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The Use of Plastic Waste as Replacement of Coarse Aggregate in Concrete Industry

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Abstract: Recycling solid waste is one of the most important ways to reduce carbon footprints and put sustainability into practice. This research aims to bridge the gap between the results of previous studies and the effectiveness and sustainability benefits of using plastic waste (PW) in concrete mixes by partially replacing coarse aggregate with PW. Furthermore, we examine the suitability of the concrete produced for use as a construction material. The research methodology is based on studying the physical and mechanical behavior of concrete produced by partially replacing coarse aggregate with 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% PW. For the conventional concrete–CC mix of 0% PW, the design strength, f_{cu}, was 35 MP, with a slump of 100 mm, using a water–cement ratio of 0.5, a M.A.S of coarse aggregate of 20 mm, and a sand F.M. of 2.2. According to British standards, BS, slump and density tests were carried out for concrete samples produced in their fresh state and strength tests, ultrasonic testing, etc. for concrete samples after hardening. The results indicated that there is no significant difference between the dry density and bulk density of concrete produced at all its age stages, regardless of the percentage of PW that replaces the aggregate. It also indicated that the compressive strength, the flexural strength, and the splitting tensile strength of the produced concrete decrease steadily and significantly when aggregates are replaced by PW by more than 2.5%. It was found that the decrease in compressive strength does not exceed 1% for concrete with 2.5% PW compared to the strength of CC, while the compressive strength of concrete with 5% PW decreases by 24%. The maximum reduction rate of the flexural strength and splitting tensile strength was 40% and 32%, respectively, for concrete at 12.5% PW compared to the strength of CC. Therefore, PW concrete can retain its strength when used in small quantities of up to 2.5% and can be applied in structural works.

Keywords: plastic waste; concrete densities; compressive; flexural and splitting tensile strength

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1. Introduction

The manufacturing of building materials has serious environmental impacts. Concrete is the dominant construction material, with its utilization estimated to exceed 1.6 billion tons annually. This amount is approximately responsible for emitting 7% of carbon dioxide, which is known as a major cause of many environmental issues, such as climate change and global warming, ozone layer depletion, and many others. However, the principle of sustainable development has emerged to deal with such issues. Concrete production is responsible for 2–3% of the annual energy demand and 8–9% of the total atmospheric CO_2, which created an additional challenge that must be faced in the construction industry. Now, PW represents a serious environmental threat in the modern era, resulting from the huge consumption of it all over the world. An example of PW, polyethylene terephthalate (PET), is widely used in the production of bottles and jars, carpet, clothing, industrial strapping, rope, automotive parts, fiberfill for winter jackets and sleeping bags, construction materials, and protective packaging. Plastic consists of several toxic chemicals. Thus, plastic pollutes the soil, air, and water. Since plastic is a non-degradable material, landfilling waste with plastic means that harmful substances are preserved forever. The hazards of plastic bottles are numerous. Ninety percent of all floating garbage patches in the oceans are believed to originate in the Pacific Ocean, and they consist primarily of plastic waste. Studies have estimated that about 100,000 marine mammals and more than a million seabirds die annually because of ingesting plastic waste or becoming entangled in plastic debris [1]. The threat of plastic waste seems to be constantly increasing. Many countries have restricted the use of plastic bags, and many are in the process of doing so. Therefore, it is not surprising that the linear economy contributes significantly to the growing plastic waste crisis. To address the mentioned environmental problems regarding plastic waste, it is necessary to act towards more sustainable models, as many studies were conducted on the possibility of recycling this waste and using it in different proportions with coarse aggregate in the concrete industry and studying the extent of its impact on its physical and mechanical properties, where different and varied results were obtained. Therefore, the overall objective of this study is to determine the effect of replacing coarse aggregate with PW at a specified level of percentages on concrete properties in an attempt to evaluate the results of previous studies to reduce the negative environmental impact of PW and produce an innovative, environmentally friendly construction material.

