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Evaluation of Concrete Incorporated with Waste Plastic and Tyre Rubber as Partial Replacements for Fine Aggregate

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Abstract The improper disposal of waste plastic and tyre rubber significantly contributes to environmental pollution; however, these materials can be repurposed for use in construction. This study investigates the impact of partially replacing fine aggregates with recycled plastic and tyre rubber waste on the strength properties of concrete. Concrete samples were prepared with 0, 5, 10, and 15% replacement of fine aggregates using plastic waste, tyre rubber waste, and a combination of both, while maintaining a constant water-cement ratio of 0.5. The samples, cast using 100 mm x 100 mm x 100 mm size cubic moulds were tested for compressive strength at 7, 14, and 28 days. Results revealed that increasing the percentage of waste replacement improved workability and compacting factor but reduced compressive strength. At 28 days, compressive strength ranged from 10.83 N/mm² to 8.28 N/mm² for plastic waste, 12.83 N/mm² to 5.67 N/mm² for rubber waste, and 12.02 N/mm² to 9.10 N/mm² for the combined waste, compared to 15.80 N/mm² for the control mix. The findings indicate that 5 to 15% of all waste-based mixtures exhibited lower strength than the control, rubber waste contributed to higher strength than plastic, while the combined waste mixtures displayed intermediate strength.

At 5% of plastic and rubber (12.02 N/mm^2) is higher than 10% and 15% (11.74 N/mm^2 and 9.10 N/mm^2) respectively. It also clearly showed that as the percentage of the plastic and rubber fibres increased from 10% upward the compressive strength of the concrete decreased. This study highlights the potential of using recycled waste materials in concrete, particularly for low-bearing structural applications, promoting sustainable construction practices and environmental conservation.

Keywords: Compacting factor, Compressive strength, Plastic waste, Slump, Waste tyre and rubber.

I. Introduction

One of the major challenges facing Nigeria and many other developing nations today is waste management [1]. The inadequate disposal of waste materials such as plastic, rubber, agricultural residues and wood wastes such as sawdust and many more have been recognized as lack of adequate waste management and therefore, contributing significantly to environmental pollution [2].

In developing countries, including Nigeria, however, much of the waste generated is discarded improperly, often through landfills, spread on reclaimed land, or even dumped into water bodies or streams, leading to flooding that can cause substantial loss of life and property [3]. According to [4], recycling waste materials presents a viable alternative for raw materials in construction. Waste Plastic and tyre rubber have been used to reinforce composite concrete to obtain lighter weight and reduce shrinkage effects, which serve to reduce environmental waste [5].

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Research has demonstrated that waste products such as glass, plastic, and rubber tyres can be repurposed to create both coarse and fine aggregates, which are valuable in the production of concrete and mortar. Rubberized concrete is recognized as an eco-friendly, lightweight alternative, thus utilizing rubber particles from used tyres in place of traditional aggregates [6] has demonstrated effective and reliable useable. [7] found that concrete with a 5% substitution of shredded tyre-derived aggregates demonstrated workability and compressive strength comparable to that of conventional concrete.

[8] evaluated concrete performance with different plastic waste for kerb application and observed that utilization of plastic aggregate in concrete reduced overall workability and fresh density of concrete; using plastic waste as partial replacement for natural coarse aggregate up to 20% satisfies the kerb design requirement and the strength loss were not detrimental. [9] Discovered that rubberized concrete exhibited the highest impact resistance when 20 to 40% of the coarse aggregate was replaced with rubber. Their findings indicated that rubberized concrete performed better than normal concrete under impact loads, while normal concrete proved to be more sensitive to strain rates [10].

