits

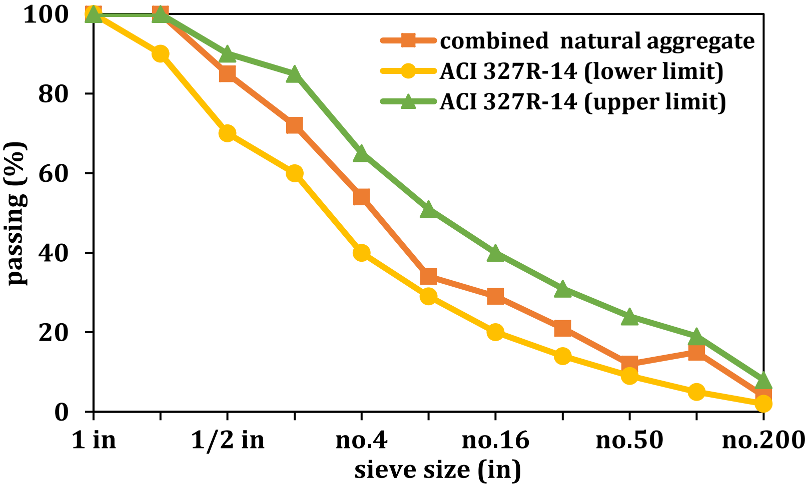

Figure 3. Combined Natural aggregate gradation and ACI 327R-14 limits**.**

2.1.2 Recycled aggregate

Similar to the natural aggregate, recycled aggregate in both coarse and fine was sieved according to **ASTM (C136M-19),** and materials finer than 75m (No.200) according to **ASTM (C117-17**). The recycled fine and coarse aggregate were adopted **(ASTM C33/C33M-18, 2018). Figs. 4 and 5** show the Gradation of the fine and coarse recycled fine; recycled aggregate properties are given in **Table 2.** A grading limit for combined aggregate used in roller-compacted concrete pavement (RCCP) is recommended by **(ACI 327R-14)** as illustrated in **Fig. 6.**

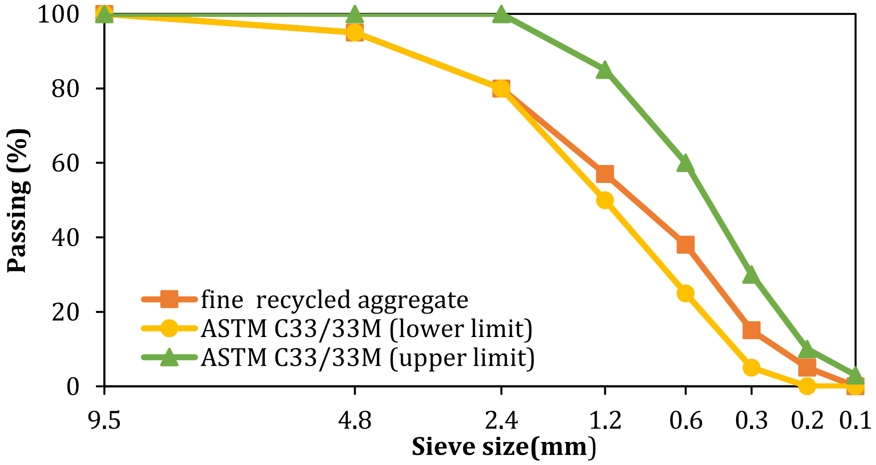

Figure 4. Gradation of fine recycled aggregates and ASTM C33 limits

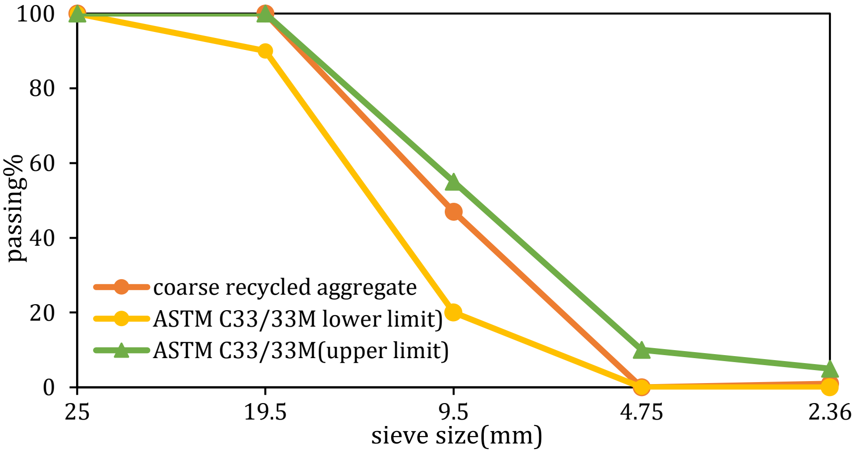

Figure 5. Gradation of coarse recycled aggregates and ASTM C33 limits

Table 2. Recycled aggregate properties

Test	Coarse recycled aggregate	Fine recycled aggregate	ASTM (C33-18) limits
Bulk specific Gravity	2.43	2.10	--
Absorption of water (%)	7	9	--
SO_3 (%)	0.47	0.51	--
Abrasion by Los Angeles Test (%)	15	--	50% (max)
Fractured aggregates (%)	96	--	--