2. Literature Review

Recent studies indicate that several scientific efforts aim at reducing the environmental impact of the concrete industry, either by using mineral components as partial substitutes for cement or by incorporating organic waste as partial replacements for cement, sand, or coarse aggregate. Kule (2018), in his assessment study of the effects of using plastic as a partial replacement for coarse aggregate in concrete, concluded that the slump of concrete increases with an increase in the percentage of replacement of PW for coarse aggregate due to the lack or absence of plastic absorbing water and, thus, obtaining a highly workable concrete [2]. It also became clear to him that the density of PW concrete decreases with an increase in the percentage of PW in the concrete due to the lower specific gravity of the PW compared to the specific gravity of the coarse aggregate. Moreover, he found that the compressive strength of the concrete produced increased by increasing the percentage of the replacement of PW for the coarse aggregate by more than 50%. The study conducted by Osubor et al. (2019) investigated the density and compressive strength of concrete produced by replacing coarse aggregate with flaky plastic waste, including using PET in volume percentages ranging from 5% to 20%, and by changing the particle size of the PET (from 3 mm to 7 mm) [3]. They concluded that the compressive strength of concrete decreases with an increasing percentage of flaky PET and an increasing particle size. The density also decreases with an increase in the percentage of flaky PET and an increase in its particle size. Sau et al. (2023) conducted a study on the mechanical properties and durability of concrete produced by replacing coarse aggregate with percentages (0–40%) of plastic waste PET [4]. They concluded that the permeability of concrete increases as the percentage of PET replacement increases and that the density of concrete and its compressive strength decrease as the replacement percentage of PET increases, increasing the period of exposure to the atmosphere. Therefore, they recommended using PET concrete for lightweight concrete purposes. On the other hand, there are many assessment studies conducted on the behavior of light concrete produced from replacing coarse aggregate with electronic plastic waste. Examples of this were created by Manjunath (2016), Ahmed et al. (2021), and Botchway et al. (2022), who replaced coarse aggregate with electronic plastic waste at percentages of 0%, 5%, 10%, 15%, and 20% [5–7]. In general, they concluded that the compressive strength value decreases for concrete produced with replacement percentages of 5% and 10% but increases when replaced with percentages of 15% and 20%, and the density increases as well. It was also concluded that the water absorption of the concrete produced decreases, as it disappears when replaced by 15% or more. Kayentao et al. (2023) evaluated the properties of modified concrete using PET bottle waste as a partial replacement for coarse aggregate. Modified concrete samples were designed using a water–cement (W/C) ratio of 0.50 and varying percentages of PET replacement (3%, 7%, 10%, and 15% by volume) [8]. Dreux Gorisse's formulation approach was used to make the final products, and the mechanical properties of the samples were determined using Controlab presses. This modified concrete with PET chips has shown that, with a 10% replacement of PET chips, the fresh density decreases by 3.56%, and the hardened state density decreases by 2.01%. The water absorption and thermal conductivity of the formulated concretes decreased. However, the results showed that the slump of these fresh concretes increased as the percentage of plastic aggregate replacement increased. Based on the results, incorporating PET aggregates into concrete contributes to good workability and lightweight concrete structures and provides some thermal comfort in concrete structures. According to the study conducted by Kayentao et al. (2023), concrete with a water-to-cement ratio of 0.5 is produced by replacing waste polyethylene plastic bottles with coarse aggregate in proportions of 0%, 3%, 7%, 10%, and 15% by volume [8]. It was found that, by increasing the proportion of coarse aggregate with plastic waste, the workability of the produced concrete improves and the density of the concrete decreases. Whether in its fresh or hardened state, its compressive strength and tensile strength decrease, but at a slight rate. The porosity of the concrete produced also increases, but within acceptable limits, and the thermal conductivity decreases. Accordingly, the researchers conclude that concrete, produced by replacing coarse aggregate with plastic waste of up to 15%, can be used in the construction of sidewalks, stairs, interior walls, short walls, storage tanks, non-structural slabs, coating works, etc. Saikia and De Brito (2012) conducted an extensive review of some research related to replacing cement or aggregate with plastic waste and studied its effect on some of the properties of produced concrete, such as the slump values of fresh concrete, unit weight and density, different types of concrete strength (compressive, tensile splitting, and flexural), toughness, abrasion resistance, thermal conductivity, etc. [9]. The most important results obtained were that the density decreases with increasing the percentage of replacement, and therefore, it is recommended to use it for producing lightweight concrete. The strength of concrete also decreases with increasing the percentage of replacement, as it was observed that the compressive strength decreases by 72% compared to CC when replacing 20%. They also concluded that the rate of decrease in tensile strength is less than that of compressive strength, which is attributed to the fact that the concrete produced by replacement is more ductile than CC. In general, concrete produced by replacement is less fire-resistant and less thermally conductive and leads to improved permeability. Tota-Maharaj et al. (2022) investigated the effects of waste plastics as a partial fine-aggregate replacement for reinforced low-carbon concrete pavements, demonstrating environmental engineering concepts for tackling plastic waste and giving an alternative to conventional aggregate [10]. Moreover, in a review of previous studies conducted by Guo et al. (2023) and Edmund et al. (2018) on the use of plastic as a partial replacement for aggregate, they concluded that the slump of concrete increases with an increase in the percentage of replacement of PW for coarse aggregate [11,12]. In contrast, they found that the compressive strength of PW concrete decreases with an increase in the percentage of PW replaced by aggregate, as well as the bulk density of concrete. Accordingly, their recommendation was to use plastic as a partial replacement for aggregate, with admixtures that maintain compressive strength, when aiming to produce light concrete. Therefore, the importance of this research paper lies in investigating the variations in the results obtained in the above studies related to the slump of concrete in its fresh state and the density and strengths of hardened concrete produced by replacing coarse aggregate with different percentages of PW and then obtaining the ideal replacement ratios with which environmentally friendly concrete can be produced.

