Fabrication of Sustainable Roller-compacted Concrete Pavement containing Plastic Waste as Fine and Coarse Aggregate

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ABSTRACT

The primary goal of this practical lab analysis was to obtain a sustainable and eco-friendly Roller-Compacted Concrete (RCC), by lowering the consumption of natural resources and energy and utilizing plastic waste. The experiment performed involved six RCC mixes with partial weight replacement of coarse or fine aggregate of specified percentages with waste plastic along with a reference mixture (R.M), utilizing different curing methods, namely spraying with water two times per day, immersing in water, and utilizing ISO SMART CURING W 1035 material. Three types of plastic were used in the analysis: polyvinyl chloride (PVC) as coarse aggregate replacement and polyethylene terephthalate (PET) and high-density polyethylene (HDPE) as fine aggregate replacement. The mixes were tested regarding compressive, flexural, and splitting tensile strength. The results of the study indicate that the RCC containing 10% PVC (CP10) exhibited a reduction in compressive strength of 5.25, 5.69, and 5.99% for water, spray, and coating curing, respectively at 28 days related to the R.M, followed by the mix including 20% PVC (CP20) with a decrease ratio of 12.79, 13.52, and 13.20%. Mixtures with 5% PET and HDPE (FP5, FH5) can be accepted, since their results were nearest to R.M with a percentage decrease of 4.16, 3.52, and 3.74% for PET and 3.18, 3.13, and 3.14% for HDPE. Treating with coating material achieved the best results, exhibiting improvement in compressive, flexural, and tensile splitting strength, while the water spray method performed worse than water curing.

Keywords-Roller Compacted Concrete (RCC); waste plastic; PVC; PET; HDPE

I. INTRODUCTION

Roller Compacted Concrete (RCC) is a kind of concrete that is more cost-effective and environmentally friendly than conventional concrete [1]. The RCC mix includes only 12% cementitious fabrics rather than 15% [2]. RCC is manufactured operating an identical technique with that adopted to construct asphalt pavement. The mixture consists of cement, combined aggregates, and water, and it is then compressed by weighty vibrating steel drums with rubber tires [3, 4]. The cement industry is a major contributor to environmental problems [5-10]. Green concrete, an eco-friendly alternative, is made by substituting aggregate with waste materials [11-14], thus reducing pollution and protecting the environment [15, 16]. The lack of accurate forms to accumulate, transfer, and process plastic waste generates confusion around this issue [17]. The main advantages of reusing plastic in RCC are: (a) Preventing the accretion of plastic waste, (b) maintaining the natural crude materials and lowering the need of suitable infrastructure, and (c) reusing plastic scrap in RCC, which is more viable than other recycling strategies [18].

II. MATERIALS AND MIXTURE DESIGN

The mixtures used for RCC included the subsequent:

- Cement: Ordinary Portland Cement (OPC) was utilized for this project. To determine its physical properties and chemical composition, a sequence of traditional trials was completed according to ASTM C150/C150M.
- Aggregates: Coarse crushed aggregate with a nominal maximum size of 19 mm was employed with fine aggregate of size less than 4.75 mm. The ASTM C33 grading criteria were considered. Tables I and II show the features of fine and coarse aggregates. Limestone filler fabric that passed via sieve number 200 was deployed. Based on ACI 327R, the combined aggregate used in RCC has grading boundaries. In this study, these boundaries were utilized to

specify the grading of the combined aggregate as illustrated in Figure 1.

- Waste plastic: PVC, PET, and HDPE were collected from bottles, vegetable boxes, and pipes. The collected plastic waste was crushed and shredded into small particles to obtain the plastic coarse and fine aggregate for use in RCC specimens as aggregate weight alternatives by 10% and 20% for coarse aggregate, and 5% and 10% for fine aggregate. The preparing process is illustrated in Figure 2, and the fitting requirements are evidenced in Table III.