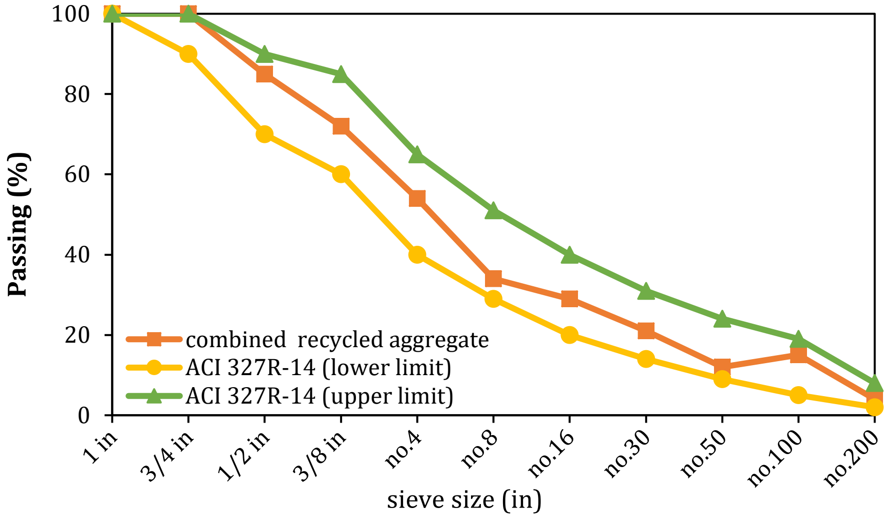

Figure 6. Combined recycled aggregate gradation and ACI 327R-14 limits

2.1.3 Cement

This investigation was carried out using Iraqi / Taslujah ordinary Portland cement (type I); the results of the physical and chemical tests are seen in **Table 3.**

Table 3. Physical and chemical properties of cement

	Test	Result	(ASTM C150 / C150M-20)
Physical Properties	Fineness, specific surface area by air-Permeability, m^2/kg	345	260 (min)
	Setting Time (initial), hr: Min	02:10	00:45 (min)
	Setting Time (final), hr: Min	03:45	6:15 (max)
	Autoclave expansion %	0.042	0.8 (max)
	Compressive strength, MPa		
	3 day	30	12 (min)
	7 day	37	19 (min)
Chemical properties	(SiO_2) %	21.27	
	(AL_2O_3)%	5.27	
	(Fe_2O_3)%	3.20	
	(Cao) %	62.40	
	(MgO) %	1.61	6 (max)
	(SO_3) %	2.01	3 (max)
	(I.R.) %	0.56	1.5 (max)
	(LOI) %	2.55	3 (max)

2.1.4 Filer

The powder filler used in this research is limestone powder. This material passes through sieve No.200. One of the choices typically utilized as filler in RCCP is limestone powder. Due to its widespread availability and low price. **Table 4** presents the findings of the investigations into the chemical and physical properties.

Table 4 Chemical and Physical Properties of Limestone Filer (LF)

Criteria	LF	Criteria	LF
SiO_2, (%)	1.01	MgO, (%)	0.11
AL_2O_3, (%)	1.52	SO_3, (%)	0.22
Fe_2O_3, (%)	0.25	LOI, (%)	32.35
Cao, (%)	64.46	Particle size distribution (nm)	475.9

2.2 Mixture Proportions

Seven different mixtures of roller-compacted concrete pavement RCCP were prepared. The reference mixture was prepared using natural aggregates (coarse and fine aggregates), and other mixtures were prepared by replacing the natural aggregates with the recycled aggregates; the recycled coarse aggregates replaced the coarse aggregates for three mixtures with the replacement ratio (10, 15, and 20%) by volume. The three mixtures other than the fine aggregate have been replaced by volumetrically recycled fine aggregate. The **(ASTM D1557-12, 2012)** specification can be a practical option for obtaining the proper water content and density for RCCP. This investigation used cement, natural aggregates (NA), recycled aggregate (RA), and limestone filler to create RCCP mixtures. A cement content of 13% by weight of the total dry components was used by **(ACI 327. R, 2014)** standards. Gradation tests were conducted, and the results were used to determine the amount of aggregates that should be used. The aggregates used were: 50% coarse aggregate, 45% fine aggregate, and 5% filler. The modified Proctor test was employed to determine the maximum dry density and optimum moisture content (OMC) of RCCP mixes **(ASTM D1557-12, 2012),** according to various water values presented by **(ACI 327.R, 2014)** and **(ACI 211.3.R, 2002).** An **ASTM D1557-12** procedure (Process C) was used to evaluate roller-compacted concrete pavement (RCCP) mixture proportions. From 4.5 percent to 8.5 percent, the molding water percentages varied in this procedure. The results are shown as curves with dry density (kg/m^3) and OMC values (percent)**,** as illustrated in **Figs. 7** and **8.**

