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Research Article

Effect of non-biodegradable waste materials on the strength performance of concrete

Ajibola Ibrahim Quadri[a]*, Lekan Makanju Olanitori, Abdulhakeem Sadiq[b]

Department of Civil and Environmental Engineering, Federal University of Technology, Akure. P.M.B 704, Nigeria.

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Abstract

Waste usage in the construction industry has reduced global environmental pollution. Reusing waste materials as substitutes for cement in concrete constituents and other construction materials can lower cement and concrete manufacturing costs, solid waste, and landfill space. Engineers are still unsure as to what extent waste can be repurposed to produce optimal strength for the production of concrete. Reutilization of waste materials has been employed in this paper by adopting 3.5%, 7%, and 10% of six wastes (plastic bags, rubber tires, cement sack strands, can waste, PET bottles, and waste from glass) as substitutes for aggregate in concrete production. At 10% replacement, the cement sack strand absorbed more water than other waste materials and about 5.8% less than the control specimen. Despite the fact that glass waste has a low water absorption rate, there was no discernible increase in strength after 28 days due to brittle damage under loading. At 10% and 7% partial replacement, can waste had about 9% and 12.5% higher compressive and tensile strengths than the control specimen. As a result, it is proposed that using wastes that may enhance concrete properties will lower the need for normal coarse and fine aggregates, enabling natural resource conservation.

1. Introduction

Concrete constitutes nonhomogeneous materials of different aggregate types, cement, and water in varying proportions based on the strength requirements. It is a man-made material conglomerate with rock-like properties, and having varied compression and tensile strength properties. The tensile strength accounts for about 10% of its compressive strength, giving rise to low performance under tensile loading, and it is the most widely used for construction because of the availability of material constituents at a cheap rate [1,2]. During the production process, concrete can flow and take on different shapes based on various mix ratios and preparation techniques [3]. Many materials, including agricultural materials, synthetic materials, and industrial waste, are now being used to make concrete of varying strengths. To remove the effect of CO2 in the environment, the most common material target from concrete constituent is cement. According to reports, a tonne of cement production always results in a tonne of CO2 discharge into the surroundings [4]. consequently, the share of the cement industry to total global CO2 discharge from fossil fuel combustion stood at about 7% [5]. Recently, these materials, particularly industrial wastes, have made significant inroads into concrete production by replacing a percentage of natural aggregate (fine or coarse aggregate) in concrete with them to produce lightweight concrete and a method of reducing environmental pollution.

*Corresponding author: aiquadri@futa.edu.ng
[a] orcid.org/0000-0001-5328-9379; [b] orcid.org/0009-0001-8985-7611
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Industries' waste is gradually increasing these days and causing huge environmental issues. It has been determined that recycling and reusing waste is the best option for reducing the volume of solid waste that could end up in disposal sites, with all the negative effects on the environment and financial loss that could result. Moreover, the world's rapid industrialization and urbanization drive infrastructure development. This process causes several issues, including a shortage of construction materials and increased productivity of waste and other products [6]. The continual advancement of concrete technology has increased the choices for incorporating cutting-edge and sustainable solutions into concrete designs and applications using industrial waste. Non-biodegradable waste, such as glass, plastics, rubber, etc., with substantial environmental impact, has been worked on using cutting-edge technology to reduce the impact of CO2 generated during cement production and to produce lightweight concrete as an aggregate substitute. However, recycling some of these industrial wastes is often expensive and not sustainable for the green environment. According to [7], the majority of used non-biodegradable materials are not recycled but rather dumped, which contributes to several significant environmental issues. The pollution of rivers, lands, and oceans by waste plastic makes it a potential threat to aquatic life. However, because of their light weight, flexibility, moisture resistance, and cost-effectiveness, non-biodegradable materials will eventually replace many currently used composite materials, such as material used in producing concrete [8].