TABLE I. CHARACTERISTICS OF FINE AGGREGATE

Parameter	Results	ASTMC33
Specific gravity	2.57	----
Absorption %	1.2	----
Clay lumps and friable particles %	0.83	≤ 3
Sulfur trioxide (SO_3) %	0.09	----

TABLE II. CHARACTERISTICS OF COARSE AGGREGATE

Parameter	Results	ASTMC33
Specific gravity	2.64	----
Absorption %	0.60	----
Clay lumps and friable particles %	0.53	≤ 3
Sulfur trioxide (SO_3) %	0.08	----

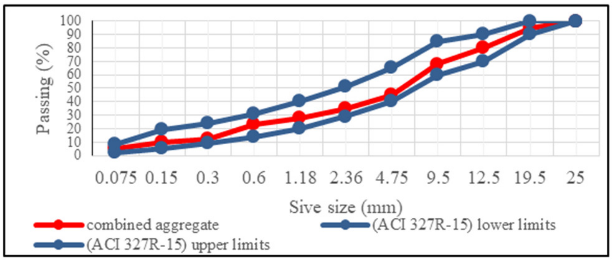


Fig. 1. Graduation of combined aggregates.

Fig. 2. Preparing process of plastic waste.

TABLE III. PLASTIC WASTE CHARACTERISTICS

	Specific gravity	Density (kg/m^3)
PVC	1.4	175
PET	1.3	402
HDPE	0.95	348
Test method	ASTMC127-15	ASTMC29/29M

*These types of plastic have no absorption (%)

III. MIXTURE PROPORTIONS

This study investigated six separate RCC blends with plastic waste and a reference mixture (R.M). The experiment used various components to obtain RCC blends, including cement, aggregates, PVC (10% and 20%) with mix IDs CP10 and CP20 as coarse aggregate replacement, and PET and HDPE with mix IDs FP5, FP10, FH5, FH10 as fine aggregate replacement, respectively. The cement was selected as a ratio by weight of all dry components employing the ACI 327R design, with a ratio of 12%. Additionally, gradation trials were conducted to determine the magnitude of the coarse crushed aggregate, sand, and filler at 55%, 40%, and 5%, respectively. To achieve the correct water content and density for RCC, the ASTM D1557 was followed. Depending on diverse water content bounded by ACI 327R and ACI 211.3R, the optimum moisture content (O.M.C %) comparable to maximum dry density (max γ dry kg/m³) per kind of waste plastic was computed using the modified proctor trail (method C) in accordance to ASTM D1557. Five point-modified Proctor arc was produced utilizing moisture content varying from 4.5 to 8.5% with an increasing step of 1%. For separately examining Proctor point, 6 kg of combined aggregates, i.e. 2.4 kg of fine aggregate, 3.3 kg of coarse aggregate, and 0.3 kg of filler were blended with the computed cement and water.

IV. CASTING PROCESS

Adopting the ACI 327R recommendations the ASTM C1435 vibrating hammer on cylinders strategy was utilized and measurements regarding compressive and splitting strength were taken [19, 20].

V. PRACTICAL JOB LAB TRIALS

The RCC mix was operated to mold forms:

- Cylinders with a size of 150 mm × 300 mm were employed for compressive and splitting tensile strength tests. They were cured with three different curing methods: spraying with water two times per day until the day of the test, the coating method with ISO SMART CURING W 1035, and the normal curing/ submerging in a tank of water at 23 ± 2°C until the trial according to ASTM C192, ASTM C39, and ASTM C496.
- Prisms with a size of 100 mm × 100 mm × 400 mm for flexural strength tests, were cured through the aforementioned three different curing methods.

The materials used in the preparation of laboratory RCC specimens were 807.17 kg/m^3 fine aggregate, 1103.28 kg/m^3 coarse crushed aggregate, 271.9 kg/m^3 cement, 126.58 kg/m^3 tap water, and 99.7kg/m^3 filler. Figure 3 presents the practical lab procedures.

VI. RESULTS AND DISCUSSION

A. Modified Compression Results

Figure 4 displays the results of the Procter compaction test that determines the Optimum Moisture Content (OMC). The maximum dry density presents an insignificant change when the replacement proportion of aggregate weight is small.