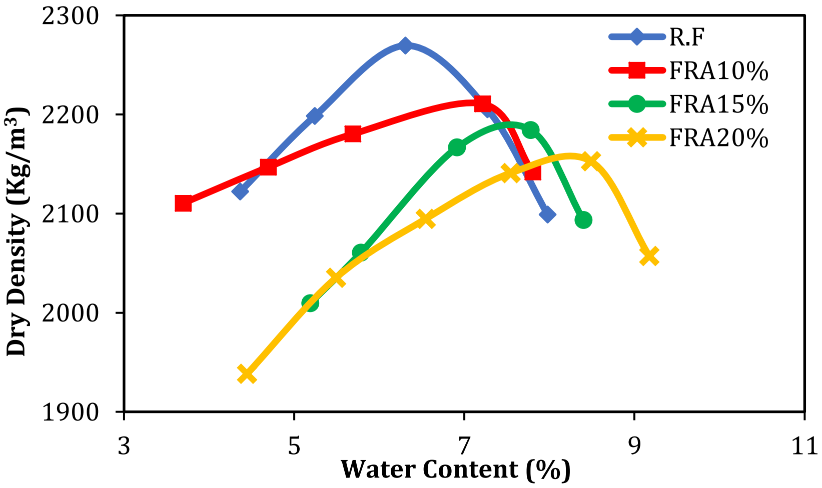

Figure 7. The relationship between optimum moisture content and maximum dry density (kg/m$^{3)}$ for reference mix and mixes with FRA of RCCP

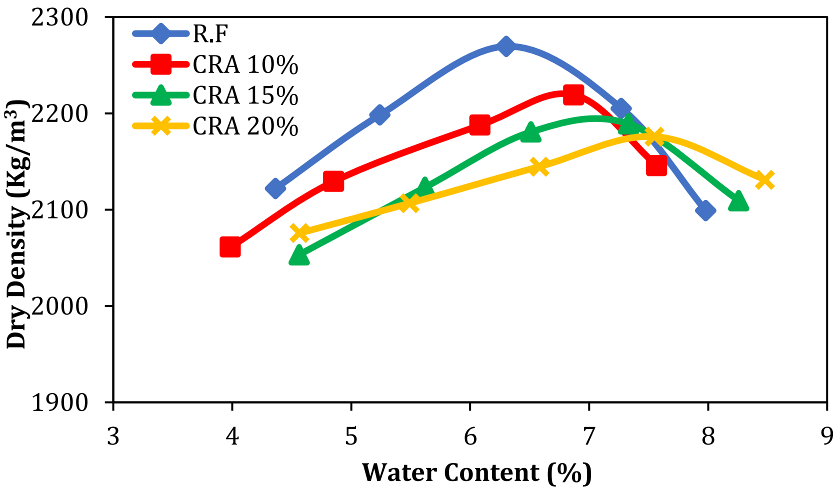

Figure 8. The relationship between optimum moisture content and maximum dry density (kg/m^3) for reference mix and mixes with CRA of **RCCP**

2.3 Procedure of Casting

To perform destructive testing, two types of samples were created (cylinder samples and beam shape samples). The vibrating hammer was used to compact the materials by **ASTM (C1435/C1435M 14)**. Four layers of compression were applied to cylindrical samples with a diameter and height of 15 cm and 30 cm, respectively. Additionally, prismatic molds were used to compress beam-shaped models (10 x 10 x 50) cm in two layers. After the casting process, the specimens were stored in a laboratory for 24 hours. Afterward, the samples were extracted from the molds and kept in a water tank at 23 °C until the required testing period (28 and 90 days). Pictures of the casting process can be seen in **Fig. 9**.

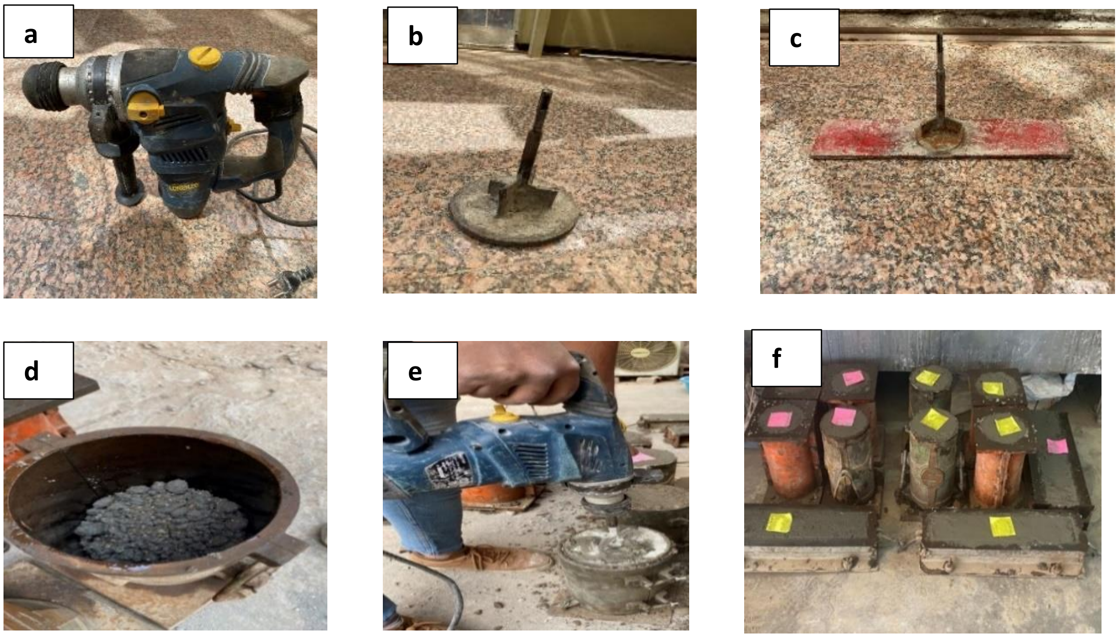

Figure 9. (a) Vibrating hammer (b) and (c) tamping plate (d) RCCP mix in mold (e) smoothing and leveling the top layer of the RCCP mold (f) the RCCP mixes after compaction

