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Producing Sustainable Roller Compacted Concrete by Using Fine Recycled Concrete Aggregate

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Abstract

One-third of the total waste generated in the world is construction and demolition waste. Reducing the life cycle of building materials includes increasing their recycling and reuse by using recycled aggregates. By preventing, the need to open new aggregate quarries and reducing the amount of construction waste dumped into landfills, the use of recycled concrete aggregate in drum compacted concrete protects the environment. Four samples of PRCC were prepared for testing (compressive strength, tensile strength, flexural strength, density, water absorption, porosity) as the reference mix and (10, 15, and 20%) of fine recycled concrete aggregate as a partial replacement for fine natural aggregate by volume. The mix is designed according to (ACI 327-15) with the specified cylinder compressive strength (28 MPa). The results showed a decrease in mechanical properties with an increase in partial replacement compared to the reference mixture and an increase in water absorption and porosity at 28 days. This is because old cement mortar on the surfaces of fine recycled concrete aggregates leads to higher porosity and water absorption than fine natural aggregates. At 90 days, results improved slightly. This is due to the non-aqueous cement in the recycled fine concrete aggregate.

Keywords: Pavement roller compacted concrete, construction and demolition, Recycled aggregate, Fine natural aggregate, Fine recycled concrete aggregate.

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إنتاج الخرسانة المرصوصة بالحدل باستخدام ركام الخرسانة الناعم المعاد تدويره

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الخلاصة

ثلث إجمالي النفايات المتولدة في العالم هي نفايات البناء والهدم يشمل تقليل دورة حياة مواد البناء زيادة إعادة تدويرها وإعادة استخدامها باستخدام الركام المعاد تدويره. من خلال منع الحاجة إلى فتح محاجر جديدة للركام وتقليل كمية نفايات البناء التي يتم إلقاؤها في مدافن النفايات، فإن استخدام ركام الخرسانة المعاد تدويره في الخرسانة المضغوطة في أسطوانة يحمي البيئة. تم تحضير أربع عينات من PRCC للاختبار (مقاومة الانضغاط، قوة الشد، قوة الانحناء، الكثافة، امتصاص الماء، المسامية) كمزيج مرجعي و (10، 15 و20٪) من الركام الخرساني المعاد تدويره الناعم كبـد يـل جزئي للغرامة الركام الطبيعي من حيث الحجم. تم تصميم المزيج وفقًا لـ (ACI 327-15) مع قوة ضغط الأسطوانة المحددة (28 ميجا باسكال). أظهرت النتائج انخفاضًا في الخواص الميكانيكية مع زيادة الاستبدال الجزئي بالمقارنة مع الخليط المرجعي وزيادة امتصاص الماء والمسامية في 28 يومًا. وذلك لأن وجود الملاط الإسمنتي القديم على أسطح الركام الخرساني الناعم المعاد تدويره يؤدي إلى ارتفاع المسامية وامتصاص الماء مقارنة بالركام الطبيعي الناعم. في 90 يومًا، تحسنت النتائج قليلاً. ويرجع ذلك إلى الأسمنت غير المهدرج في الركام الخرساني الناعم المعاد تدويره.

الكلمات المفتاحية: رصيف الخرسانة المرصوصة بالحدل، البناء والهدم، الركام المعاد تدويره، الركام الناعم الطبيعي، الركام الخرساني المعاد تدويره الناعم.

1- INTRODUCTION

Due to rising industrial waste, academics have focused on recycling solutions. Highways are essential to a country's growth and have received much attention. RCCP is a zero-slump concrete pavement made of aggregates, cement, and water. After being prepared with standard asphalt paving equipment, this mixture is squashed and compacted with a vibratory roller. Production plant floors, mine roadways and ports, military vehicle terminals, parking lots, and warehouse floors may use RCCP **(ACI 325.R10).** Extraction costs are rising due to the difficulty in locating natural aggregates. This indicates that old concrete structures should be rescued and recycled as new sources of building materials **(Arshad et al., 2017).** According to the statistics from 1997, Denmark utilized 0.9 million out of 1.06 million metric tons of repurposed old concrete for building purposes. In 1999, Sweden had an annual production of recycled materials from old asphalt pavement that reached 0.8 million metric tons. Of this amount, 95 percent was employed in constructing new asphalt pavement **(Schimmoller, 2000).** According to **(Florea and Brouwers, 2012; Salih and Abed, 2016; Ali et al., 2022),** many European countries have set a high threshold for their recycling aims, ranging from 50 to 90 % of their construction and demolition (C&D) waste production. This is because landfilling is expensive, and in some cases, even more, expensive than recycling**.** Fewer than 100 highway paving projects in the United States, some of which are generated from pavements displaying D-cracking and alkali-silica reaction (ASR) damages, had included RCA in concrete for pavements by the middle of the 1990s. This was the case in the United States **(Burke et al., 1992).** The use of fine RCA in concrete mixtures has raised specific concerns, mostly because of the fine RCA's greater mortar and impurity levels compared to coarse RCA. The angularity, rough surface roughness, and strong absorption of tiny RCA particles are all caused by the adherent and loose mortars **(Evangelista et al., 2015).** These characteristics of fine RCA are responsible, in many instances, for issues with workability, a loss in concrete strength, and considerable increases in volumetric instability (i.e., shrinkage, creep, and coefficient of thermal expansion (CTE)) **(Obla et al., 2007)**. According to the findings of a study that was conducted by (**Fan et al., 2015),** mortars that contained anywhere from 25 % to 100 % fine RCA experienced greater drying shrinkage than the control specimens at all of the ages that were tested (7, 14, 21, and 28 days). This was because the higher porosity of this constituent allows for water to evaporate more quickly than the control specimens.

(Salih and Abed, 2016) investigated the effect that different curing procedures and Porcelanite (a local material) at varying percentages of fine aggregate substitution had on the properties of roller-compacted concrete. They concluded that the optimal proportion of Porcelanite to use as a percentage (volumetric) replacement for fine aggregate is 5%. These may be attributable to the filler effect and the increased amount of CaO and SO_3 in the product. Recycled concrete aggregates, debris from buildings, and reclaimed asphalt pavement were also used as aggregates in the production of concrete for paving (RCA). The findings of the research indicate that making use of these materials is advantageous in terms of waste management; in addition, it has been shown that the use of these waste materials in enough amounts and with help make has the potential to enhance the mechanical properties of concrete pavement **(Evangelista and de Brito, 2007; Hossiney et al., 2010).** **(Sereewatthanawut and Prasittisopin, 2020)** used fine RCA obtained from laboratory-made concretes that were then crushed. These concretes were manufactured under controlled situations. According to the findings of this research, the fine RCA produced in the laboratory could be used in concrete at up to a 30 percent replacement ratio without having a significant impact on the mechanical properties (compressive strength, split tensile, elastic modulus, and abrasion resistance) of the concrete that was investigated**. (Khatib, 2005)** investigated fine recycled concrete's influence on traditional concrete's mechanical properties with replacement ratios (25, 50 and 100%). The results showed that the reduction after 28 days was 10% compared to the control mix, and the decline may be reached 30% with the replacement level of 100%.