In a study by [11], the impact of sand replacement with sawdust at 10, 15, and 30% of fine aggregate weight was assessed. The results showed that strength increased with a 10% substitution, while a decrease in strength occurred as the sawdust replacement percentage rose. [12] Studied the impact of adding rubber powder to concrete beams, to provide a guide for understanding the role of rubber powder in concrete. Their findings revealed that the addition of rubber powder had a negligible effect on the increase of the tri-axial compressive strength. [13] Highlighted that various waste products have been used throughout the years to develop composite materials, where the combination of multiple materials leads to improved properties compared to using the materials individually. [14] Observed that the incorporation of plastic, rubber, and steel wastes into concrete is used in diverse applications like industrial flooring, concrete paving, precast concrete, shotcrete, and hydraulic structures. This practice can positively impact the mechanical properties of the concrete.

Another study was conducted by varying proportions of heat-processed waste PET and river sand as fine aggregates and granite as coarse aggregate for concrete production and revealed that 10 – 40% of PET-modified mixes achieved adequate strength [15]. The impact of adding waste polyethylene (PE) and silica fume (SF) on the engineering properties of cement mortar investigated by [16] revealed that waste PE enhances the malleability of concrete and results in a significant decrease in compressive strength but improved with an increase with 20% SF. [16] was limited to waste polyethylene (PE) and silica fume (SF). This study thus focuses on determining the physical and strength properties of concrete incorporated with varying percentages of plastic and tyre waste as partial replacement for fine aggregate (sand).

II. Materials and Method

A. Materials

The materials utilized for this study were locally sourced. These included used or waste plastic bottles, waste tyre, wooden moulds, 20 mm iron-rod, water, sand and cement. The discarded or waste plastic bottles were collected at the various locations within Ibadan metropolis. The bottles were washed and dries, and cut into sizes ranging from of 15-20 mm sizes and thereafter, grind with mechanical grinder at the Shredder shop, Bodija market. The waste tyres were obtained from a company located at Apata Ibadan, Oyo State, Nigeria. Figure 1(a) and (b) show the two processed waste materials: plastic and ground tyre wastes. The other materials used were cement, fine and coarse aggregate and water. The cement used was the Ordinary Portland Cement made conformable to the requirement of [17]. The impurities in the sand used were removed and the sand was made conformable to the requirements of [18]. The potable water was used in all the mixes was in accordance with the requirement of water concreting and curing as specified by [19].

(a) Ground waste plastics **(b) Ground waste tire rubber**

Figure 1: Waste Materials used in this Study

B. Methods

i. Preparation and casting

Adopted in the study was the standard mix of 1:2:4 (concrete ratio mix) for concrete as specified in NIS-75 (1974). Each ground waste plastic and tyre were used separately and then combined to assess their effect at different percentages of 0, 5, 10 and 15% replacement with 0.5 water-cement ratio in different concrete cubes. The production was made by weighed sand, cement, coarse aggregate and waste materials were manually mixed thoroughly until a homogeneous mixture was achieved and poured into wooden moulds of 100 x 100 x 100 mm by set as shown in Figure 2 and cured in the water tank for periods of 7, 14, and 28 days. The mix design for the concrete cubes production is as shown in Table 1.

Figure 2: Concrete Moulding

Table 1: Quantity of Materials Required for each Set of Concrete Cubes

	Control	Ground Waste Plastic			Ground Waste Rubber			Ground Waste Plastic and Rubber		
Materials	**0%**	**5%**	**10%**	**15%**	**5%**	**10%**	**15%**	**5%**	**10%**	**15%**
Cement (kg)	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Water (kg)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Coarse Aggregate (kg)	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01
Fine Aggregate (kg)	0.64	0.608	0.576	0.544	0.608	0.576	3.39	0.608	0.576	3.39
Waste (kg)	0.00	0.032	0.064	0.096	0.032	0.064	0.096	0.032	0.064	0.096

ii. Sieve analysis of fine and coarse aggregates test

These tests were conducted in accordance with [20] by which sieves used for the fine and coarse aggregates were ranged from 5.0 mm to 0.63mm and 32.00 mm to 6.36 mm respectively with bottom pans. The sieve mesh was cleaned with iron brush to remove particles before and after test. The electronic balance was used to weigh each of the weight of sieve W_2 The sieves were arranged and 1000 g of total weight of the specimen W_1 poured in through the sieves and shake properly for the finer material to pass through the sieves. The weight of the sieve and its content were weighed W_3 and from the weight specimen's percentage retained (PR)was weight of specimen retained calculated W_4 using Equation 1 and particle distribution coefficients of fine and coarse aggregates (Coefficient of uniformity, Cu and Coefficient of gradation, Cc) were computed using Equations 2 and 3.