3. Materials and Methods

3.1. General

Any material used as a construction material must have specific engineering properties that are responsible for its quality and capacity and help to determine its field of application. To achieve this, the following methodology was followed in the research.

The necessary physical tests were conducted to design the concrete mix, including tests of bulk particle density (SSD), absorption, and sieve analysis, for both a fine aggregate and a coarse aggregate and verifying their compliance with British specifications.

1. Samples of concrete mixtures of partially replaced coarse aggregate with (2.5%, 5%, 7.5%, 10%, and 12.5%) PW and other samples of CC concrete according to British specifications were prepared (Table 1);

Table 1. Pulse wave, densities, and compressive strength values of CC and PW concrete at 28 days.

%PW	V_p m/s	ρ_d Kg/m^3	ρ_{sat} Kg/m^3	ρ_{im} Kg/m^3	ρ_b Kg/m^3	f_{cu} MPa
2.5	4.993	2433	2448	1446	2426	39
5	4.699	2363	2379	1368	2337	30
7.5	4.626	2333	2348	1344	2323	28
10	4.646	2287	2301	1296	2276	28
12.5	4.468	2202	2217	1215	2196	24
CC	4.756	2474	2491	1487	2462	40

2. The consistency-testing program was implemented in accordance with British Standard BS 1881 [13]. This program was conducted to identify the mechanical properties of concrete, such as compressive, tensile, and split strength, and then compare them with their counterparts in CC concrete.

3.2. PW Preparation

This process involved collecting empty plastic bottles from various areas of the Najran region in Saudi Arabia, shredding them into small particles, washing away fats and impurities, and then grinding them. Then, it was partially replaced by coarse aggregate in certain weight percentages.

3.3. Experimental Program

The methodological framework used in this study is introduced in Figure 1. A concrete mixture of Portland cement, conforming to ASTM C150 and having coarse and fine aggregates compliant with BS 882-1992 [14] and potable water as ingredients of the CC mix, as well as others by partially replacing the coarse aggregate with PW at weight percentages that were mentioned above, was designed and prepared according to the British Standard. A Hobart mixer, with a 5 L capacity, was used to mix the concrete ingredients. The ingredients were mixed following the method described in BS 1881 [13]. To ensure that the mixtures had the required workability, a slump test, as described in BS 1881-102: 1983, was conducted for each [15]. Following the BS 1881-125 procedure, specimens consisting of seven 100 mm cubes, as well as three cylinders with a diameter of 100 mm and a height of 200 mm and three prisms with dimensions of 100 × 100 × 500 mm, were cast and prepared to test the compressive, splitting, and flexural strength, respectively, for each concrete mixture [16].