2.4 Mechanical Properties

2.4.1 Compressive Strength

Compressive strength tests were performed on cylindrical specimens with dimensions of 15 cm diameter and 30 cm height collected from the tank by **ASTM (C39/C39M-15)**. Samples were tested at 28 and 90 days after they had been cured. The testing load was applied with a 0.3 MPa/s rate using the 3000 KN capacity crushing machine; **Fig. 10** shows the samples in the test machine.

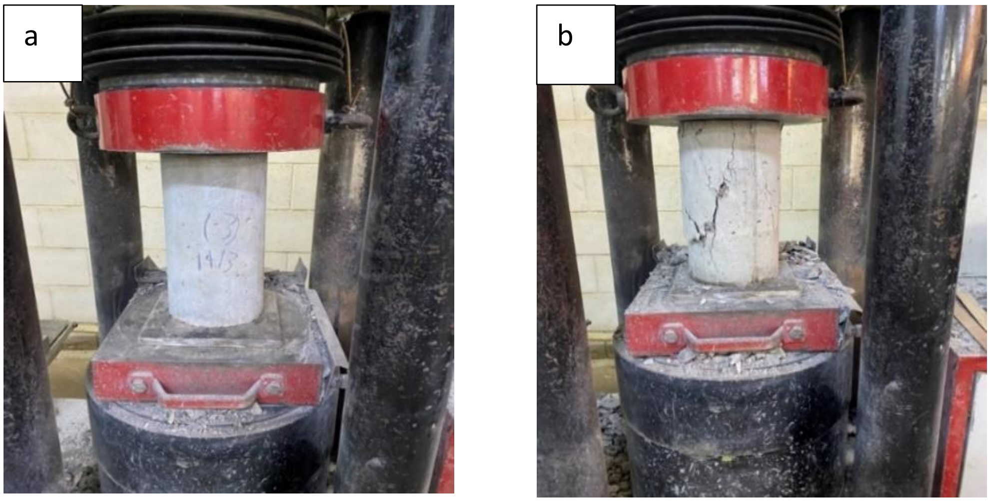

Figure 10. (a) the RCCP specimen in the test machine, (b) the specimen after the test

2.4.2 Splitting Tensile Strength

(ASTM C496-11) was the method used to conduct the test on cylinder samples with diameters of (15 cm in diameter and 30 cm in height). The test was carried out on samples cured for 28 and 90 days. With a loading rate ranging from (0.7 to 1.4) MPa/min, the compressive testing equipment with a capacity of 3000 KN was used. **Fig. 11.** shows the tensile strength test produced.

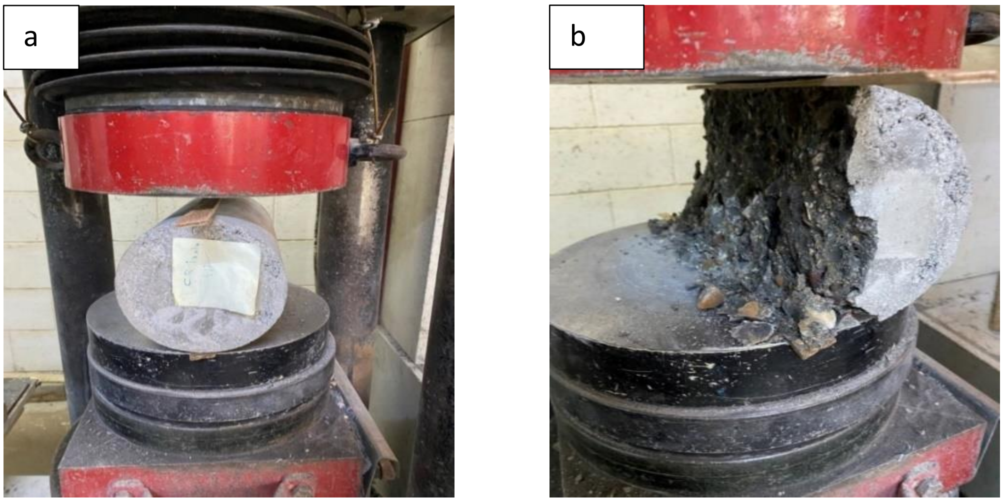

Figure 11. (a) RCCP Sample in the testing machine, (b) RCCP sample after test2.4.3 Flexural Strength

The flexural strength was investigated on beam shape samples with dimensions of (10*10*50) cm. Testing was performed after the specimens were taken from the curing tank. Specimens were examined using **(ASTM C78/C78M-18)** (two-point loading). The specimens were put in the testing machine so that the surface of the specimen would be in touch with the machine. Each sample was given a calculated average of three readings. **Fig. 12**. Shows the specimens in the test machine.