Over the last decade, varieties of industrial non-biodegradable wastes such as plastic waste, polystyrene, rubber tires, and waste glass have been used as alternatives for natural aggregate in concrete [9–11]. Research by Taha and Nounu [12] has proven that solid waste can substitute about 20% of fine aggregate in concrete with appropriate mechanical properties. The shapes and sizes of the substitute waste aggregate can affect the consistency of concrete [13]. There is always a reduction in strengths of concrete when the percentage replacement of waste aggregate is increased [14]. Vanitha et al., [6], investigated the use of plastic waste as a substitute for coarse aggregate in M20 concrete grade using 0-10% replacement with a 2% increment. The optimal concrete compressive strength was determined at 4% of the partial replacement. Manjunath [15], adopted electronic-plastic waste to partially replace coarse aggregate in M20 concrete grade, the flexural and compressive strengths improved substantially at 10% partial replacement. Plastic has some advantages in the partial replacement of concrete, such as non-degradability and durability, resistance to chemicals and moisture, and increased bonding capacity at high temperatures [16]. However, plastic materials have a low melting point and poor bonding properties at low temperatures, reducing the concrete strength. Islam et al., [17] adopted waste pet as an alternative in fresh and hardened concrete, an increase in the waste pet produced a lower compressive strength of concrete. PET aggregate concrete could have high workability at a low water-cement ratio. Choi et al., [18] reported that the structural efficiency of waste PET lightweight aggregate concrete and compressive strength decreased when the percentage replacement was increased; however, workability increased above 120% at 75% replacement compared with the natural aggregate. This implies that the consistency of PET concrete may not increase strength.

Thiruppathi, [19] investigated some factors influencing the performance of rubber tire concrete, such as aggregate shape, size, and curing time. Despite the low-strength development, rubber aggregate concrete demonstrated the potential to become a long-term solution for rubber waste management. When rubber tire waste was substituted for coarse aggregate in concrete with varying percentage by Ganjian et al., [20], there was no significant improvement in concrete strength at up to 5% replacement, however, with higher replacement ratios, appreciable changes were observed. On the use of waste glass as aggregate in concrete, Srivastava et al., [21] concluded that waste glass could be adopted as a coarse aggregate substitute for up to 50% replacement without substantial change in compressive strength. However, Keryou, [22] concluded that the optimum strengths of glass concrete was achieved at 25% replacement of coarse aggregate. It is essential to note that the density, shape, size, and tensile properties of glass can significantly impact the performance of glass concrete [23].

A reassessment of the literature confirms that concrete strength can be improved using industrial waste as a partial substitute for natural aggregate in concrete. However, the question of to what extent the partial substitution of these natural aggregates can affect concrete strength and durability has not been answered. This study, therefore, investigates the consequences of the partial substitution of natural aggregate in concrete with non-biodegradable waste materials. Waste PET, plastic bags, rubber tires, glass waste, cement sack strands, and can waste are considered for the substitution of natural aggregate to ascertain concrete sustainability performance and serve as a panacea for industrial waste. In reality, cement sack strand and plastic bags cannot fully substitute the main function of coarse aggregate in concrete matrix, as coarse aggregate occupies over 50% of the volume of the concrete matrix and provides the majority of the strength in this study; however, these materials should be used as reinforced fiber in concrete [24]. Fig. 1 shows some selected waste materials in literature against their compressive strengths [25–36]. It can be seen that waste materials in concrete can produce high strength waste concrete depending on the mix proportion. In research by Evram et al. [25], the aggregate used was replaced by PET at 5% to 20%, the optimum concrete strength was at 15% partial replacement. Thorneycroft et al. [28] reported that replacing sand by 10% volume of recycled plastic can save above 800 million tons of sand every year by adopting suitable mix design for concrete.