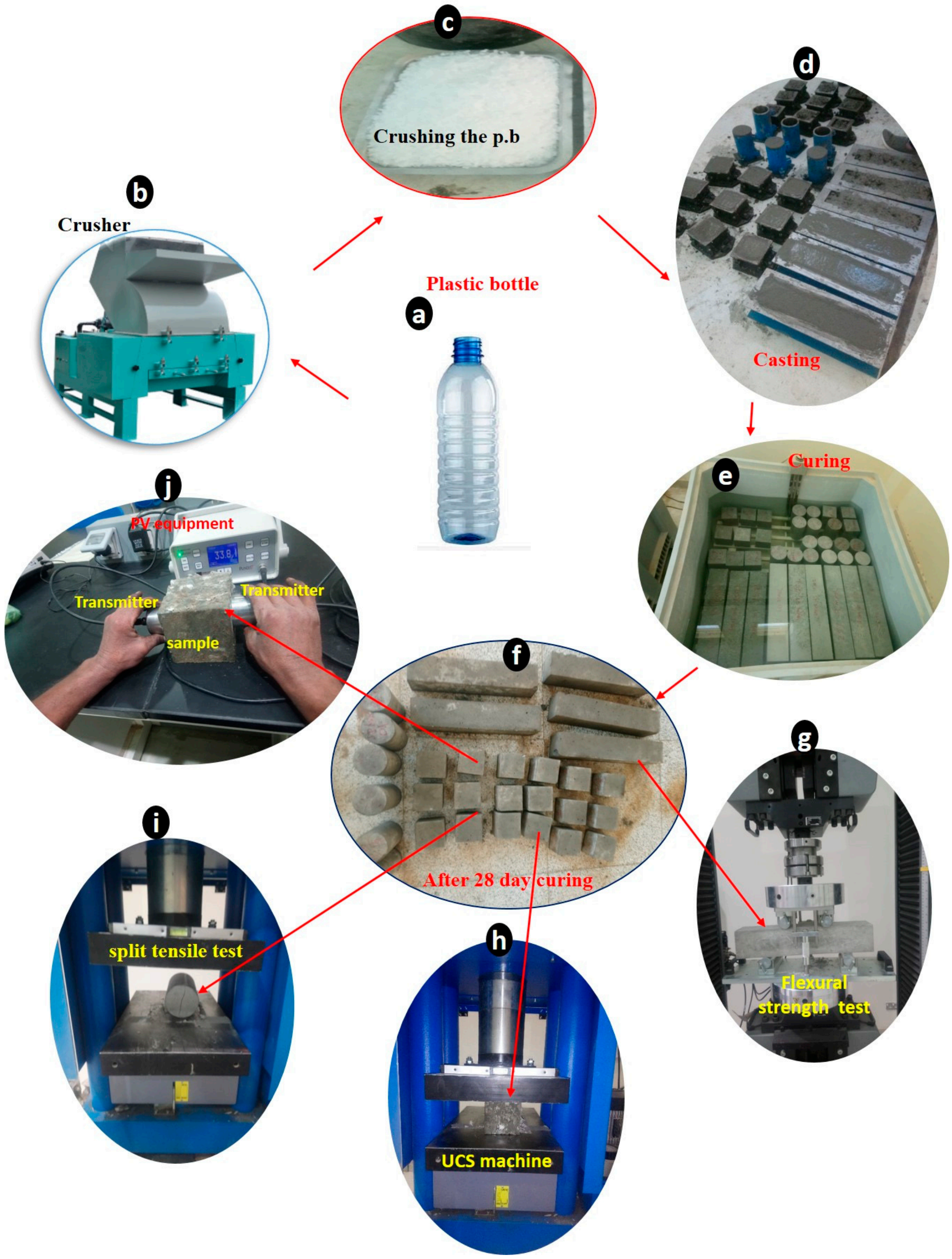

Figure 1. Methodological framework used in this study. (**a**) Collection of samples in plastic bottles; (**b**) Crusher machine used for crushing; (**c**) Plastic bottles after crushing; (**d**) Casting of the samples; (**e**) Curing of the samples; (**f**) Preparation of samples for testing; (**g**) Flexural strength testing of the samples; (**h**) Samples placed under the compressive strength testing machine; (**i**) Splitting tensile test being performed; (**j**) Ultrasonic testing of the samples.

The compressive, splitting, and flexural strength tests were carried out as per BS 1881: Part 116, BS: Part 117, and BS: Part 118, respectively [17–19]. The compressive strength test was conducted on the cube specimens, with strength results representing the average of three specimens at 7, 14, and 28 days of age. The splitting and flexural strengths of the produced concrete were determined as the average of three cylinder specimens and three prism specimens, respectively, at 28 days of age, as the average of three specimens for each.