To achieve the study’s goals, the PRCC mixtures were differently Prepared by replacing the natural fine aggregate with fine recycled aggregate. The replacement percent of coarse and fine recycled aggregate was (10%, 15%, and 20%) by volume of natural aggregate. Materials are proportioned according to ASTM D1557-12, as indicated in American Concrete Institute Committees; ACI 327R. Eighty four cylindrical samples of (150×300 mm) dimensions, and fourty two prismatic samples of (100x100x500 mm) size are prepared and casted in steel molds using vibrating hammer and tamping plate. After 28 and 90 days of normal curing, the samples are brought from the water tank to be tested.

2. EXPERIMENTAL WORK

2.1 Materials

For this project, ordinary Portland cement was utilized. By (**ASTM C150/C150M-20)**, **Tables 1** and **2** exhibit cement's chemical composition and physical characteristics.
In this investigation, the fine natural aggregate and natural coarse aggregate were sieved by the **(ASTM C136M-19),** and the materials were finer than 75m (No.200) by the standard **(ASTM C117-17). Figs. 1** and **2** illustrate the fine and coarse aggregate grading adapted to the **(ASTM C33/C33)**.

Table 1. Physical 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 days	30	12 Min.
	7 days	37	19 Min.

Table 2. Chemical properties of cement

	Test	Result	(ASTM C150 / C150M-20)
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.

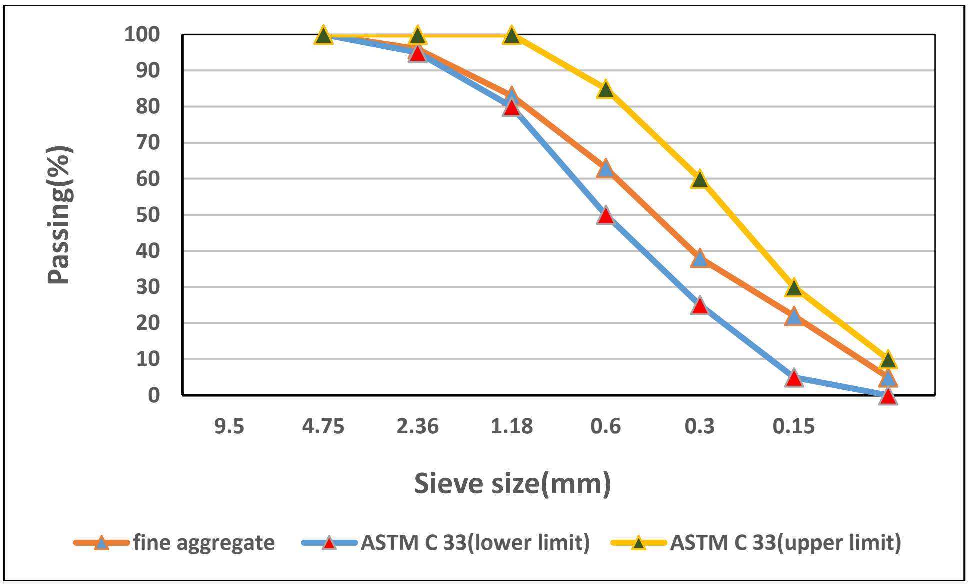


Figure 1. Gradation of fine aggregates and ASTM C33 limits.

Figs. 1 illustrate the fine aggregate grading adapted to the **(ASTM C33/C33)**, and **Table 3** summarizes the natural fine and coarse aggregate characteristics**. Fig. 2** shows that **(ACI 327R-14)** offers recommendations for a grading limit for mixed aggregate utilized in PRCC**.**

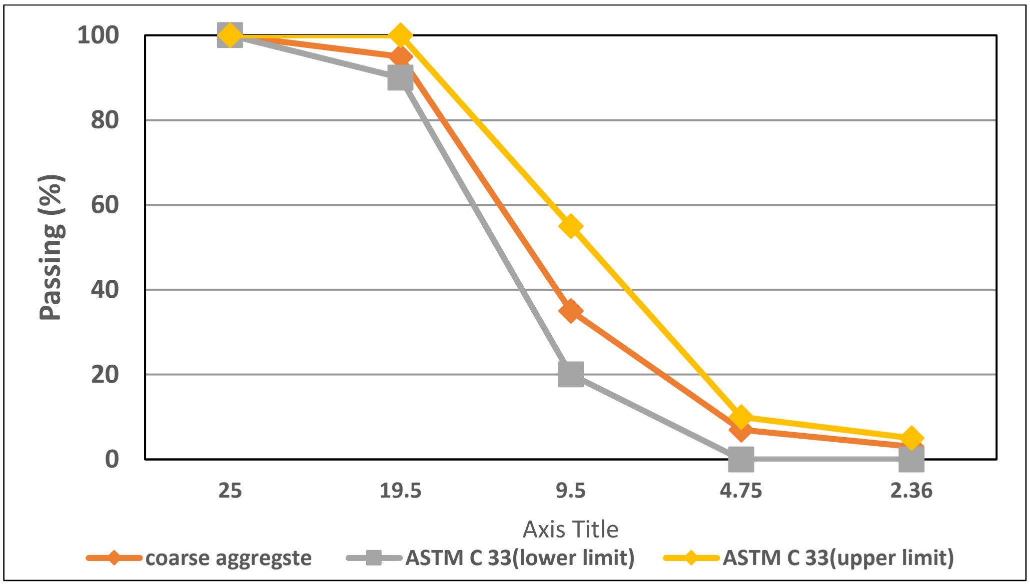


Figure 2. Gradation of coarse aggregates with ASTM C33 limits.