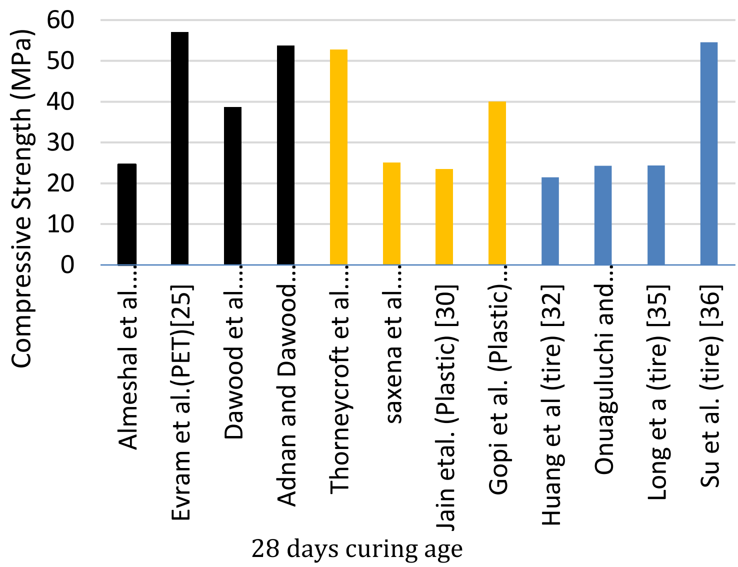

Fig. 1 Wastes materials versus compressive strength in 28 days

2. Methodology

The study used grade 43 Ordinary Portland Cement (OPC), the initial setting time was determined to be 30 minutes and a specific gravity (SG) of 3.2. The physical characteristics meet the requirements of [37]. The maximum size of coarse aggregate was measured as 20 mm with SG 2.81 and fine aggregate of 4.75 mm fine standard sieve were adopted having

SG of 2.65. Six waste materials were employed in the current research to replace coarse aggregate in concrete; waste PET bottles, plastic bags, rubber tires, glass waste, cement sack strands, and tin waste as shown in Fig. 2. The glass waste is the mixture of broken glass bottles and mirrors collected from different household. Since the waste materials are lightweight, it may be inefficient to substitute the natural aggregate with the corresponding weight of waste. Three partial replacements of 3.5%, 7%, and 10% by volume of coarse aggregate were therefore used. The waste materials were cut into the sizes of the coarse substitute aggregate up to the biggest size of 20 mm. The maximum length of plastic and cement sack strand used is 50 mm to be used as fiber in concrete. The concrete mix was designed following (BS 206-1) [38] recommended for M20 grade concrete. M20 concrete is commonly used in most construction projects. The concrete mix proportions adopted is 1:2:4, with a water-to-cement ratio (w/c) of 50%.

Fig. 2 Waste materials used for partial replacement of natural aggregate

2.1 Test on Aggregates

2.1.1 Sieve Analysis Test

To determine the soil gradation, particle size distribution evaluation with sieve gradation from 9.5 mm to 75 µm arranged from top to bottom was performed on the sand according to the British Standards [39]. The sand sample was collected and dried in an oven for 24 hours to remove excess moisture. 400 g of oven-dried sample was measured for the sieve analysis, and the particle gradation was calculated using equations 1 and 2.

$$W_d = \left(\frac{100}{100 + m_n}\right) W_6 \tag{1}$$

$$P_p = \left(\frac{W_d - W_s}{W_d}\right) \times 100\ \% \tag{2}$$

W_d Is the weight of the dried sample (in g), m_n is the moisture content (in %), and W_6 is the weight of the remaining sample to an accuracy of 0.01 g. The percentage of a particle passing the 75 µm test sieve is denoted as P_p, the weight of the sample reserved in the sieve measured to an accuracy of 0.01 g is denoted as W_s.