$$\text{PR} = \frac{W3-W2}{W1} \times 100 \qquad (1)$$

Where:

W_1 is total weight of the specimen,
W_2 is the weight of sieve,
W_3 is the weight of sieve + specimen retained and

$$\text{Coefficient of uniformity (Cu)} = \frac{\text{D } 60}{\text{D } 10} \qquad (2)$$

$$\text{Coefficient of gradation (Cc)} = \frac{(\text{D}30)^2}{\text{D}60 \text{ X D } 10} \qquad (3)$$

iii. Workability test

Testing for the workability of the various mixtures of the sand replacement with plastic and tyre rubber waste in the concrete was conducted by filling the fresh concrete into the slump cone placed vertically on non-porous fat metal surface and held down in position. The cone was filled in three layers and each layer was compacted 25 times with a tempering rod of 16 mm in diameter and 800 mm long. Thereafter, slump cone was removed vertically and the height of the concrete slump was determined by measured different between the cone height and the concrete slump as shown in Figure 3a and also compacting factors were carried on fresh concrete using a compacting test equipment Figure 3b, in accordance with [26], compacting factor (CF) was computed using Equation 4.

$$CF = \frac{W2 - W1}{W3 - W1} \qquad (4)$$

Where:

W_1 is weight of empty cylinder,
W_2 is weight of empty cylinder plus partially compacted concrete and
W_3 is weight of empty cylinder + fully compacted concrete.

(a) Slump Test (b) Compacting Factor Test

Figure 3: Workability Tests

iv. Compressive strength test

The compressive strength of the specimens of different mixing at 0, 5, 10, and 15 % of sand replacement was determined following standard procedures given by [21]. Three cube specimens each were crushed at 7, 14 and 28 days for each of the percentage replacement respectively, using a computerized 1560 kN WAW-1560B compression testing machine having an accuracy of ± 1% as shown in Figure 4. The compressive strength (C.P) was calculated using Equation 5.

$$CP = \frac{F}{A} \qquad (5)$$

Where:

F = applied load and
A = the cross-sectional area of the specimen.