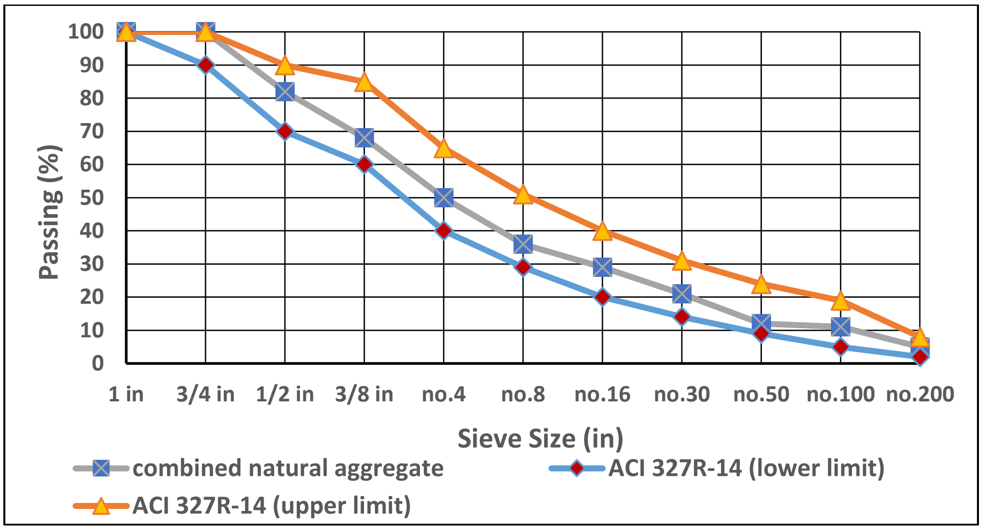


Figure 3. Combined natural aggregate gradation with ACI 327R-14 limits.

Table 3. Natural aggregate properties

Test	Coarse aggregate	Fine aggregate	ASTM (C33-18) 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	--	--

Like that of the fine natural aggregate, the fine recycled concrete aggregate was sieved by **ASTM (C136M-19)**, and materials more acceptable than 75m (No.200) by **ASTM (C117-17)**. **ASTM C33/C33M** was used for the fine recycled concrete aggregate. From what is shown in **Fig. 4**. The fine recycled concrete aggregate characteristics are given in **Table 4**.

Table 4. Fine recycled concrete aggregate properties

Test	Fine Recycled aggregate	ASTM (C33-18) limits
Bulk specific Gravity	2.10	--
Absorption of water (%)	9	--
SO_3 (%)	0.45	--

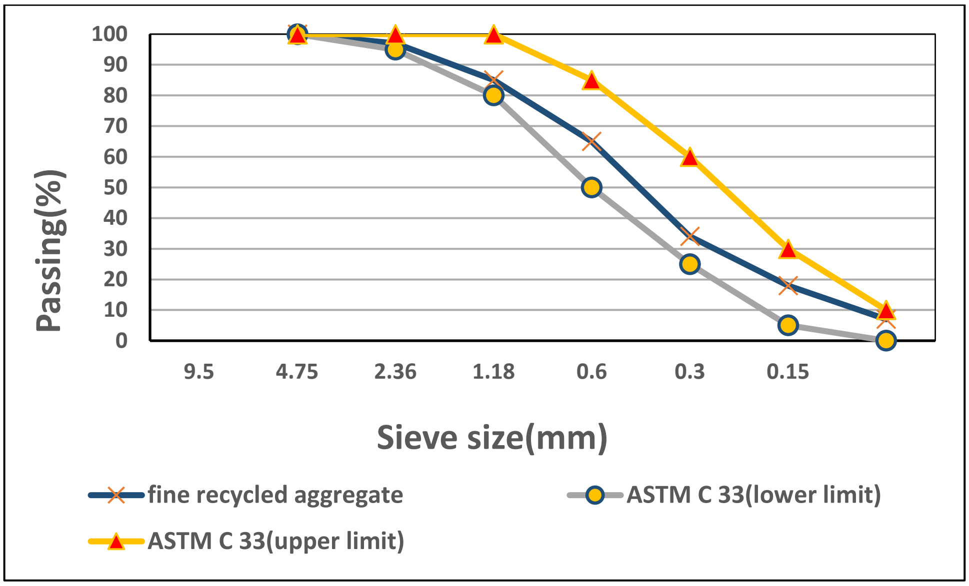


Figure 4. Gradation of fine recycled concrete aggregates with ASTM C33 limits.

The filler used in this study is limestone powder. This material passes from a 75m (No.200) sieve. It is widely available and cheap. **Table 5** shows chemical and physical characteristics.

Table 5. The chemical and physical properties of limestone filer

Criteria	LP	Criteria	LP
SiO_2, (%)	5.05	MgO, (%)	1.59
AL_2O_3, (%)	1.62	SO_3, (%)	0.22
Fe_2O_3, (%)	0.61	LOI, (%)	32.35
Cao, (%)	49.08	Particle size distribution (nm)	475.9

2.2 Mix proportion

Four different PRCC mixtures were created. The control mix was made with natural aggregates (coarse and fine aggregates), and the other mixtures were made by replacing the fine natural aggregates with fine recycled concrete aggregates; the fine recycled concrete aggregates replaced the fine natural aggregates in three mixtures with replacement ratios of (10, 15, and 20%) by volume. **(ASTM D1557-12)** may be used to determine RCCP's water content and density. This study employed cement, natural (coarse and fine) aggregates, fine recycled aggregate, and limestone filler to make RCCP mixtures. **(ACI 327. R, 2015)** requirements utilize 13% cement by weight of total dry components. The results of grading tests determine the amount of aggregates to be use. The aggregates used were: 50% coarse aggregate, 45% fine aggregate, and 5% filler, according to water values reported by **(ACI 327. R, 2015)**. RCC mixture proportions were examined using **ASTM D1557-12** Process C. This process used 4.5 to 8.5 % molding water. **Fig. 5** exhibits dry density (gm/cm^3) and Optimum Moisture Content OMC (%).