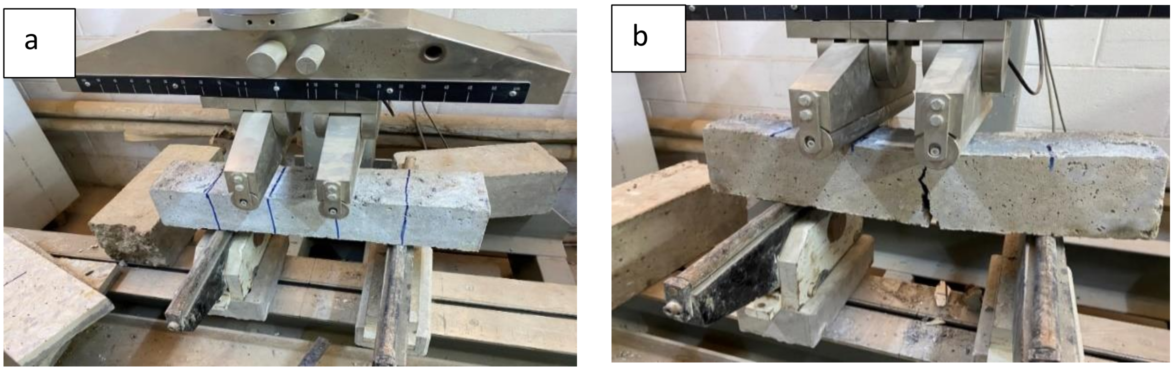

Figure 12. (a) RCCP Sample in the test machine, **(b)** RCCP Sample after the test

3. RESULTS AND DISCUSSION

3.1 Maximum Dry Density (MDD)and Optimum Moisture Content (OMC)

The results of the modified proctor test are shown in **Table 5**. When recycled aggregate (RA) was used as a partial replacement of the natural aggregate (NA) as coarse and fine, it was observed that the maximum dry density was reduced. This reduction was due to the lower specific gravity of RA than the NA **(Hansen, 1992; Youg and Teo, 2009; Vieira et al., 2016)**. The lowest fresh density was achieved when coarse and fine recycled concrete aggregates were used. This was because the RA-specific gravity was lower than the NA it replaced (coarse and fine), as given in **Table 5** and shown in **Fig.s. 7** and **8**.

Table 5. Maximum dry density and optimum moisture content for different RCCP mixes

Mix-ID	Maximum dry density (kg/m^3)	Optimum moisture content (%)
R.F	6.1	2210
CR 10%	6.63	2204
CR15%	6.82	2201
CR20%	7.13	2198
FR10%	6.7	2202
FR15%	6.9	2200
FR20%	7.3	2194

The optimal water content increased when recycled aggregate was replaced with a partial replacement of natural aggregate (coarse and fine). The change in the optimal water content may be due to the contaminated cement mortar on the recycled aggregate surface **(Gomez-Soberon, 2002; Xiao et al., 2005; Etxeberria et al., 2007; Verian, 2012)**. Fine, recycled concrete aggregate absorbed more water than coarse, recycled concrete, which has different absorption properties. According to (**Olorunsogo and Padayachee, 2002; Levy and Helene, 2004; Verian, 2012)**, this was a result of the connected paste's porous nature on the surface of recycled concrete aggregate.

3.2 Compressive Strength

The compressive strength was presented and discussed at 28 and 90 days for reference mix and RCCP mixes containing partial replacement of fine recycled aggregate by 10%, 15%, and 20% by partial volume replacement and coarse recycled aggregate by the same percentage of replacement. The vital goal of the RCCP design was to meet the specific compressive strength recommended by **(ACI 327R, 2014**) and a minimum compressive strength requirement. RCCP, being the principal structural layer, must have a minimum 28-d compressive strength of 28 MPa. The results of the compressive strength testing at 28 and 90 days for reference mix and other RCCP mixes are shown in **Fig.s. 13** and **14.** The reference compressive strength result was equal to 32.5Mpa, which was within the requirement of **(ACI 327R, 2014)**, while the mixes containing partial replacement of fine aggregate showed a reduction equal to 29.77MPa,27.83MPa and 25.33MPa for 10%, 15%, and 20% and mixes containing partial replacement of coarse aggregate showed reduction equal to 30.43, 29.47, and 27.55 for 28 days take to consideration that 10% replacement of fine aggregate is still within the specified(28MPa) compressive strength design, while all mixes of containing partial replacement of coarse aggregate are still within the specified compressive strength. This decrease was due to two interfacial transition zones (ITZ).