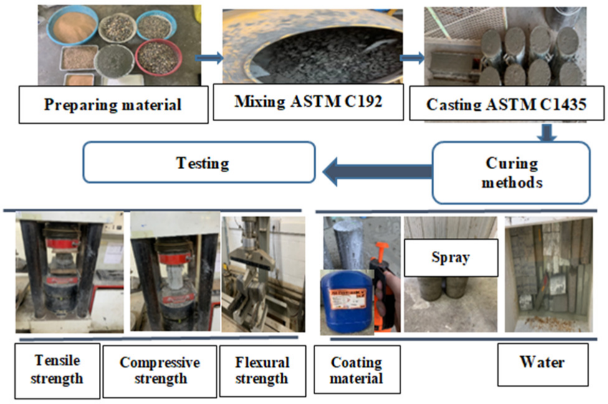


Fig. 3. Practical lab procedure.

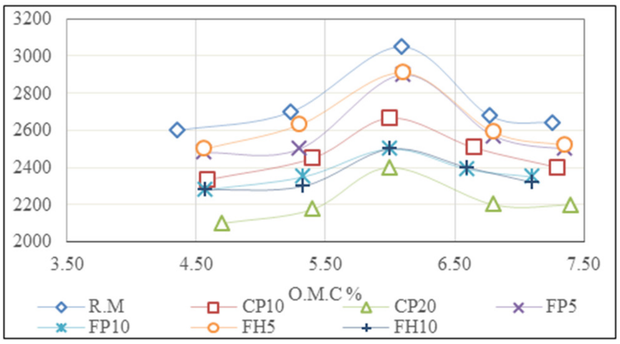


Fig. 4. Moisture density arc for the diverse blends.

The PVC blend showed lesser O.M.C than the reference mixture [21], while PET and HDPE blends exhibited almost similar values [22] with a drop in the maximum dry density with percentage replacement of aggregate weight increasing from 5% to 20%.

B. Compressive Strength

The compressive strength test results of RCC specimens after 7, 28, and 90 days of curing are depicted in Figure 5. It can be seen that RCC blends achieved the best results when treated with the coating material after 28 days, while the spray curing demonstrated a reduction of 6.73-8.56% after 28 days. The reason for this reduction is the loss of water from some of the voids as a result of evaporation. On the contrary, the coating method retains moisture and reduces evaporation losses [23]. It can also be noted that RCC blends with diverse plastic percentage had compressive strength that declined from the R.M by 5.25-12.79% after 28 days of water curing, 5.69-13.52% of spray curing, and 5.99-13% of coating curing. With increasing replacement ratio the values of the RCC mixtures were reduced compared to those of the R.M, due to the existence of the Interfacial Transition Zone (ITZ) [24] and the decline in bond strength between cement paste and plastic waste aggregate [25]. In RCC, the strength of aggregate contributes to the total strength of the material and around 75% of the total volume is composed of aggregate, which is stronger than plastic [26]. Consequently, the quantity and strength of the aggregates play a crucial role in determining the strength of concrete. Additionally, plastic is more angular, irregular, and permeable than aggregates and its porosity raises the specific surface area [27]. Additionally, the reduced compressive strength may be attributed to the lower density of plastic (175, 402, and348 kg/m^3 for PVC, PET, and HDPE, respectively) compared to that of the coarse (1565 kg/m^3) and fine (1785 kg/m^3) aggregates [28]. After 90 days, the reduction was less than that after 28 days for RCC mixes made with plastic, due to the lesser influence of the plastic and cement hydration growth [29].