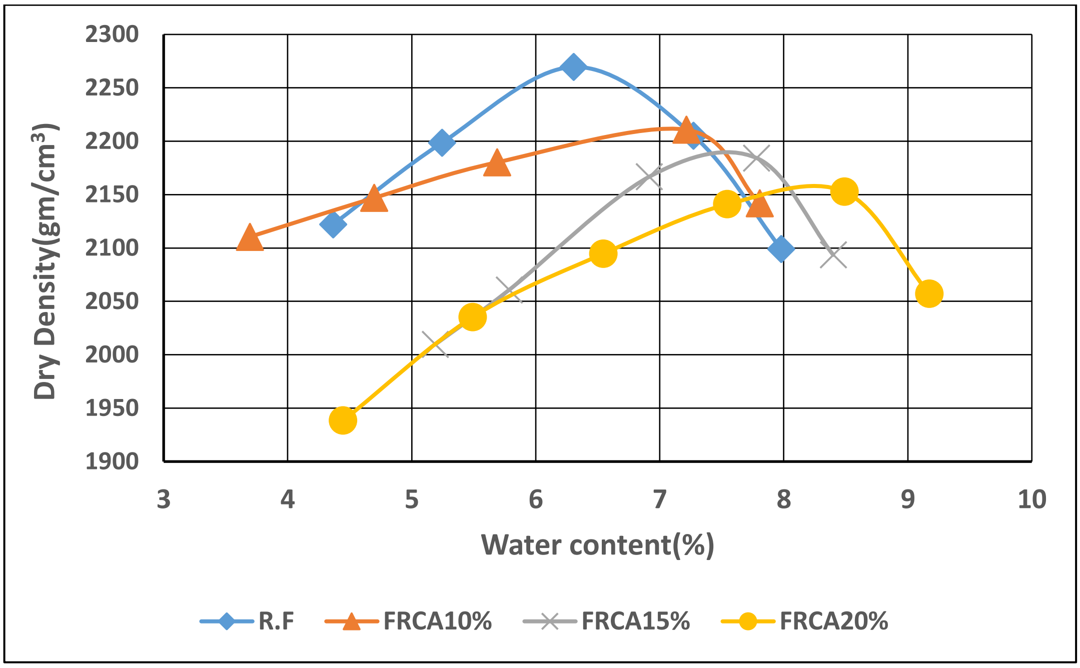


Figure 5. The relationship between optimum moisture content and maximum dry density for reference mix and mixes with FRCA of RCCP.

2.3 Producing and Casting

Two kinds of samples were prepared for destructive testing (cylinder samples and beam shape samples). **ASTM (C1435/C1435M 14)** employed a vibrating hammer to compress the materials. Four layers of compression were performed on cylindrical specimens with diameters and heights of 15 cm and 30 cm, respectively. Rectangular molds were also utilized to compress beam-shaped models (10 * 10 * 50 cm) into two layers. After the casting process, the specimens were kept in a laboratory for 24 hours. Following that, the samples were removed from the molds and preserved in a water tank at 23 °C for the duration of the testing period (28 or 90 days). **Fig. 6** shows images of the casting process.

2.4 Mechanical Properties

2.4.1 Compressive Strength

ASTM (C39/C39M-15) performed tests of compressive strength on cylinder-shaped cured samples obtained from the water-curing tank. The dimensions of the samples were 15 cm in diameter and 30 cm in height. After the samples had been cured for 28 and 90 days, they were tested. The load for the test was increased at a rate of 0.3 MPa/s using the crushing machine with a capacity of 3000 KN. The samples were presented in the testing machine, as shown in **Fig. 7**.

Figure 6. (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

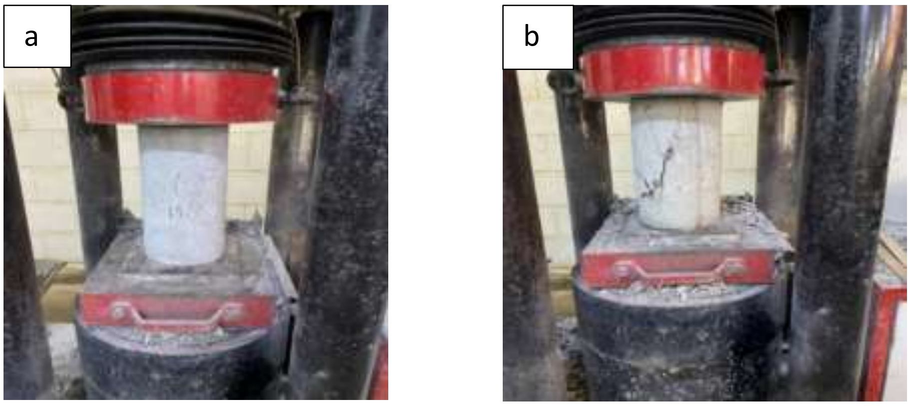


Figure 7. (a) RCCP specimen in the test machine, (b) RCCP specimen after the test.

2.4.2 Tensile Strength

(ASTM C496-11) was used to evaluate 15cm x 30cm cylinder samples. The test used samples cured for 28 and 90 days. At 0.7 to 1.4 Mpa / min, 3000 KN compressive testing equipment was used. Figure 10 depicts a tensile test. **Fig. 8** shows the tensile strength test produced.

2.4.3 Flexural Strength

The flexural strength was determined by testing beam-shaped samples with dimensions of 10 × 10 × 50 cm. After the specimens were removed from the curing tank, they were put through the testing process. **(ASTM C78 / C78M-18)** was the testing standard applied to the specimens (three-point loading)? After the specimens were prepared for testing, they were placed in the device such that the surface of the specimen would be in contact with the device. The estimated average of the three measurements was then applied to each sample. **Fig. 9** illustrates the specimens being tested within the device.