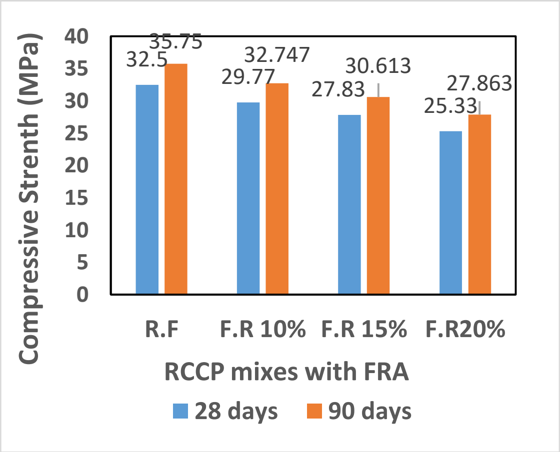

Figure 13. Compressive strength of RF mixes and RCCP mixes replaced with FRA for 28 and 90 days

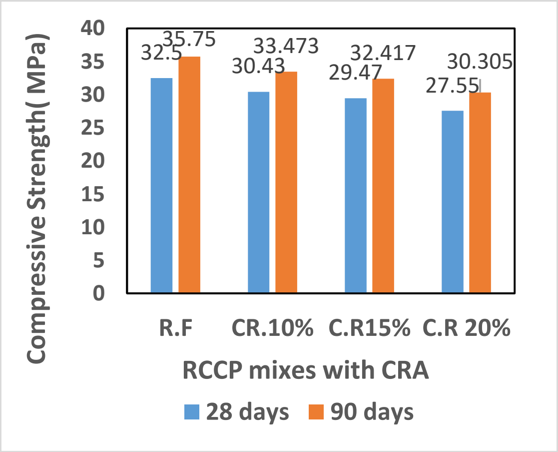

Figure 14. Compressive strength of RF mixes and RCCP mixes replaced with CRA for 28 and 90 days

Compared to aggregate or hydrated cement paste, the binding strength of ITZ was lower. In natural concrete, the ITZ occurs between the aggregate and mortar, but in RCA concrete, it occurs between the original aggregate, old mortar, and new mortar **(Tam et al., 2005; Etxeberria et al., 2007; Kong et al., 2010; Kou et al.,2011 Zhang et al., 2017)**. In addition to this, the decreased compressive strength was caused by the presence of old cement mortar on the recycled aggregate surface, leading to higher porosity and water absorption than the natural aggregate **(Debieb et al., 2009; Zhao et al., 2015; Kurda et al., 2017)**. **Fig.s 15** and **16** show the Percentage reduction in compressive strength of the RCCP mixes with partial replacement of recycled aggregate compared with the reference mix. All mixes' compressive strengths are still increasing after 90 days, but those incorporating coarse recycled aggregate continue to show the largest increase. This was due to the recycled aggregate containing non-hydrated cement particles **(Banthiaand Chan, 2000; Evangelista de Brito, 2007)**.

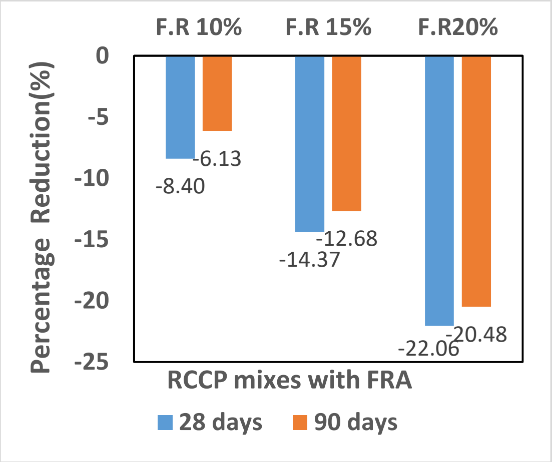

Figure 15. Compressive Strength Percent reduction of RCCP Mixes replaced with FRA Compared with R.F Mix

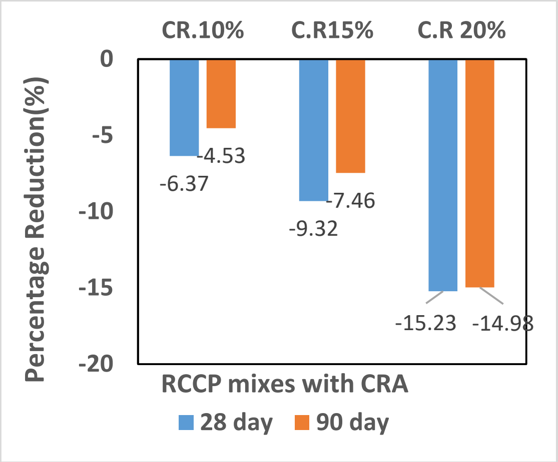

Figure 16. Compressive Strength Percent reduction of RCCP Mixes replaced with CRA Compared with R.F Mix

3.3 Splitting Tensile Strength and Flexural Strength

The findings of the strength at 28 and 90 days are shown in **Fig.s 17**, **18, 19,** and **20,** respectively**.**

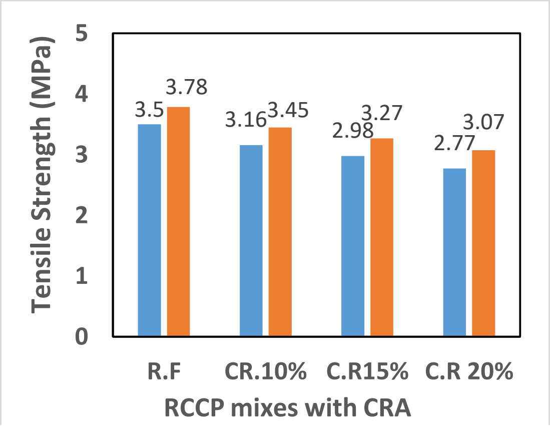

Figure 17. Tensile Strength of R.F and CRA replacement RCCP Mixes at 28 and 90 Days