In order to determine the homogeneity and structural integrity of the PW concrete produced, ultrasonic tests, UPV, were conducted. Knowing the dry density ρ_d; the saturated density ρ_{sat}; and the submerged density ρ_{im}, the triple weight method Mohamedsalih et al. [20] was used to determine the bulk density, ρ_b, in (kg/m^3) using the following relationship:

$$\rho_b = \frac{1000\rho_d}{\rho_{sat} - \rho_{im}}$$

4. Results and Discussion

4.1. Workability of the Fresh PW Concrete

To measure the workability of the freshly produced PW concrete, a slump test was performed for each concrete mixture in accordance with BS 1881—Part 102 [15]. It was observed that the decreasing value of the slump increases as the percentage of replacement of coarse aggregates with PW increases, as shown in Figure 2. This observation is consistent with most of the previous research conducted in this regard, such as that conducted by Sharma and Bansal [21], Gu et al. [22], and Li et al. [23]. In fact, most of the previous studies did not mention the reasons that lead to lower concrete workability when the proportion of coarse aggregates is increased with plastic. Considering the limited availability of cement paste in the concrete mix and the fact that the higher the percentage of plastic replacement with coarse aggregate, when the surface area of the aggregate particles is greater, there will not be enough cement paste to coat the increased particle surface area with an increasing replacement percentage. In addition, the texture of the plastic particles is rougher than that of the natural coarse aggregate particles, meaning that the surface area of the rough surfaces of the particles increases with the increase in the percentage of replacement, which results in low-working concrete. As mentioned by Alqahtani and Zafar [24] and Batayneh et al. [25], the reduction in slump is attributed to the increase in friction between the plastic particles, which leads to reduced fluidity.

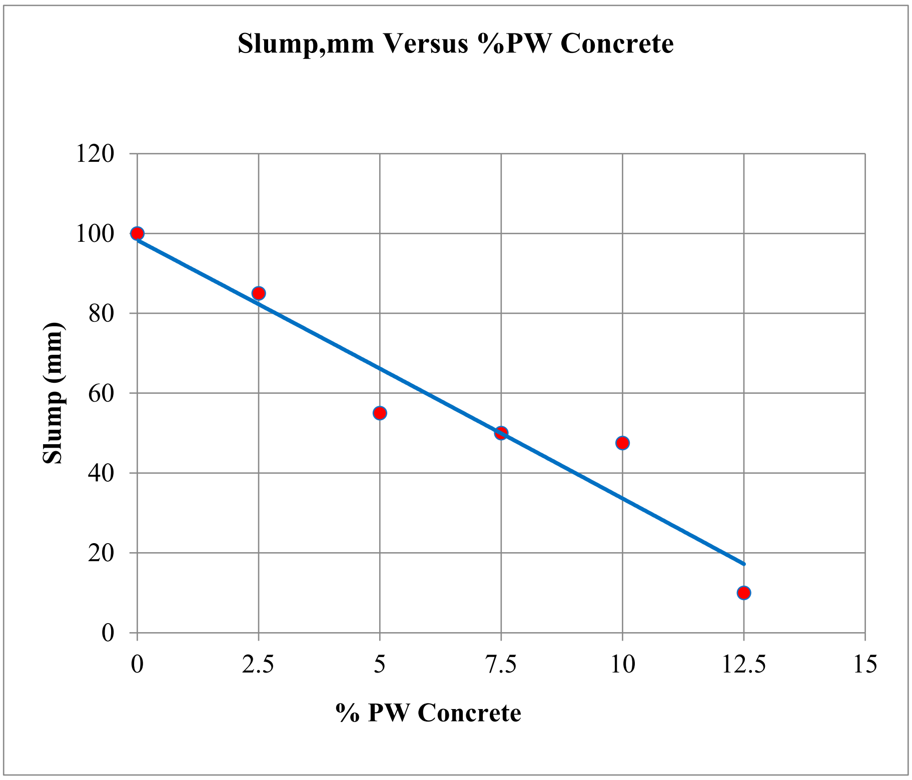

Figure 2. Slump vs. percentage of PW in concrete.

4.2. Density of the Hardened PW Concrete

The bulk density, ρ_b, depends on how densely the concrete is packed and, consequently, on the size, distribution, and shape of the particles. Therefore, comparing bulk densities of concrete produced using PW is more useful and gives a clear picture of the size of particles and granules, how they were distributed, and to what degree they were compacted. Through the study of Figure 3, the concrete content of the PW percentage versus the dry density of concrete produced revealed that the dry density of the PW concrete is always lower than that of the CC that is produced without PW, and this is due to the fact that plastic bottles are usually manufactured from polyethylene terephthalate, PET, with a specific gravity of 1.3–1.4, or polycarbonate, with a specific gravity of 1.15–1.2 [16,25]. However, the specific gravity of the plastic is much less than the specific weight of the aggregate. In detail, it is observed that the dry density of 2.5% PW concrete decreased by 1% from the density of the reference concrete, CC, while the maximum decrease in density was 11% for 12.5% PW concrete.