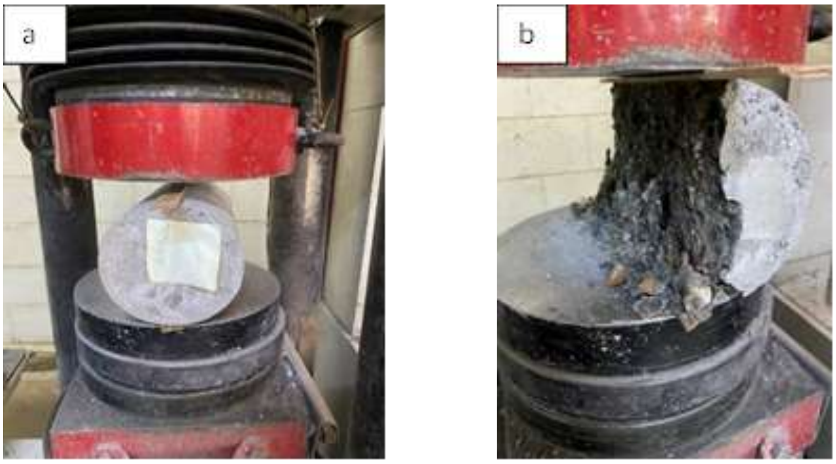


Figure 8. (a) RCCP sample in the testing machine, (b) RCCP sample after test

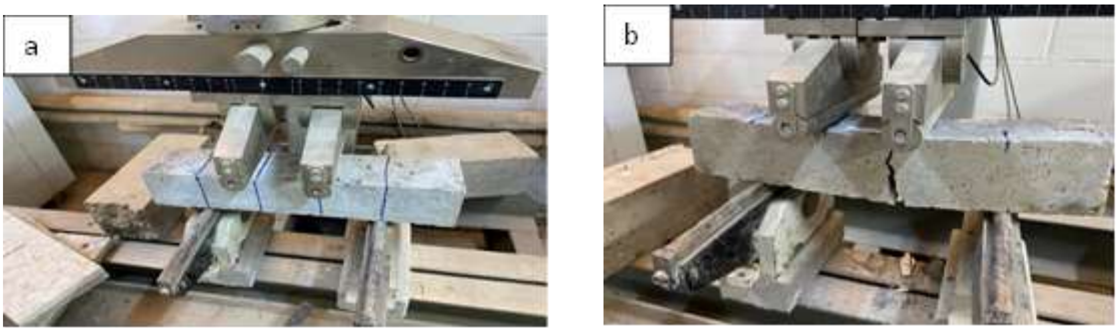


Figure 9. (a) RCCP sample in the test machine, (b) RCCP sample after the test.

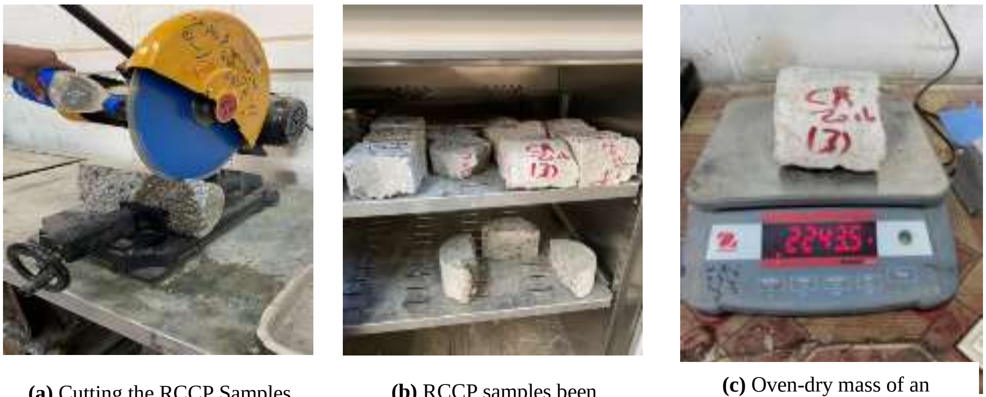
2.4.4 Density, Porosity, Air void

The method used to determine the density, porosity, and absorption of PRCC specimens is described in detail in **(ASTM C642-13)**. Individual pieces of cylinders and prisms were tested, with a volume of more than 350 cm3 for each piece obtained by cutting the cylinder and prism specimens into individual pieces. The test was carried out on specimens that had been cured for 28 and 90 days. **Fig. 10** depicts some images of the testing process.

3. RESULTS AND DISCUSSION

3.1 Maximum Dry Density and Optimum Moisture Content

The results of the modified proctor test are shown in **Table 5**. When Fine recycled concrete aggregate was used instead of the fine natural aggregate, it was observed that the maximum dry density was reduced. This reduction is related to fine recycled concrete aggregate having the lowest specific gravity than the natural aggregate **(Hansen, 1992; Yong et al., 2009; Vieira et al., 2016)**. The lowest fresh density is achieved when fine recycled concrete aggregates are used. This is because the fine recycled concrete aggregate's specific gravity is lower than the fine natural aggregate. As seen in **Table 6**. When fine recycled concrete was replaced with fine natural aggregate, the optimal water content increased. The changes in the optimal water content may be due to the contaminated cement mortar on the recycled concrete aggregate surface **(Gómez-Soberón, 2002; Xiao, Li and Zhang, 2005; Etxeberria et al., 2007; Verian, 2012)**. He absorbed more water in the fine recycled concrete aggregate than the fine natural aggregate, which has different absorption properties. According to **(Olorunsogo and Padayachee, 2002; Levy and Helene, 2004; ACPA, 2009; Verian, 2012)** this is a result of the connected paste's porous nature on the surface of fine recycled concrete aggregate.



(a) Cutting the RCCP Samples

(b) RCCP samples been drying in the oven

(c) Oven-dry mass of an RCCP sample (Mass A)

(d) SSD mass after immersion and boiling (Mass C)

e) Immersed apparent mass after immersion and boiling (Mass D)

Figure 10. The procedure of density, absorption, and air void

Table 6. Maximum dry density and optimum moisture content for different PRCC mixes

Mix-ID	Optimum moisture content (%)	Maximum Dry density kg/m^3
R. F	6.1	2210
FR10%	6.7	2202
FR15%	6.9	2200
FR20%	7.3	2194

3.2 Compressive Strength

The compressive strength was presented and discussed for 28 and 90 days for reference mix and RCCP mixtures containing partial replacement of fine recycled aggregate by 10%, 15%, and 20% by partial volume replacement. The vital goal of RCCP design was to meet specific compressive strength recommended by **(ACI 327-14)** and a minimum compressive strength requirement. RCCP, being the principal structural layer, must have a minimum 28mpa compressive strength of 28 days. The results of the compressive strength testing at 28 and 90 days for reference mix and RCCP mixtures with a partial replacement of fine aggregate are shown in **Fig. 11**. The reference compressive strength result was equal to 32.5Mpa, which was within the requirement of **(ACI 327-14)**. At the same time, the mixtures containing partial replacement of fine natural aggregate showed a reduction equal to 29.77mPa, 27.83mPa, and 25.33mPa for 10%, 15%, and 20% for 28 days, taking into consideration that 10% replacement of fine aggregate is still within the specified compressive strength design. This decrease is due to two interfacial transition zones (ITZ) types. The ITZ represents the bond between the aggregate and pastes is usually weaker than the aggregate or hydrated cement paste. In PRCC made with fine natural aggregate, the ITZ occurs between the aggregate and mortar, while in concrete containing fine recycled concrete aggregate, the ITZ takes place between the original aggregate and old mortar and new mortar **(Etxeberria et al., 2007; Tam and Tam, 2007; Kong et al., 2010; Kou, Poon and Agrela, 2011; Zhang et al., 2017)**.