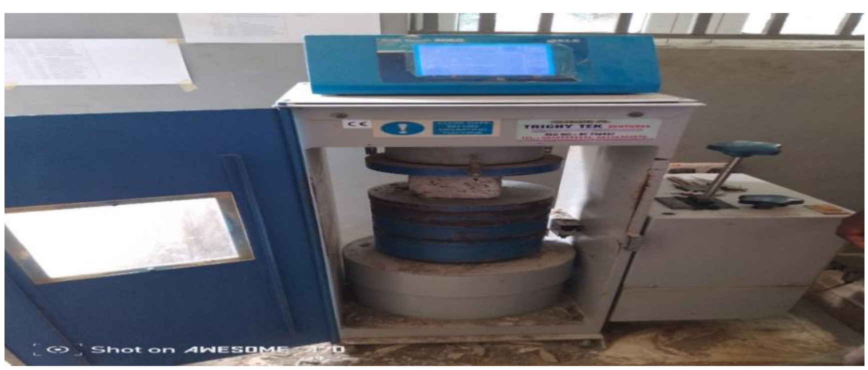

Figure 4: Compressive Strength Machine

III. Results and Discussion

A. Sieve Analysis

The result of the sieve analysis test conducted by [20] on fine aggregate (sand) and coarse aggregate are presented in Figure 5a and b, respectively. The Figures indicate the percentage cumulative passing versus sieve size for sand and coarse aggregate, respectively. The grading curve of fine aggregate in Figure 5a shows the coefficient of uniformity (C_u) and coefficient of gradation (C_c) values of sand as 4.08 and 1, respectively. The Cu and Cc were 5.3 and 3.0 for granite respectively as indicated in the grading curve in Figure 5b. These values are slightly lower that the C_u value of 4.47 and C_c value 1.04 as obtained for river sand but higher than 1.55 and 1.05 for granite by [22]. [23], obtained the C_u value of 2.9 and C_c value 1.0 for sand; 1.34 and 1.17, respectively for granite, and 2.52 and 1.0 for plastic waste, respectively. The results in the previous studies indicate higher C_u value compared to those obtained in this study but lower in case of C_u value for sand, granite and plastic.

Results obtained from this study indicated that the fine aggregate (sand) is poorly graded and coarse aggregate is well graded since the C_u value for fine aggregate is less than 6 and C_c value is between 1 to 3 while the C_u value for coarse aggregate is greater than 4 and C_c value is between 1 to 3 as specified by unified soil classification system (USCS) as postulated in [24].

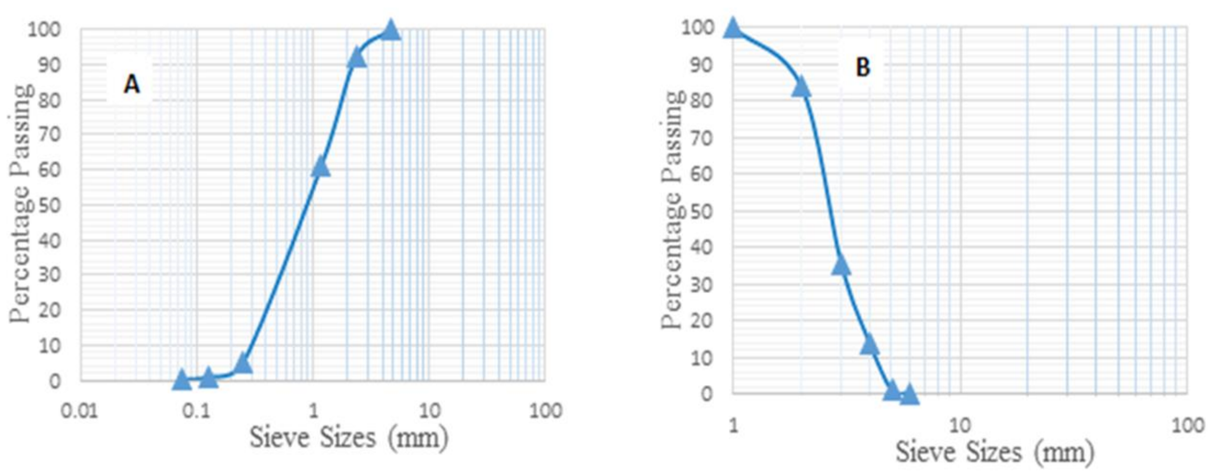

Figure 5: Particle Size Distribution Curve of (a) Fine Aggregate (b) Coarse Aggregate

B. Workability of Fresh Concrete

The influence of waste percentages on the workability of the concrete is shown in Figures 6 and 7 for slump and compacting factor tests, respectively. For slump test results, it is observed that as the waste (ground plastic, tyres and combined plastic and tires) content (percentages) in the concrete mix grew, the workability of the concrete mixes increased. That is, workability increased as the substitution of sand with waste increased from 0 to 15% for all waste added throughout the study.