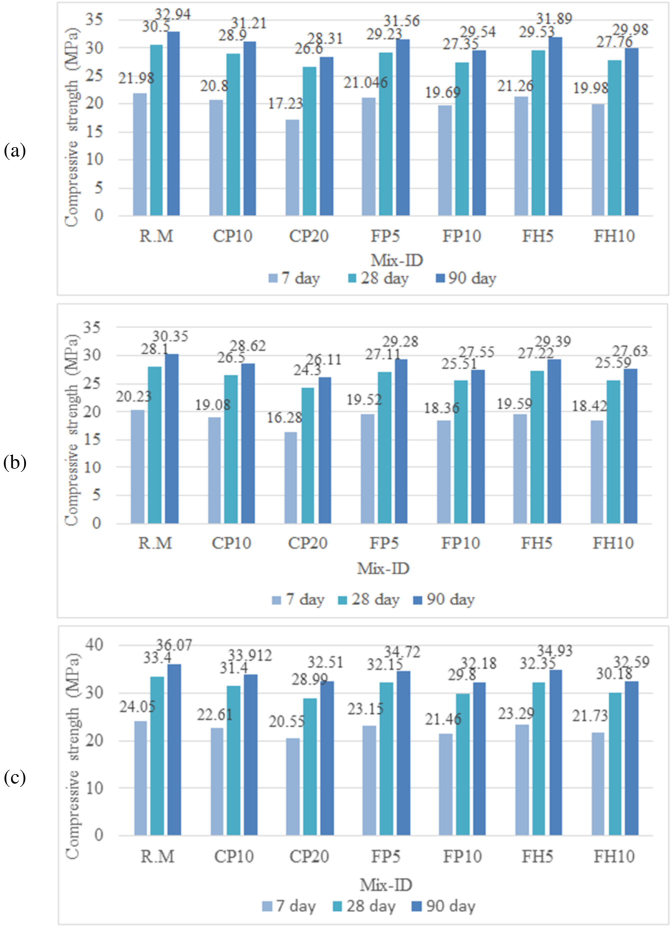


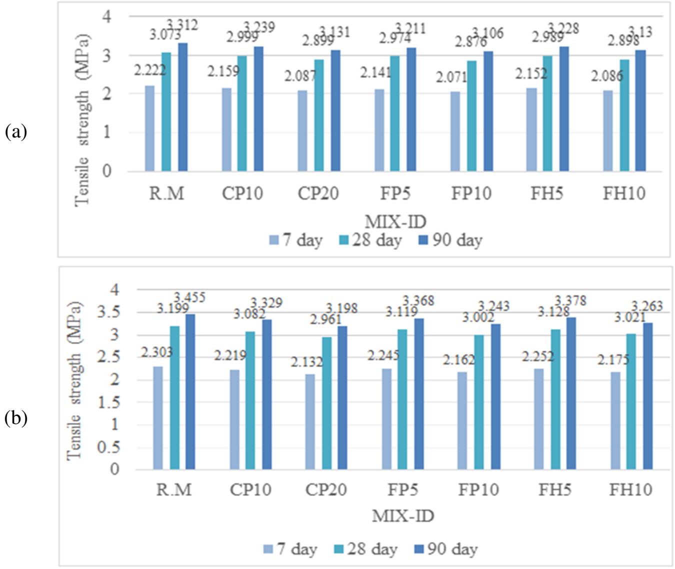
Fig. 5. Compressive strength of the RCC blends after 7, 28, and 90 days for (a) water curing, (b) water spraying, (c) coating material.

Figure 6 depicts the percentage variation in RCC blends including various plastic as compared to R.M.

C. Splitting Tensile Strength and Flexural Strength

The splitting tensile strength test results of RCC specimens after 7, 28, and 90 days of curing are illustrated in Figure 7. The result shows improvement in splitting tensile strength for mixes treated with coating material equal to 2.15-4.66% at 28 days, while water spraying curing manifested a reduction of 3.42-6.47%. The flexural strength test results of RCC specimens are illustrated in Figure 8. It can be observed that all RCC mixtures achieved improvement in flexural strength equal to 4.23-4.78% after 28 days when treated with the coating material, while the water spraying treated samples exhibited a reduction of 3.46-4.42%. The reason for this improvement when treated with the coating material is its ability to preserve moisture and reduce evaporation loss [30]. Also, it can be noted that RCC blends with various recycled plastic waste had splitting tensile strength, at the age of 28 days, which was decreased as related to the R.M by 2.41-6.39% for normal curing, 1.42-6.87% for spray curing, and 2.515-7.43% for coating curing.

Fig. 6. Variation percentage in compressive strength of the RCC blends after 28 days for (a) water curing, (b) water spraying, (c) coating material.