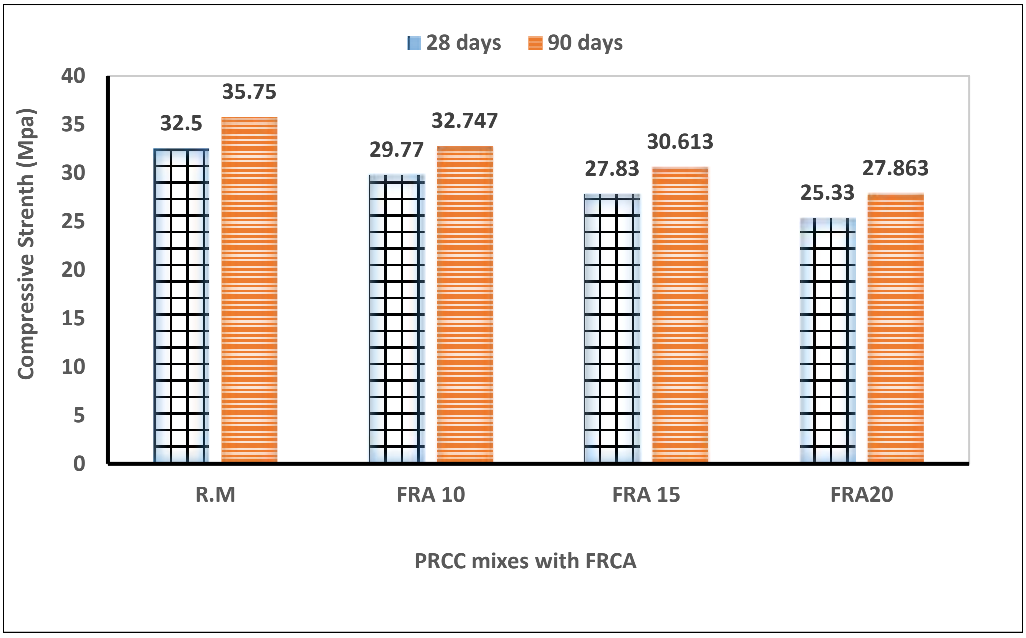


Figure 11. Compressive strength of R.F and PRCC mixtures replaced by FRCA for 28 and 90 days

Additionally, the lower compressive strength is due to the presence of old cement mortar on FRCA surfaces leading to higher porosity and water absorption than the fine natural aggregate **(Debieb et al., 2009; Zhao et al., 2015; Kurda, de Brito and Silvestre, 2017). Fig. 12** shows the Percent difference in compressive strength between the reference mix and the RCCP mixes with partial replacement of fine natural aggregate with fine recycled concrete aggregate. All mixes' compressive strengths increase after 90 days, but those incorporating coarse recycled concrete aggregate continue to show the largest increase. This is because the recycled concrete aggregate contains non-hydrated cement particles **(Banthia, 2000; Evangelista and de Brito, 2007)**.

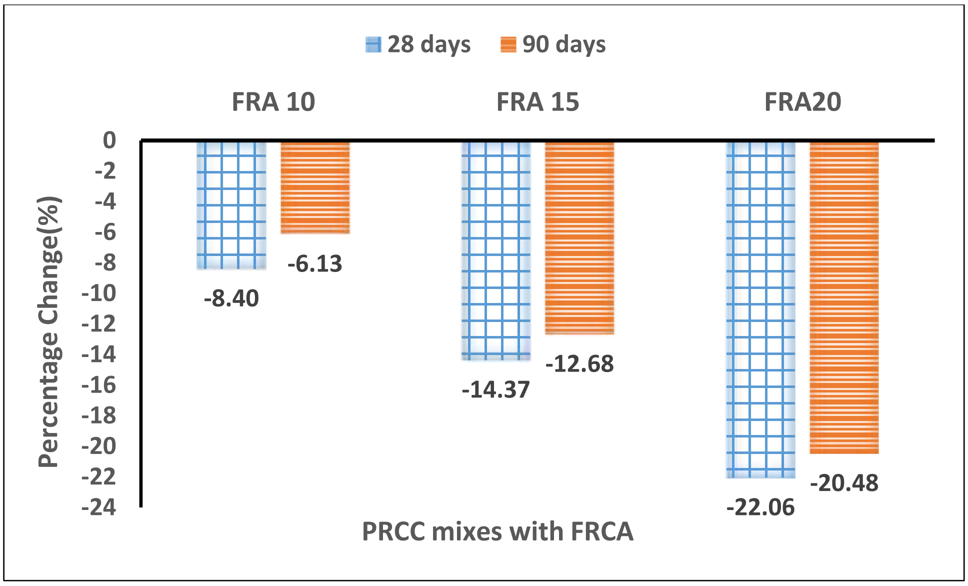


Figure 12. Compressive strength percent change of PRCC mixes replaced with FRCA compared with R.F mix

3.3 Tensile and Flexural Strength

At 28 and 90 days, the splitting tensile strength and flexural strength were calculated; the findings are shown in **Figs. 13 and 14**. The results reveal that the splitting tensile strengths ranged between 3.5 and 2.65 MPa after 28 days of curing and between 3.85 and 2.85 MPa at 90 days of curing in water. The results show that when the replacement ratio of fine natural aggregate with fine recycled concrete aggregate increases, the tensile strength of RCCP mixes decreases **(Lamond et *al.*, 2001; Katz, 2003;Etxeberria *et al.*, 2007; Federal Highway Administration, 2018)**. Because tensile strength is less affected by cement content than compressive strength, the additional cement included with the fine natural aggregate has less effect. As a result of the recycled aggregates' porous structure, it's only natural that a drop occurs as the replacement ratio increases**. (Evangelista and de Brito, 2007; Thomas, Thaickavil and Wilson, 2018).** The results show the flexural strengths of RCCP produced after 28 and 90 days of cure. The findings show that flexural strength values decreased with an increased replacement ratio of fine natural aggregate with fine recycled concrete aggregate **(Katz, 2003; Poon *et al.*, 2004; Kou, Poon and Agrela, 2011).** The findings indicate that the mixes with partial replacement fine natural aggregate with fine recycled concrete have lower flexural strength than the control mix. This is caused by the increased water absorption of fine recycled concrete aggregate and the presence of lower-density residual cement mortar bound to the recycled aggregate particles **(Kurda, de Brito**

and Silvestre, 2017). These reduced mechanical strengths result from recycled sand's lower qualities compared to the natural sand utilized; also, the presence of attached cement paste increases porosity and water absorption compared to fine natural aggregate **(Zhao *et al.*, 2015)**. **Figs. 15 and 16** show the percentage change in strength with partial replacement of fine natural aggregate. This result of the tensile and flexural strength is similar to the compressive strength.