2.1.2 Aggregate Soundness Test

The coarse aggregate was subjected to a soundness test. Aggregate passing the BS sieve size of 12.5 mm and reserved on a 10 mm was subjected to 110 °C for about 5 hours following (BS 812-121) [40]. The soundness apparatus was filled in three layers, with each layer given a 25-blow tamping rod, and then the compacted weight of the aggregate's weight was measured and recorded as M_w. The aggregate surface was leveled before inserting the plunger. The apparatus containing the specimen was loaded uniformly on the compression testing machine until the sample failed. The sample was then run through a 2.36 mm sieve, and the portion that made it through was weighed and recorded as M_S. The aggregate impact value is expressed as given in Equation 3.

$$(AIV) = \frac{M_s}{M_w} \times 100 \quad (3)$$

2.2 Slump Test for Fresh Concrete

The fresh concrete slump test was performed on the different percentage replacements for each waste material and the control sample to establish the consistency of the fresh concrete following (BS 12350-2) [41]. The inner surface of the slump cone was lubricated and laid on a flat platform. The cone was then filled up with fresh concrete in three layers and tamped with 25 strokes of the tamping rod; the brim was level after the tamping process had been completed, the cone was gradually removed, and the slump height was measured.

2.3 Casting of Concrete

The design of normal concrete mixes according to (BS 206-1) [38] was used for concrete casting. The trial mixes of various cement, sand, granite, and water ratios were used to accomplish the required concrete strength for this study. Using the pre-determined concrete mix ratios, 228 concrete cubes of 150 mm and 246 cylindrical concrete samples of dimensions 200 mm × 100 mm in length and diameter were cast. For each percentage replacement strength test for the number of days (7, 14, 21, and 28), twelve specimens were considered. The mix ratio of 1:2:4 was used to determine substitute waste material in three different percentage proportions by volume of coarse aggregate.

2.4 Test on Concrete Water Absorption

This test was conducted following the BS 1881-122 [42]. The test aims to offer a means of comparing the tendency of water absorption of various waste substitutes used. After casting, the 200 mm × 100 mm cylindrical concrete was inserted in water for 28 days to ensure proper curing is achieved. The specimens were placed in an oven at 100 °C for about a day to remove excess moisture before being reweighed. The weight of the specimens was recorded as the dry weight (W_1), and they were immersed in water at 25 ^{o}C for 24 hours. This weight was recorded as the wet weight (W_2). The rate of absorption is expressed as.

$$W = \frac{w_2 - w_1}{w_1} \times 100 \quad (4)$$

2.4 Compressive and Splitting Strength Test

The compressive and tensile strength tests on concrete are important because they provide information about the material's strength. The tests were conducted following BS 12390-3 [43]. Compressive and splitting strength tests were performed on selected concrete specimens on the 7th, 14th, 21st, and 28th days, respectively. The specimen was carefully placed and adjusted with the center of the lower pressure plate of the compression machine as shown in Fig. 3; a flat plate was placed on the specimen to distribute the load during operation. The upper pressure plate of the machine was lowered to meet the top surface of the specimen, and the load was carefully applied in an increasing stress pattern until the specimen failed. In the splitting test, the height of the cylindrical specimen was positioned on the lower plate of the machine, while the upper plate was lowered until it made contact with the specimen. The splitting tensile strength is computed using Equation 5.

$$f_{cst} = \frac{2P}{\pi l d} \quad (5)$$

Where; f_{cst} = Split Tensile Strength, P is the breaking load, l is the length of the cylinder, and d is the diameter of the cylinder.

Fig. 3 Compressive strength test

3. Results and Discussion

3.1 Result of Sieve Analysis and Slump

The distribution curve for the fine aggregate and coarse aggregate is depicted in Figs. 4 and 5. During the particle size distribution test, the plastic and cement bags analysis were not considered because they could not pass through the set of sieves; moreover, they are often used in the concrete matrix as fiber reinforcement rather than as coarse aggregate. The aggregate is well-graded, ranging between fine gravel and fine sand. The uniformity (C_u) and curvature (C_c) coefficients have been numerically calculated to determine the particle distribution in the aggregate. The percentage fines of 60%, 30%, and 10% are evaluated here. C_u is the ratio of 60% finer to 10% finer, which yielded a value of 2.11, while C_c is the ratio of the square of 30% finer to 60% and 10% combined, yielding a value of 1.15, confirming that the fine aggregate is well graded. The gravel and coarse aggregate contents were higher than the fines, which can increase water absorption and, as a result, increase the capillary pores in concrete. The natural coarse aggregate as well as the waste samples range between medium gravel and coarse sand, indicating a well-graded particle.