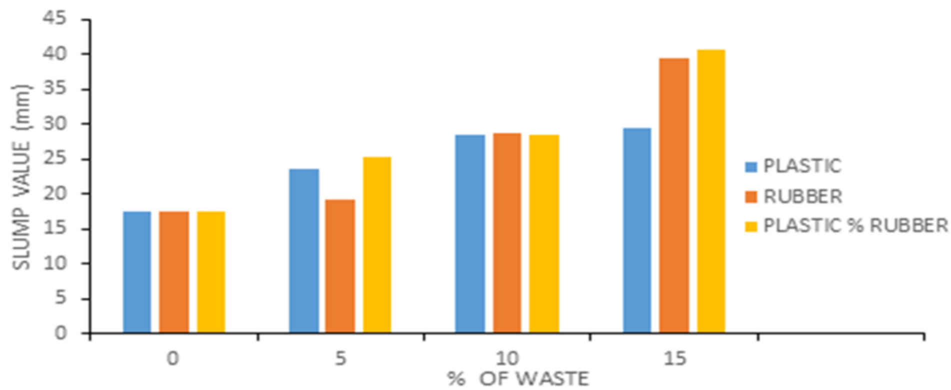

Figure 6: Influence of Waste Plastic and Tyre Rubber on Fresh Concrete Slump

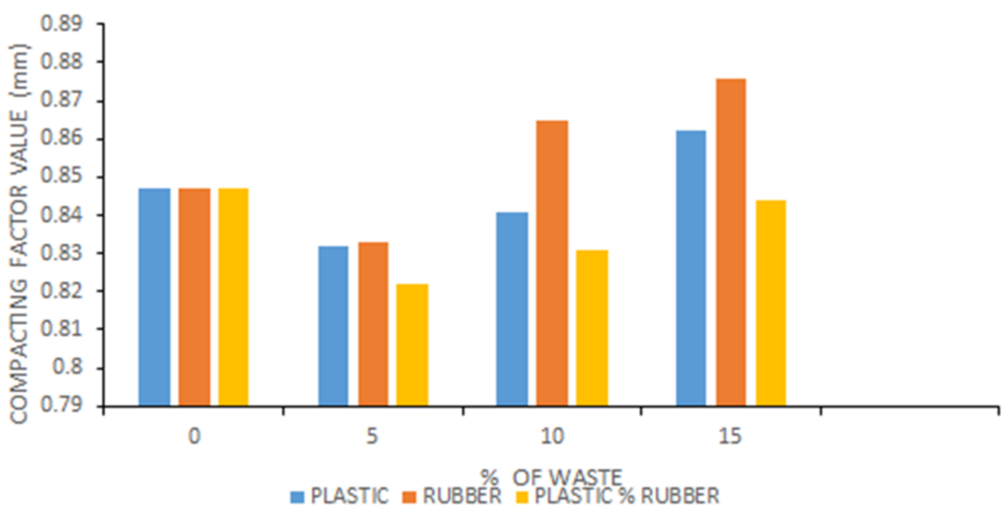

Figure 7: Influence of Waste Plastic and Tyre Rubber on Fresh Concrete Compaction Factor

It was observed that the values of slump ranged from 23.5 to 29.50 mm, 19.25 to 39.50 mm and 25.25 to 40.75 mm for plastic, rubber tyre and combined plastic and rubber, respectively as shown in Figure 3. [24] obtained slump values between 1.7cm – 3.2 cm for 0 – 10% PE and 0 - 20% SF inclusion in cement mortar.

The results of compacting factor presented in Figure 4 shows a dissimilar trend with those of the slump tests. That is the compacting factors ranged from 0.862 to 0.832, 0.876 to 0.833 and 0.822, respectively at 0 to 15% of sand replacement. These results contradicted those of [25] which found that the compacting factor and slump values increased with an increase in cement replacement with wood ash, however, it should be noted that the ash material used were not plastic waste. The results obtained in this study are within the specified limit of 0.70 and 0.98 specified by [26].