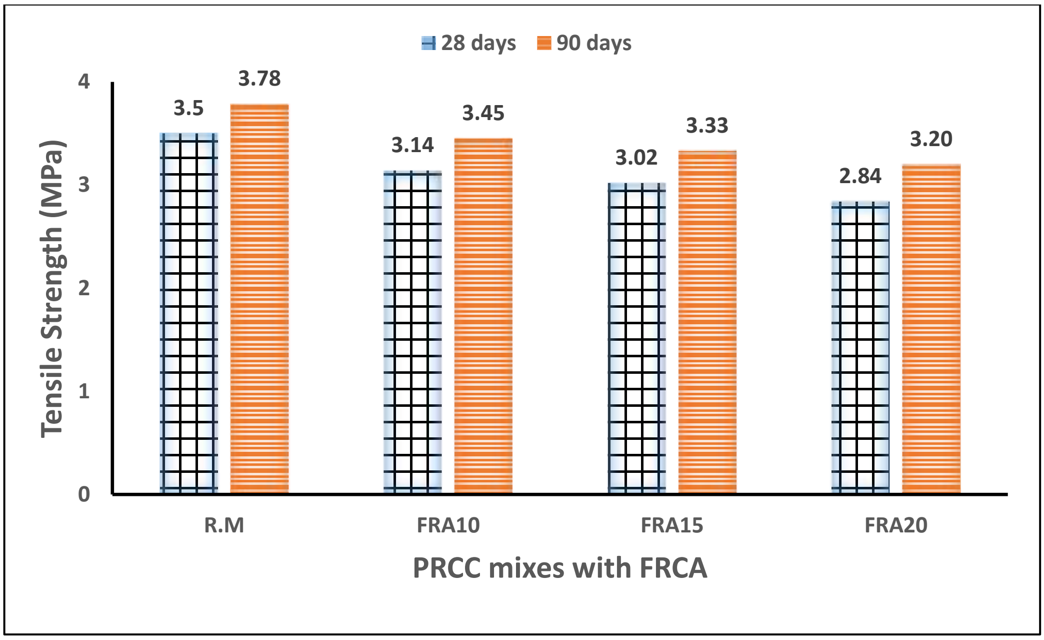


Figure 13. Tensile Strength of R.F and F.R replacement PRCC Mixtures at 28 and 90 Days

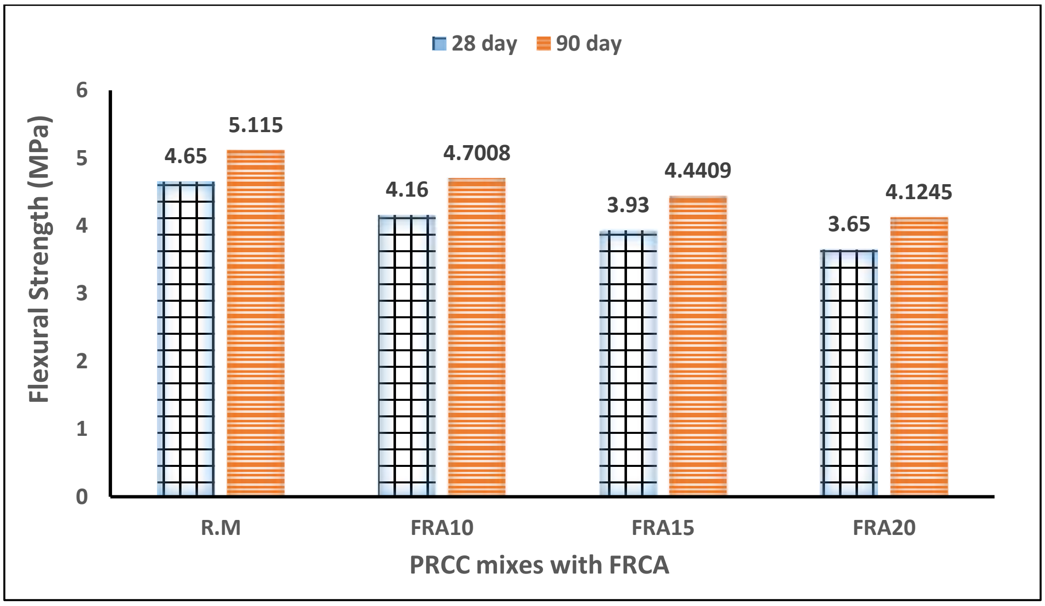


Figure 14. Flexural Strength of R.F and F.R replacement PRCC Mixtures at 28 and 90 Days

3.4 Density, Absorption, and Porosity

Fig. 17. represent the density, absorption, and porosity data at the ages of 28 and 90 days, respectively. The results show that the density was reduced and porosity and water absorption had been increased with an increased percentage of replacement of fine natural aggregate with fine natural aggregate. This is due to the rougher surfaces and more irregular shapes of FRCA and the old paste attached to the original aggregate contributes to a higher paste to natural aggregate ratio than that of natural fine aggregate **(Amorim et al., 2012; Dinis Silvestre et al., 2017; Verian et al., 2018; Silva, de Brito and Dhir, 2018)**. The porosity and absorption increased due to the large surface area of RCA and the presence of old mortars on the surface of RCA particles compared to natural fine aggregate due to the somewhat porous nature of attached mortar **(Levy and Helene, 2004; Safiuddin et al., 2014; Verian, 2012; Le et al., 2017).** The water absorption in Fine natural aggregate is more than in fine natural aggregate. This is due to the existence of old cement content in fine

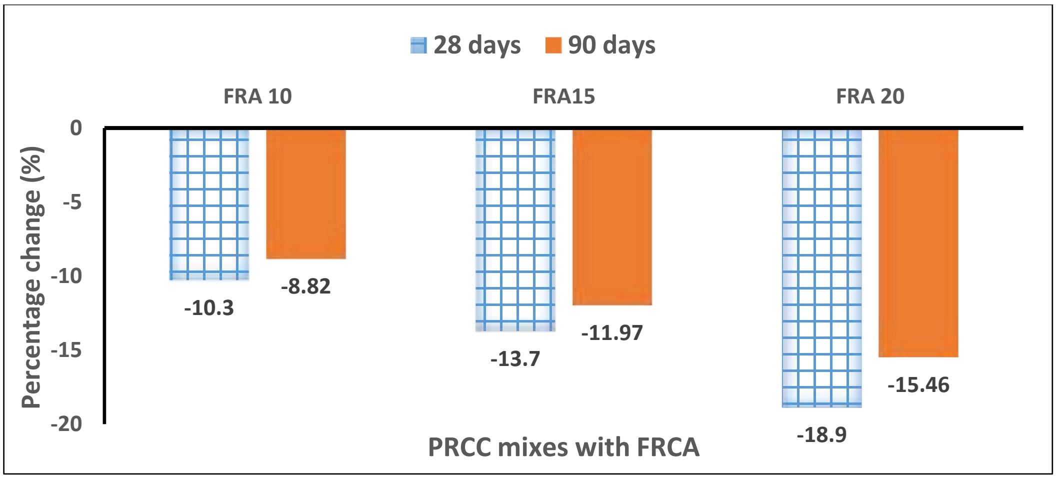


Figure 15. Flexural strength of R.F and F.R replacement PRCC mixtures at 28 and 90 days