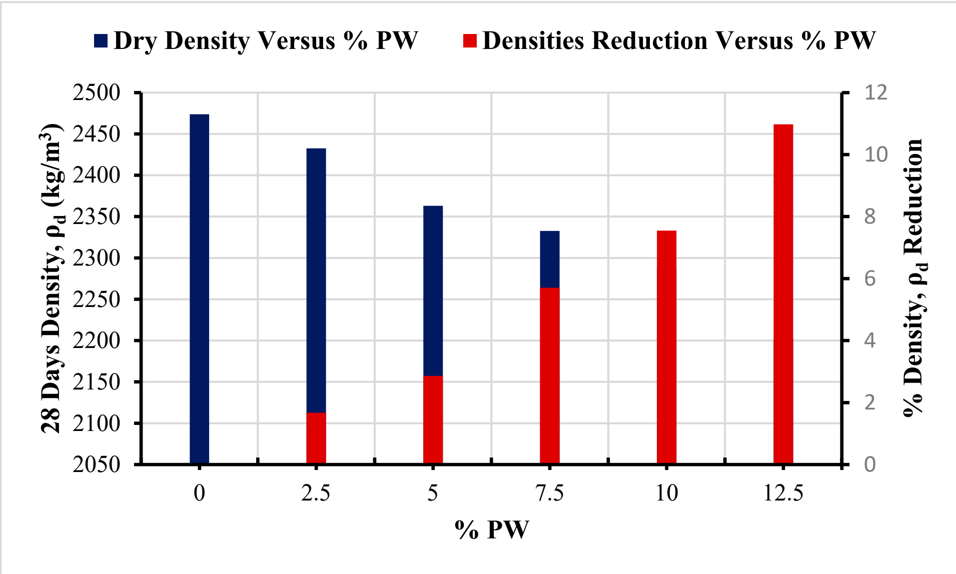

Figure 3. Reduction in concrete dry density (ρ_d) vs. percentage of PW.

From the above figures, Figures 4 and 5, it is obvious that there is no significant difference in the density values of the concrete produced with its age, regardless of the percentage of PW substitution for the aggregate. For example, it was found that the highest difference in bulk density between 7 and 28 days of age for the concrete produced by replacing 2.5% of the aggregate with PW is 0.83%.

In addition, it is noted that there is no significant difference between the dry density and the bulk density of the concrete produced, regardless of the percentage of PW replacing the aggregate (Figure 6). This is enhanced and confirmed by Figure 7 (concrete ρ_b versus V_p) and the results of the UPV test conducted on the concrete samples aged 7 days, as an example, shows that V_p decreases with an increase in the PW ratio, or in other words, by increasing voids between concrete particles (i.e., low density).

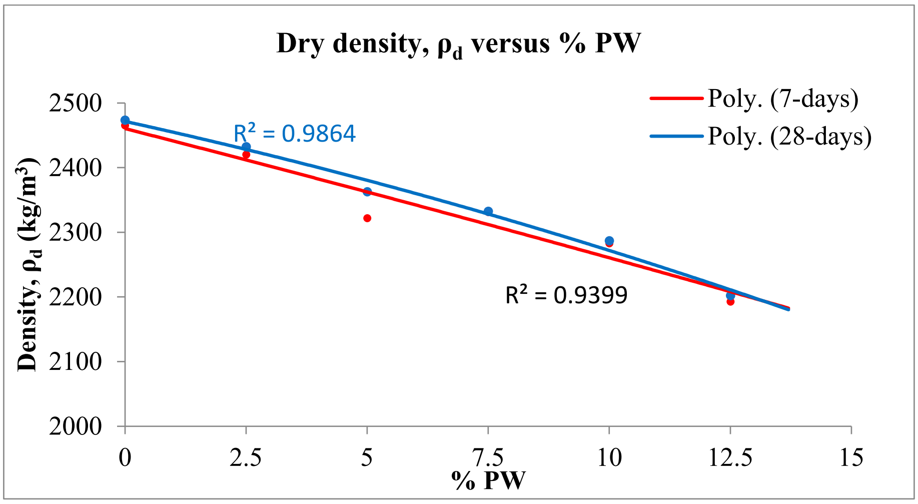

Figure 4. Concrete dry density (ρ_d) vs. percentage of PW.