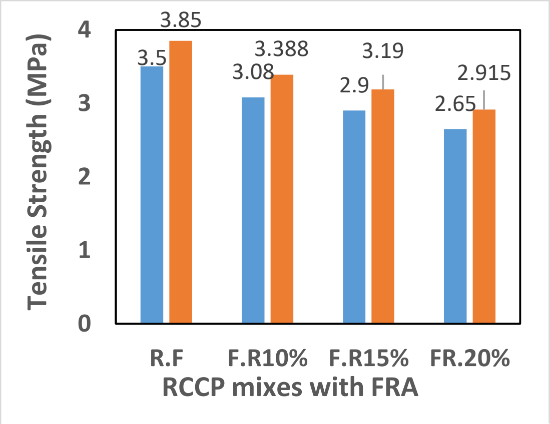

Figure 18. Tensile Strength of R.F and FRA replacement RCCP Mixes at 28 and 90 Days

For RCCP mixes with partial replacement of natural coarse aggregate with coarse recycled aggregate (CRA), the results show that the tensile strength was between 3.16 and 2.77MPa,

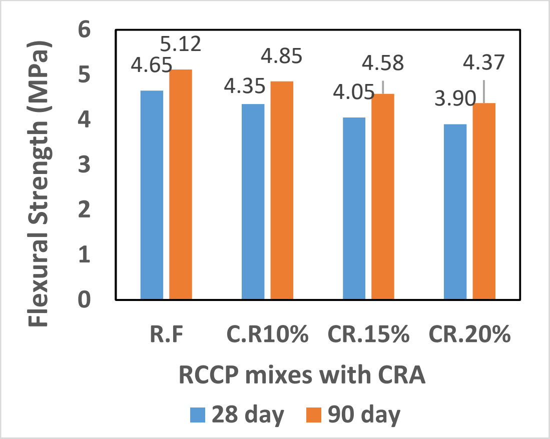

Figure 19. Flexural Strength of R.F and CRA replacement RCCP Mixes at 28 and 90 Days

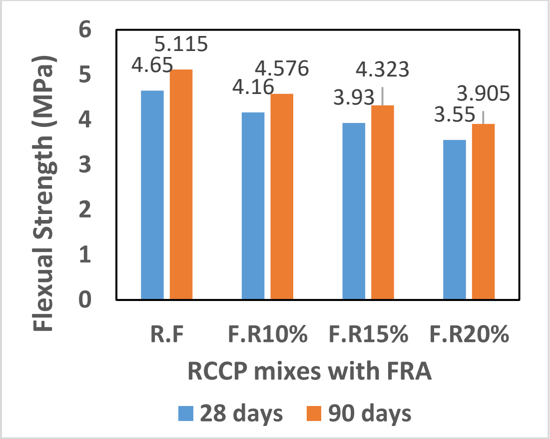

Figure 20. Flexural Strength of R.F and CRA replacement RCCP Mixes at 28 and 90 Days

The results reveal that the splitting tensile strengths ranged between 3.5 and 2.65 MPa at 28 days of curing and between 3.85 and 2.85 MPa at 90, for the flexural strength ranged between 4.65 and 3.55MPa at 28 days and between 5.12 and 3.90MPa at 90 days of curing in water for RCCP mixes with partial replacement of fine aggregate with fine recycled aggregate (FRA). For RCCP mixes with partial replacement of natural coarse aggregate with coarse recycled aggregate (CRA), the results show that the tensile strength was between 3.16 and 2.77MPa, and or flexural between 3.9 and 4.35 at 28 days, at 90 days, the tensile strength was between 3.45 and 3.10MPa, and for flexural between 4.85 and 4.35MPa. The findings show the reduction in the tensile and flexural when comparing the reference mix to the partial replacement of natural coarse aggregate with RCA for all RCCP mixes as (coarse and fine) aggregate. This was due to the physical properties (Los Angeles abrasion and impact value) between natural coarse aggregate and CRA. The result of CRA was smaller than the natural coarse aggregate (**McLean et al., 2014; Yehia and Abdelfatah,2016; Amer et al., 2016). Fig.s 21, 22, 23,** and **24** show the percentage reduction in tensile and flexural of

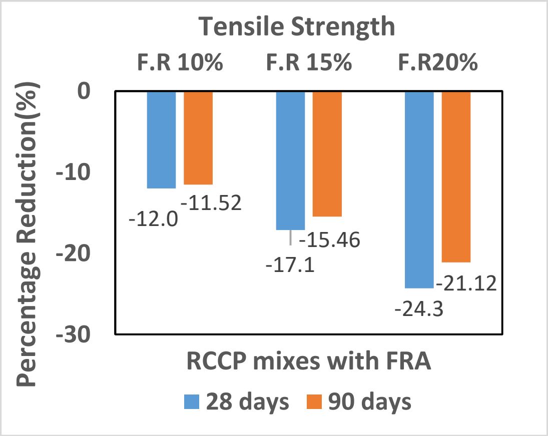

Figure 21. Tensile Strength Percent reduction of RCCP Mixes replaced with FRA Compared with R.F Mix