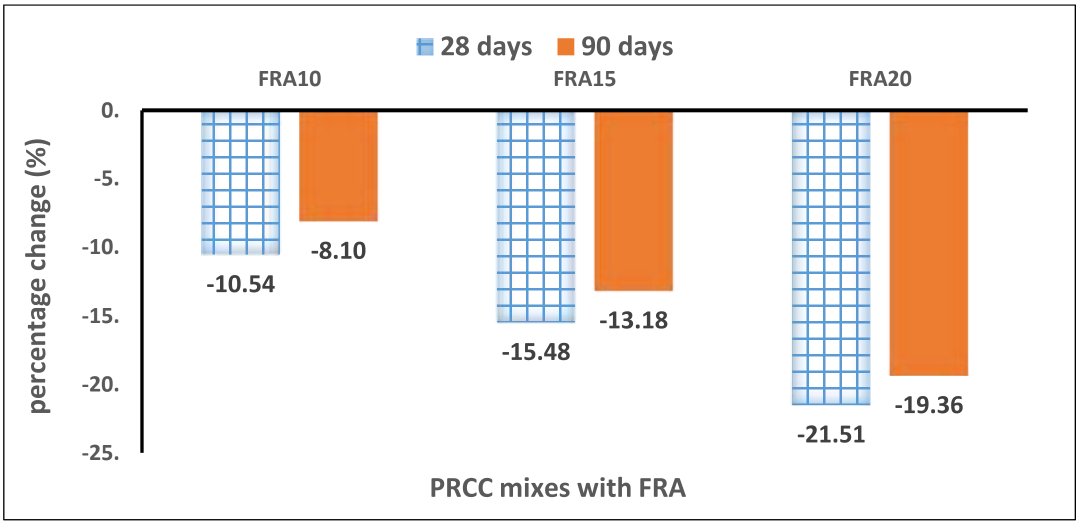


Figure 16. Flexural strength percent change of PRCC Mixes replaced with FRCA compared with R.F mix

recycled concrete aggregate **(Geng and Sun, 2013)**. An additional reason for the decrease in density and increase in water absorption is the lower specific gravity of cohesive mortar on the surface of these RCA **(Kou and Poon, 2009)**. The density of FRCA is lower than that of the fine natural aggregate. This is due to the fact that the content of lower density residual cement mortar attached to the fine recycled concrete aggregate **(Amorim et al., 2012; Belagraa et al., 2015).**

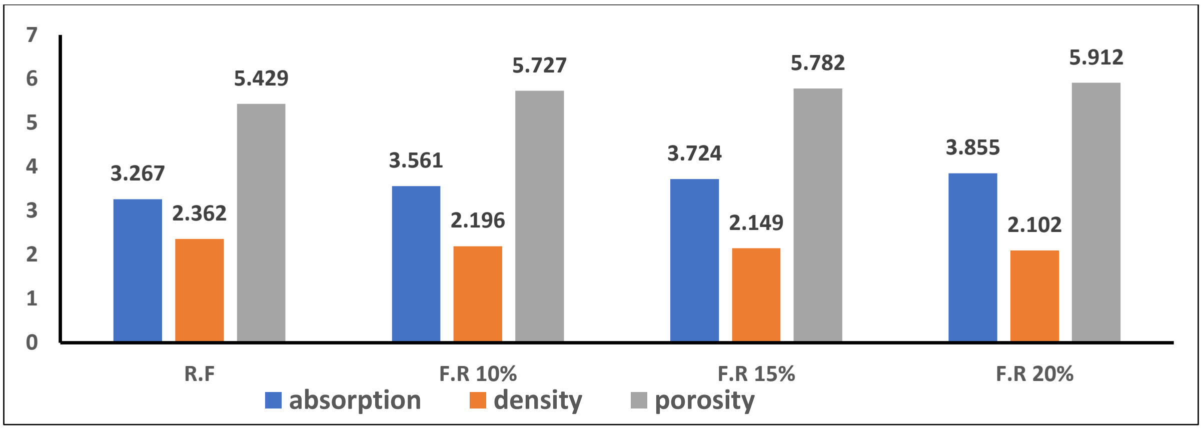


Figure 17. Density and absorption and porosity of FRCA with R.F.

4. CONCLUSIONS

This research examines the usage of fine recycled concrete aggregate in roller-compacted concrete pavement. The findings of this study are expected to promote additional research on the use of fine recycled concrete aggregate. Based on the previous findings, the following conclusions can be made

1. The maximum dry density of RCCP mixes with fine recycled concrete aggregate has been investigated. The density was reduced when fine recycled concrete aggregate was used instead of fine natural aggregate in the RCCP mixes.
2. The optimal moisture content of the PRCC mixes required for maximum compacted density has been determined. According to the findings, this value is affected by various factors such as the surface area of the fine recycled concrete aggregate and the absorption of fine recycled concrete aggregate in comparison to fine natural aggregate. As a result, each PRCC mix has a different optimal moisture content.
3. The compressive strength was achieved with the 10% partial replacement in the PRCC mix. The decrease in compressive, tensile, and flexural strength was (8.4%,14.37%, 22.06%), (12.01%,17.1 and 24.3%), and (10.54%, 15.48%, and 21.51) at 28, for 90 of curing days (6.13%,12.68%, and 20.48%), (11%, 15.46%, and 21.12), and (8.10%, 13.18%, and 19.36) respectively, compared with the reference mix made with fine natural aggregate.
4. The hardened density decreased when the fine recycled concrete aggregate was utilized instead of fine natural aggregate; the absorption and porosity increased with increase the partial replacement. this is due to the contaminated old cement on the surface of fine recycled concrete aggregate it is more porous than the fine natural aggregate.

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