The aggregate impact value AIV obtained from the soundness test of natural coarse aggregate is 18.71%, which is sufficient for concrete impact resistance. As a result, the coarse aggregate used can produce concrete with high impact resistance. Aggregate Impact Value also indicates how well aggregates absorb shock [44].

The slump test for different percentage replacements for various waste materials is presented in Fig. 6. The slump values increase with an increase in percentage replacement for all waste materials at an adopted water-cement ratio of 50%. The slump value of the control specimen is higher than the waste materials, up to 7% replacement, except for the glass waste. All the specimens showed a true slump, with can waste having the highest slump value.

3.2 Concrete Water Absorption Result

The average water absorption value of waste material concrete is presented in Fig. 7. The control mix recorded the highest water absorption value of 13.6%, far lower than the 18% recommended [45]. Pet bottles at partial replacement of 10% had the least water absorption rate of 1.2%. This implies that concrete with a high-water absorption value may have a high permeability rate when exposed to inundation and thus become weakened. On the other hand, because can waste and pet bottles have a low absorption rate and affinity for water, their presence did not encourage moisture retention in concrete. This is because some capillary pores that retain water in concrete could be filled by the materials, reducing the voids left for water to occupy.

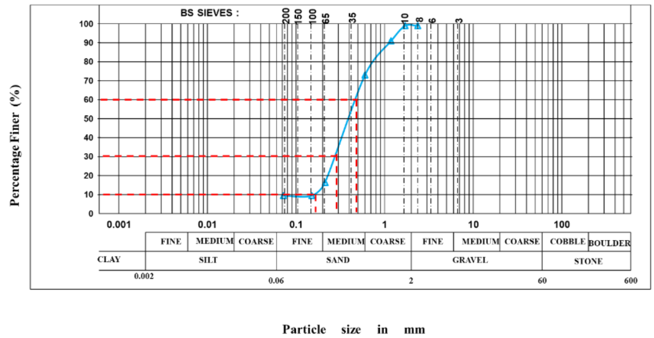

Fig. 4 Sand distribution particle curve

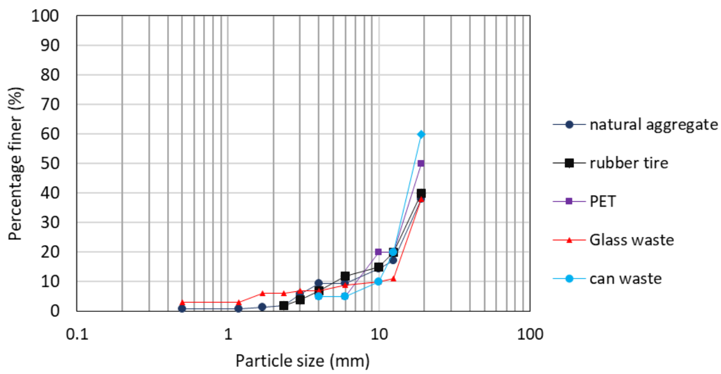

Fig. 5 Coarse aggregate distribution curve

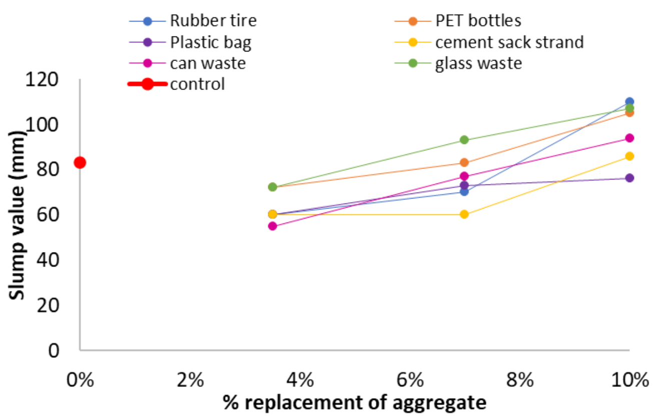

Fig. 6 Comparison of slump values for waste materials

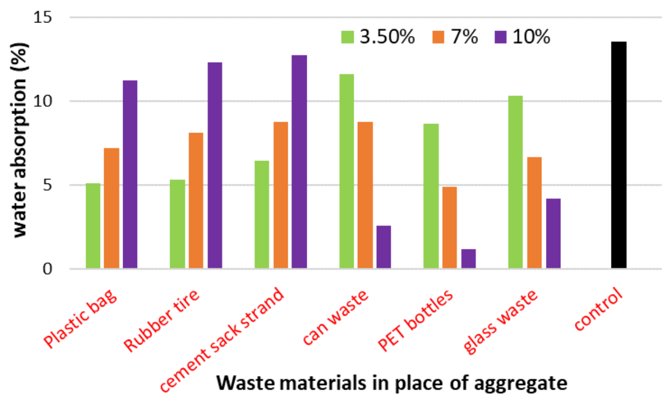

Fig. 7 Water absorption at different percentage replacement

3.3 Compressive Strength Result