A. Compressive Strength

The compressive strengths of concrete with waste plastic replacement at different percentages under 7, 14 and 28 curing days are presented in Figure 8. The strength increases as curing days increase. However, it shown in Figure 8a. The compressive strength of concrete produced at the 5% sand replacement (7.54 N/mm^2) at 7 days is higher than plastic and at 14 days (10.15 N/mm^2). On day 28, the compressive strength of concrete produced at the 5% sand replacement showed a higher strength of 10.83 N/mm^2, while 15% had a lower strength of 8.23 N/mm^2. It was observed that increases in plastic waste addition, the lower the concrete strength. This occurred as a result of increase in content replacement of plastic waste with lower specific gravity as also noted by [27]. It was also observed that the compressive strength of concrete produced from plastic waste was below the value obtained for the control concrete specimen tested. Since it did not meet the target strength, therefore, it can be used where lightweight concrete is required.

Figure 8b shows the variation in compressive strength of the concrete with varying tyre rubber waste replacement content (0, 5, 10 and 15%) at the 7, 14 and 28 days. The strength of the concrete increases as the curing day increases as shown in Figure 8b. The compressive strength of concrete produced at the 5% sand replacement (8.03 N/mm^2) at 7 days is higher than plastic and at 14 days (8.76 N/mm^2). On day 28, the compressive strength of concrete produced at the 5% sand replacement showed a higher strength of 12.85 N/mm^2, while 15% had a lower strength of 12.02 N/mm^2. Concrete samples with 5, 10 and 15% replacement of sand with waste tyre rubber achieved 12.85 N/mm^2, 12,10 N/mm^2 and 5.65 N/mm^2 while 0% replacement achieved 15.80N/mm^2 at 28. It was observed that 5% replacement gave high strength compared to others, hence lower than the control concrete specimen. The compressive strength of concrete with 5% waste tyre rubber as replacement for sand is 18.47% higher in strength compared to concrete with waste plastic. This result is in the same trend with report of [28] that 5% volume fraction of plastic fibres used for concrete reinforcement recorded 35% increase of compressive strength over control specimen, and that of 1.5% and 2.5% volume fractions of fibres had 40% and 84% decreases of compressive strength of the control.

Figure 8c shows the compressive strength of combined waste plastic and tyre rubber at different percentages (0, 5, 10 and 15%) and 7, 14 and 28 days respectively, with both waste replacement of 5, 10 and 15% in concrete samples. The compressive strength slightly decreases as the waste contents increase but the compressive strength increases with curing ages for control, 10% and 15% samples, while 5 % samples indicate slight difference, as shown in Figure 5. It was observed that 5% and 10% sand replacement with both wastes had much closed strength values of 12.02 $N/mm^2$and 11.74N/mm^2 while 9.1 N/mm^2 was obtained at 15% of both waste replacements. The compressive strength values obtained in this study were lower to the values reported by [29] who obtained compressive strength of 19. 99, 18.88, 19.33 and 17.77 N/mm^2 for 0, 5, 10 and 15% respectively, plastic waste replacement for sand. [16] obtained compressive strength between 20.8 – 29.4 MPa, 29.3 – 36.6 MPa, 39.9 – 52.9 MPa at 3, 7 and 28 days with 0 – 20% PE and 0 – 10% SF inclusion in cement mortar. It was finally observed that plastic waste, rubber waste, and a combination of both waste replacements for sand in concrete samples tested were in the same strength range at the 5% content of 28 days. It was generally noted that waste plastic inhibited the bond between cement and aggregates (sand and granite). Therefore, leads to compressive strength reduction in the concrete matrix.