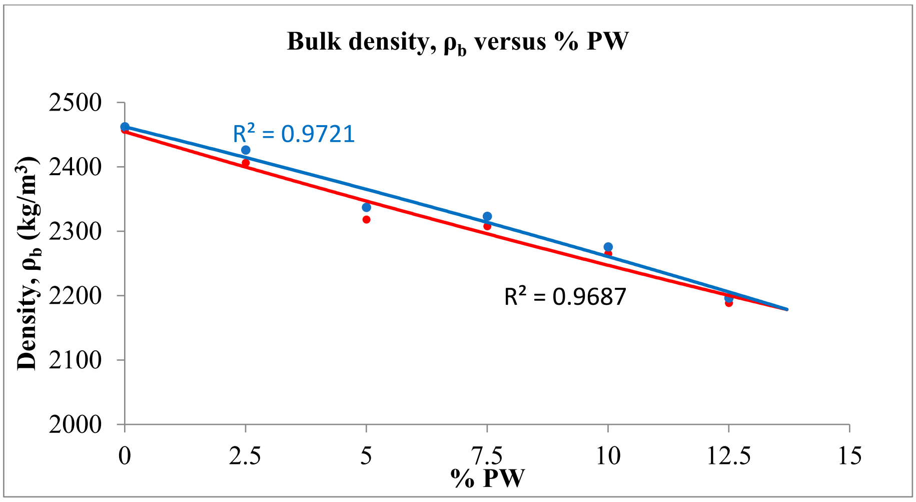

Figure 5. Concrete bulk density (ρ_b) vs. percentage of PW.

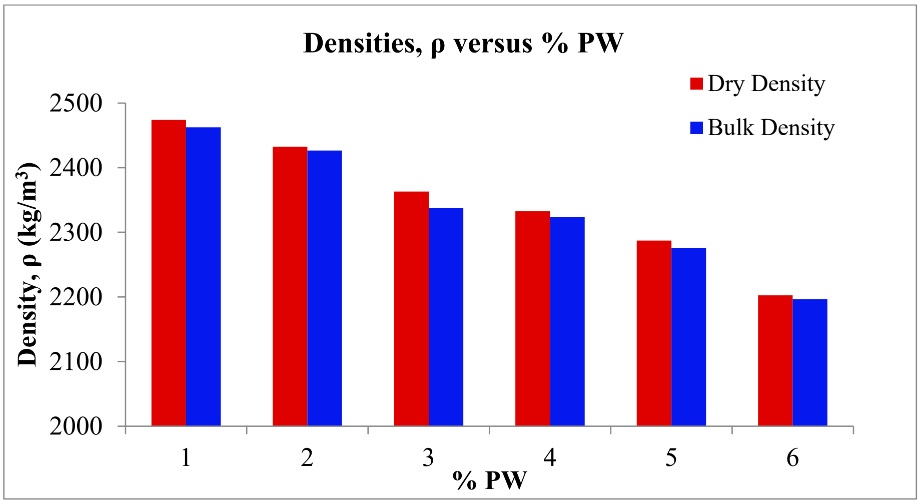

Figure 6. Concrete densities (ρ) vs. percentage of PW.

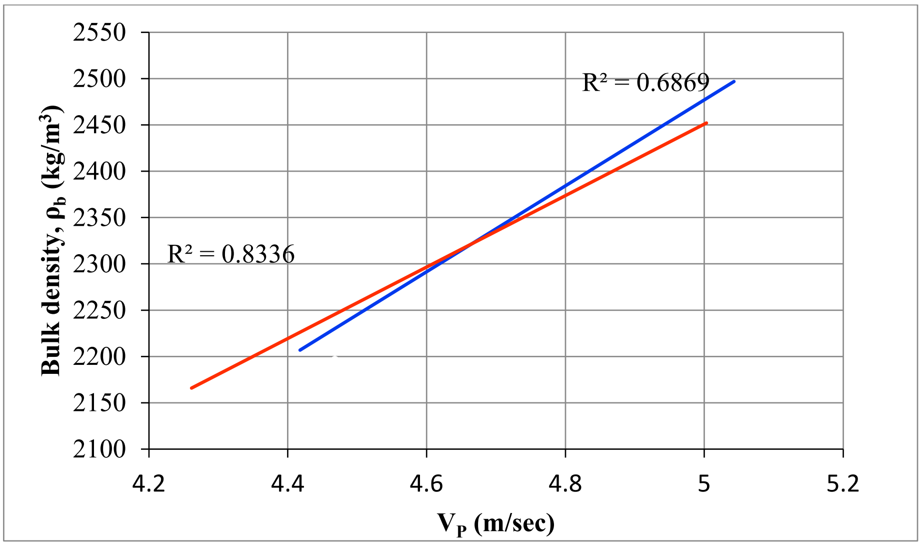

Figure 7. Bulk density (ρ_b) vs. VP (m/s).