The results of the average compressive strength obtained at the curing age of 7, 14, 21, and 28 days against the percentage replacement of coarse aggregate with waste materials are presented in Fig. 8. It can be seen that the compressive strengths of all specimens increase gradually with age. At 28-day curing, can waste has the highest compressive strength values at 10% replacement, followed by pet bottles and plastic bags at 3.5% replacement. This implies that waste material with high strength can act as reinforcement within the concrete. Although glass has a low water absorption rate, it was discovered during the compressive test that it did not contribute much to resisting the compressive load increment. Instead, it showed brittle failure (see Fig. 9). Concrete's heterogeneous material composition causes brittle failure under loading; combining a brittle material (glass) with its constituent does not improve Van der Waal's force in concrete but acts as an impurity in the concrete matrix. This could also prevent cement from completely hydrating in concrete.

3.4. Splitting Tensile Strength Result

Fig. 10 depicts the average tensile strength values of the waste materials and their respective percentage replacement. The can waste had the highest tensile strength at 7% partial replacement, which is approximately 44% higher than the control specimen. The cement sack strand had approximately 43% higher tensile strength than the control. Then, the glass waste had the lowest tensile strength, 19% lower than the control specimen. This confirms the unsuitability of glass waste as a coarse aggregate substitute in concrete production.

4. Conclusion

The properties of concrete incorporating various waste materials as coarse aggregate were investigated experimentally using 3.5%, 7%, and 10% replacement by volume of natural coarse aggregate with mix ratio 1:2:4. Consequently, the following conclusions have been drawn from the investigation.

- Can waste, pet bottles, and glass waste have low water absorption values as the percentage variation increases when compared to the control sample, which has the highest value of 13.55%. However, this does not translate to high concrete strength in this study because can waste and PET bottle concrete strengths are lower when compared to other waste materials. Nonetheless, the compressive strength of these materials can be used where concrete strength is not a priority.