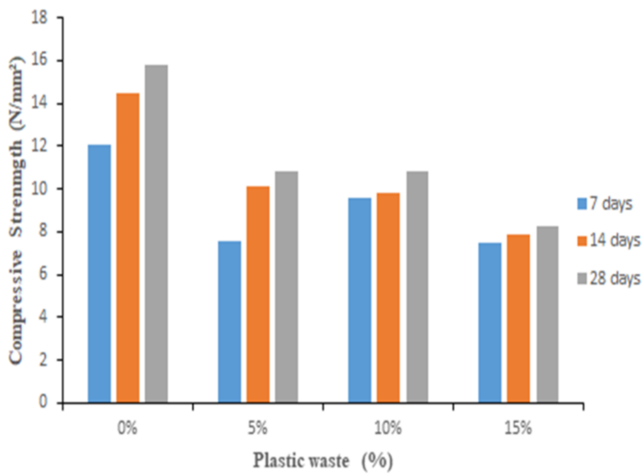

Figure 8a: Compressive Strength of Concrete with Waste Plastic

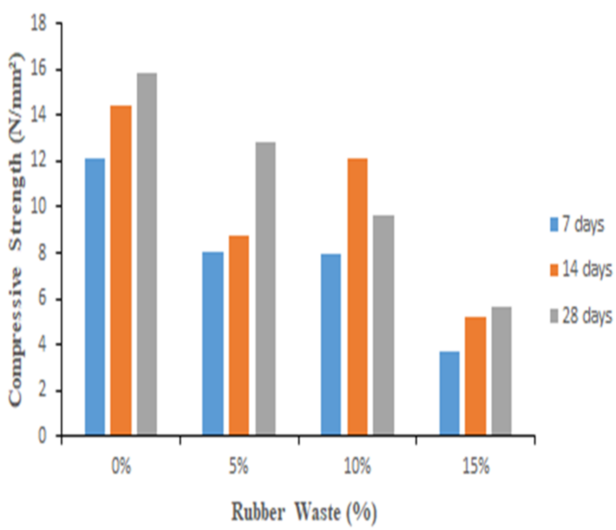

Figure 8b: Compressive Strength of Concrete with Waste Tyre Rubber

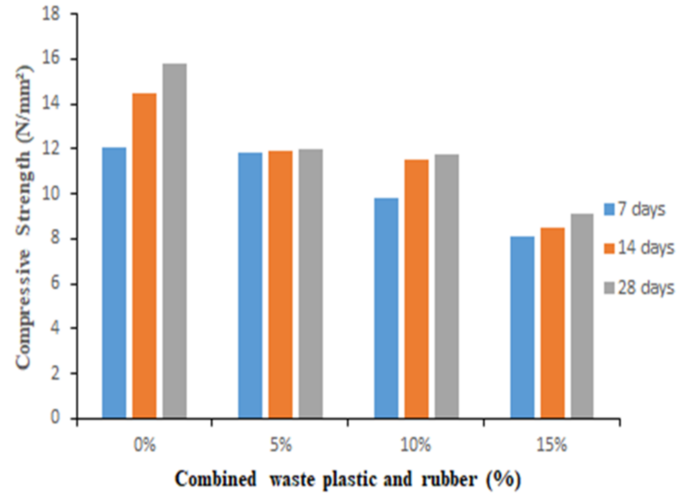

Figure 8c: Compressive Strength of Concrete with Combined Waste Plastic and Tyre Rubber

IV. Conclusion

The incorporation of waste plastic and tyre rubber as partial substitutes for fine aggregate in concrete presents a sustainable solution for applications requiring lightweight concrete while reducing environmental pollution. Based on the experimental tests conducted, the following conclusions can be drawn:

i. The workability of fresh concrete incorporating plastic, tyre rubber, and their combination increases as the proportion of waste materials in the mix rises.
ii. Results from the compacting factor test align closely with those of the slump test, confirming consistency in workability assessment.
iii. The optimum compressive strength at 5% sand replacement is 10.83 N/mm² for plastic, 12.83 N/mm² for rubber, and 12.02 N/mm² for the combination of waste plastic and tyre rubber, compared to 15.80 N/mm² for the control specimen at 28 days.

Despite the reduction in strength, this modified concrete remains suitable for low-bearing structures at a lower cost, contributing to environmental sustainability by addressing waste plastic and tyre disposal challenges. Future studies on the evaluation of the long-term durability of concrete incorporating waste plastic and tyre, including resistance to weathering, chemical attacks, and load-bearing capacity over extended periods, were recommended.

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