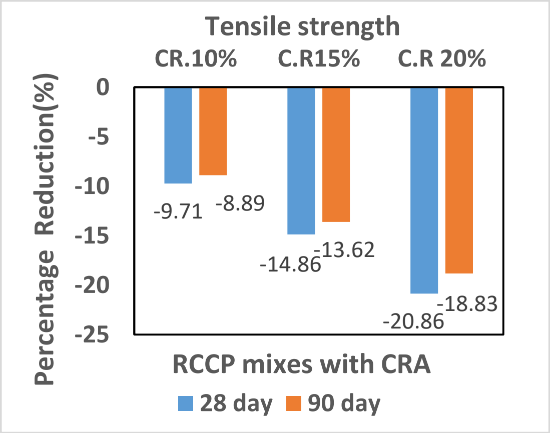

Figure 22. Tensile Strength Percent reduction of RCCP Mixes replaced with CRA Compared with R.F Mix

the RCCP mixes with partial replacement of natural aggregate with recycled aggregate (coarse and fine). Partial replacement of coarse aggregate with CRA gives better results than partial replacement of fine aggregate with FRA. This was attributed to the density of FRA being the lower density of the CRA. This was because the content of cement attached to the FRA was higher than that of CRA **(Amorim, 2012; Belagraa et al., 2015).** Additionally, the water absorption in FRA was more than in CRA. This was due to old cement content in FRA being higher than CRA **(Geng and Sun, 2013; Khalid and Abbas,2023).**

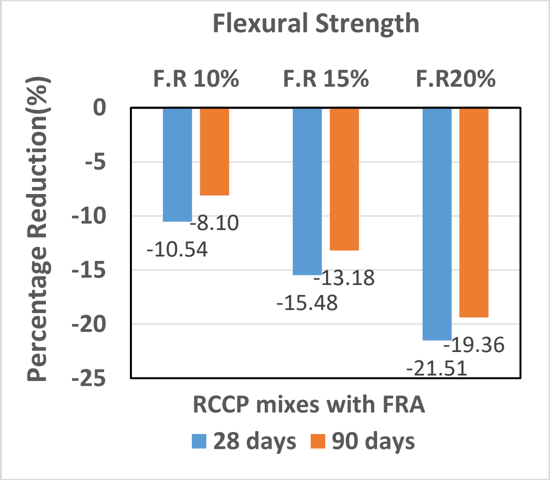

Figure 23. Flexural Strength Percent reduction of RCCP Mixes replaced with FRA Compared with R.F Mix

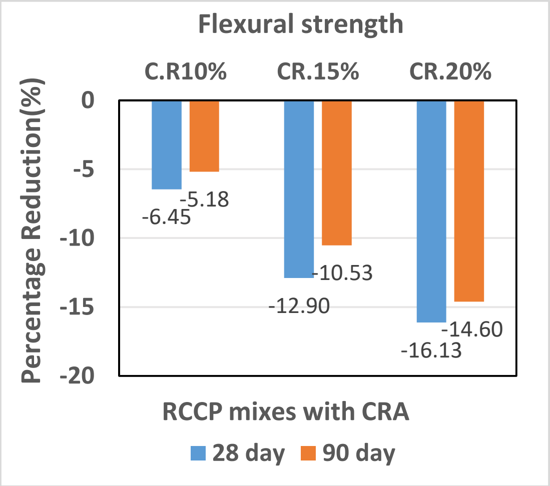

Figure 24. Flexural Strength Percent reduction of RCCP Mixes replaced with CRA Compared with R.F Mix

4. CONCLUSIONS

This work examines the use of recycled aggregate (RA) in roller-compacted pavement concrete. The findings of this study are expected to lead to more investigation and the usage of recycled aggregate. Based on the results so far, it is possible to reach the following conclusions.

- The maximum dry density of RCCP mixes with natural coarse and fine aggregate that has been partly replaced with recycled concrete aggregate by volume has been examined. The density was decreased when recycled aggregate was substituted for natural aggregate in the RCCP mixes.
- The optimum moisture content (OMC) of the RCCP mixture required to achieve maximum compacted density has been evaluated. As a result, all RCCP mixes with partial replacement of natural coarse and fine aggregate with recycled concrete aggregate increased the optimum moisture content depending on the behavior of the material used in the mixture.
- When coarse recycled aggregate (CRA) was partially replaced with coarse natural aggregate in the RCCP mixes, the mechanical properties decreased slightly compared with the reference mix. However, they were still within the required specification except for the replacement of 20%.
- The lowest mechanical properties were achieved when the fine recycling was used as a partial replacement with natural fine aggregate in the RCCP mixture compared to the partial replacement of natural coarse aggregate with coarse recycled aggregate. This

decrease was due to the higher absorbed water and porosity of fine recycled aggregate due to the old cement paste on the fine recycled aggregate.

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