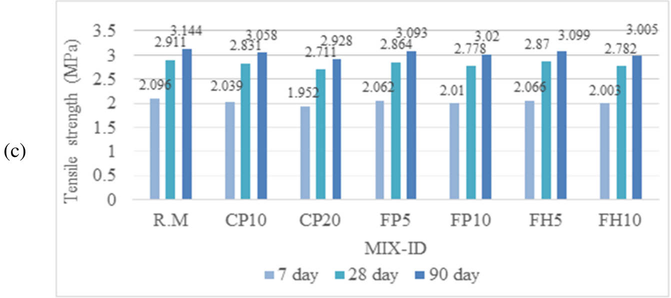


Fig. 7. Splitting -tensile strength of the RCC blends after 7, 28, and 90 days for (a) water curing, (b) water spraying, (c) coating material.

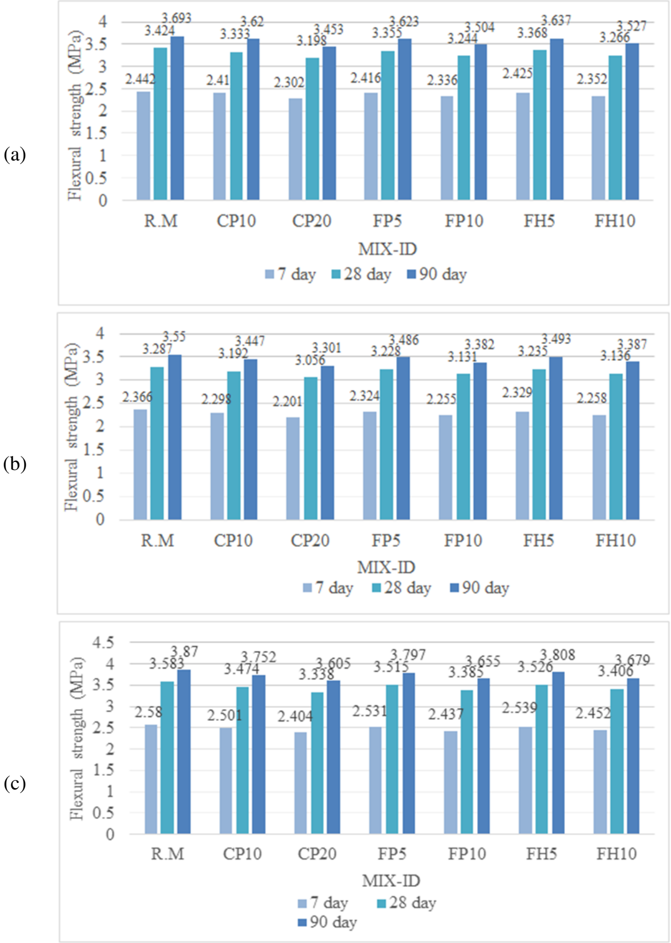


Fig. 8. Flexural strength of the RCC blends after 7, 28, and 90 days for (a) water curing, (b) water spraying, (c) coating material.

Flexural strengths were decreased as related to the R.M by 1.63-6.6% for normal curing, 1.57-7.03% for spray curing, and 1.58-6.84% for coating curing. This decrease could be attributed to the greater water absorption degree attached to the plastic surface [31]. Aggregates are stronger than plastic, which leads to better compatibility between aggregate and cement paste, This in turn enhances the ITZ between the aggregate and cement paste [32, 33]. Figures 9 and 10 depict the variation percentage in RCC blends as compared to R.M regarding splitting tensile and flexural strength, respectively.