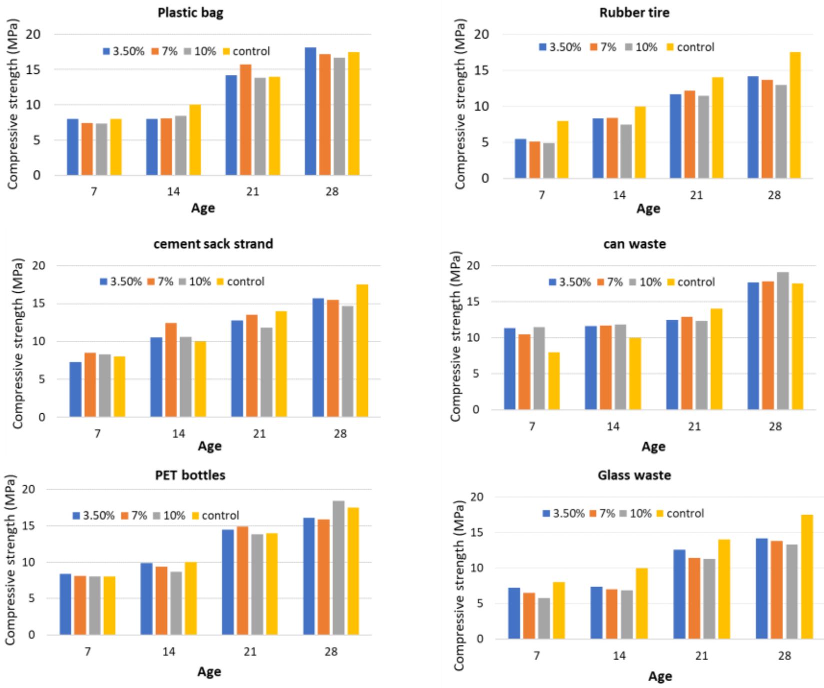

Fig. 8 Compressive strength results

Fig. 9 Failure mode of glass waste in concrete

- Glass waste had the highest workability and resistance to water absorption, implying that it can partially replace coarse aggregate in concrete; however, the glass-concrete had very low energy absorption under loading, resulting in brittle failure. This could be due to the low strength of the glass used. Glass waste with high strength is recommended, which may increase the strength of concrete more than expected.

- All the waste materials showed a gradual increase in both compressive and tensile strength with age. Can waste produced an optimum compressive and tensile strength in 28 days. The compressive strength was 10% higher than the control specimen at 10% partial replacement while the splitting tensile strength was 44% higher than the control sample at 7% replacement of natural coarse aggregate.
- Although this study used industrial waste as a substitute for natural coarse aggregate in concrete, cement sack strands and plastic bags contributed as reinforced fiber, resulting in ductile behavior under loading. As a result, the material may not be suitable where strength is a higher priority than ductility. Quality control should thus be ensured in their use.

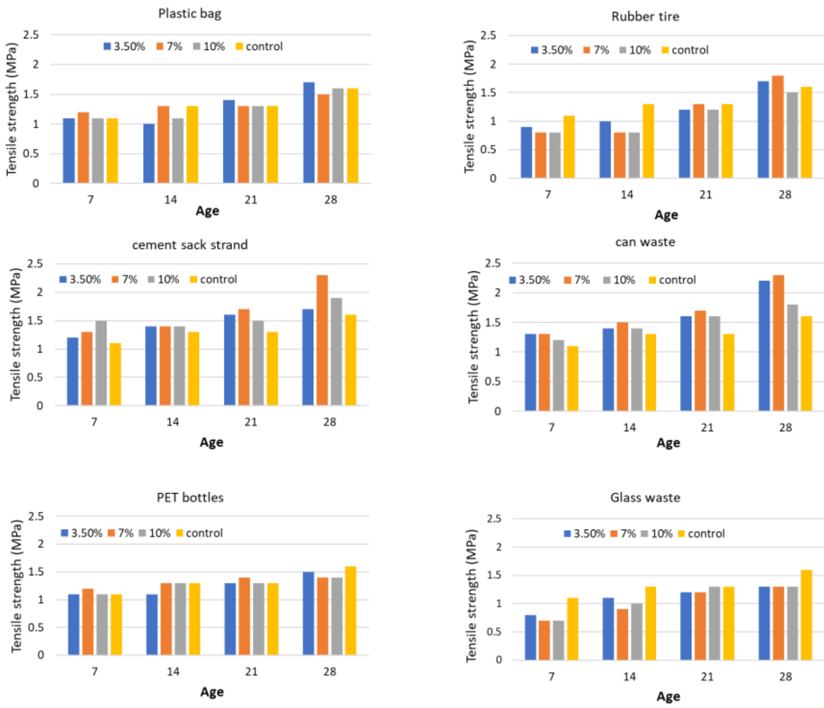

Fig. 10 Tensile strength results

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