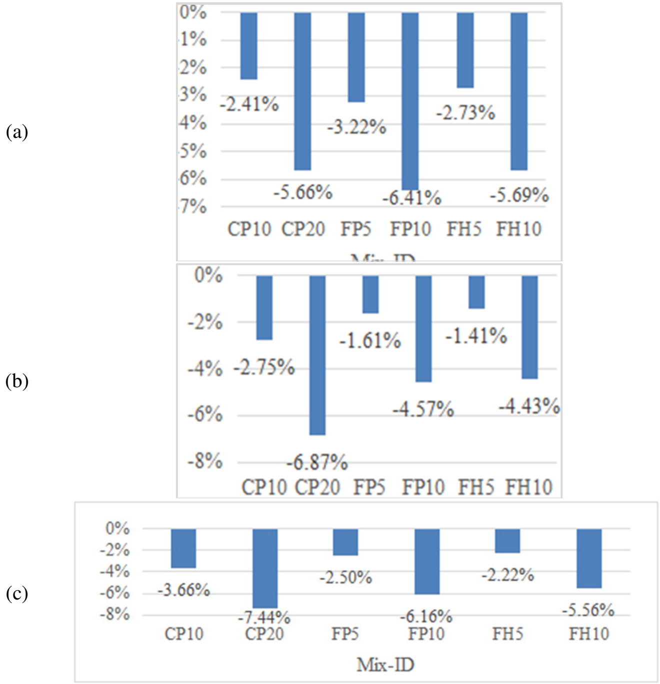


Fig. 9. Variation percentage in splitting tensile strength of the RCC blends after 28 days for (a) water curing, (b) water spraying, (c) coating material.

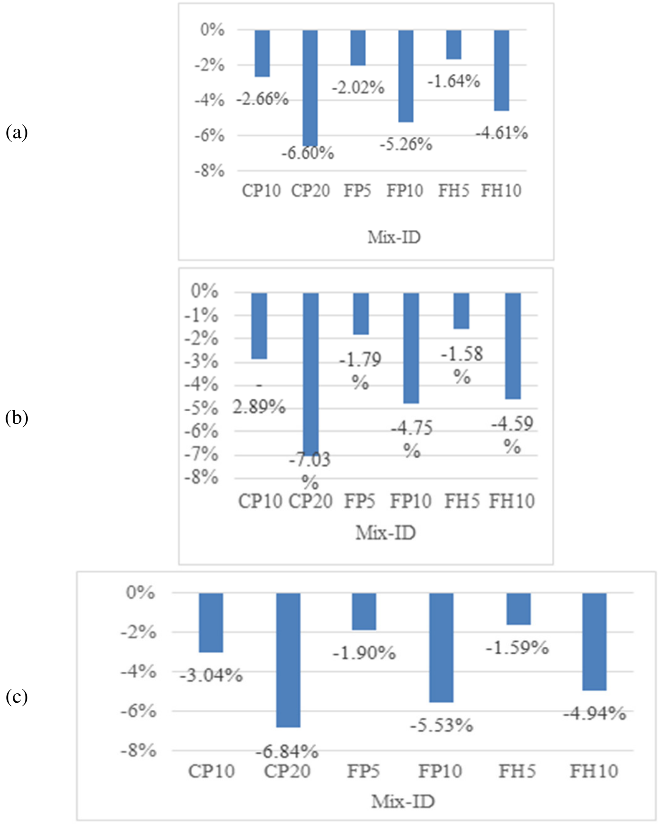


Fig. 10. Variation percentage in flexural strength of the RCC blends after 28 days for (a) water curing, (b) water spraying, (c) coating material.

VII. CONCLUSIONS

- The recommended mixture, which operates as a reference mix with a specified compressive strength of 30.5 MPa for water curing, oversteps the minimum needed level in ACI 327, which is 28 MPa. These results confirm that it is possible to safely create RCC without the risk of compressive strength drop, by using a mix proportion of 1:7.39 for cement to combined aggregate by weight, with a water to cement ratio of 0.465.
- The effects of the curing process showed that RCC mixes treated with coating material achieved the best result with an improvement percentage of 9.51% for the coating method and a reduction of up to 7.87% for water spray with regard to the reference mixture.
- It is safe to use 10% plastic coarse aggregate replacement with (28.9 MPa compressive strength), since its strength is within the ACI recommendations at 28- days.
- The reduction in compressive strength when using 20% plastic coarse aggregate replacement at 28- days is 12.79%.
- The capability to produce sustainable RCC utilizing 5% plastic fine aggregate with 29.23 MPa compressive strength for both PET and HDPE lies within the ACI recommendations at 28- days.
- After 28 days, there is a reduction of 10.33 and 8.98% in compressive strength when utilizing 10% plastic fine aggregate replacement for PET and HDPE, respectively.
- There is compatibility between the lab results for flexural and tensile strength with the compressive strength. The reference flexural and tensile strength are equal to 3.424 MPa and 3.073 MPa, respectively, after 28- days.

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