4.3. Strength of PW Concrete

4.3.1. Compressive Strength

As was mentioned in the literature review paragraph, and as expected from Figures 8 and 9 below, it is obvious that the compressive strength of the produced concrete decreases as the percentage of aggregates that are replaced with PW increases. This is despite the fact that the compressive strength value increases with age at the same rate, regardless of the percentage of PW in the concrete. The reduction in the concrete's strength was 1%, 24%, and 39% compared to the strength of CC for the concrete produced by replacing 2.5%, 5%, and 12.5% of the PW, respectively. In fact, CC is designed to have a compressive strength, f_{cu}, of 31 MPa. In any case, by tracing the rate of decrease in compressive strength of PW concrete when increasing the rate of replacement of PW by coarse aggregate, it becomes clear from Figure 9 that the decrease in strength does not exceed 1% for concrete with 2.5% PW compared to the strength of the CC, while the strength of concrete with 5% PW decreases by 24%. Actually, the strength of the concrete produced reduces at a small rate whenever the percentage of PW is low, and this is because the plastic has a superior resistance to breakage, as Batayneh et al. [25] state. Therefore, PW concrete can retain its strength when PW is used in a small amount because the surface area of the PW that replaces the area of the substituted aggregate particles is less compared to that of the concrete produced by replacing the aggregate with a higher percentage of PW.

4.3.2. Flexural Strength

As observed in the mechanical behavior of PW concrete, particularly its compressive strength, Figure 10 shows that replacing coarse aggregate with PW up to 2.5% does not significantly affect its flexural strength. In general, it is observed that the flexural strength of concrete, f_t, significantly decreases with an increase in the percentage of PW greater than 2.5%. This may be due to the low adhesion strength of the cement paste to the surface of the plastic waste particles, in addition to the hydrophobic nature of the plastic materials, which may limit the hydration of the cement. However, this decrease is consistent with the results of previous works, such as those conducted by Pezzi et al. [26].

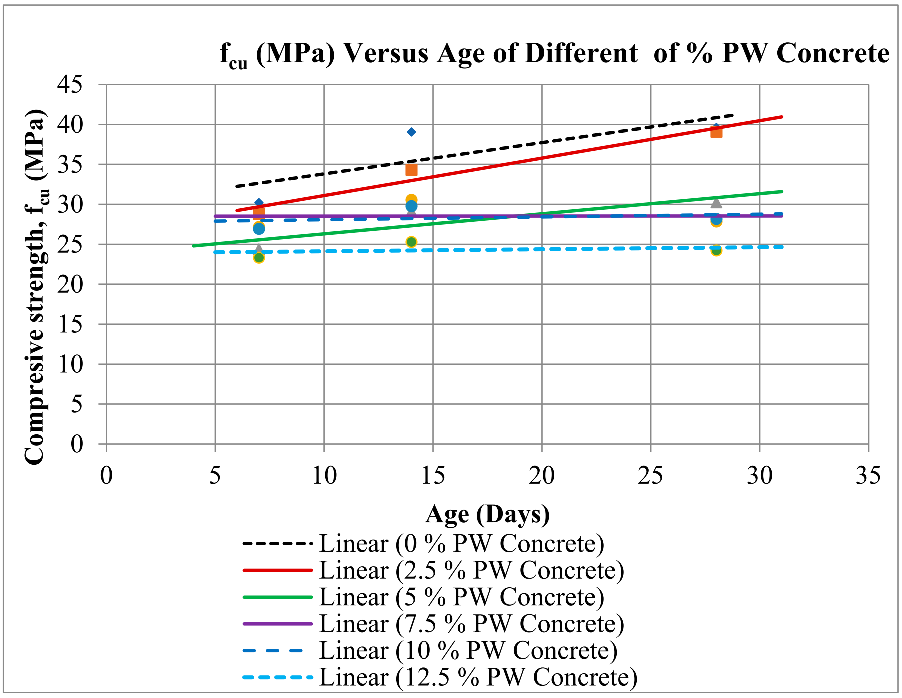

Figure 8. Compressive strength (f_{cu}) at 7, 14, and 28 days vs. percentage of PW. The points represent the average values of compressive strength (fcu) for concrete with plastic waste replacing coarse aggregates at 0%, 2.5%, 5%, 7.5%, 10% and 12.5%.

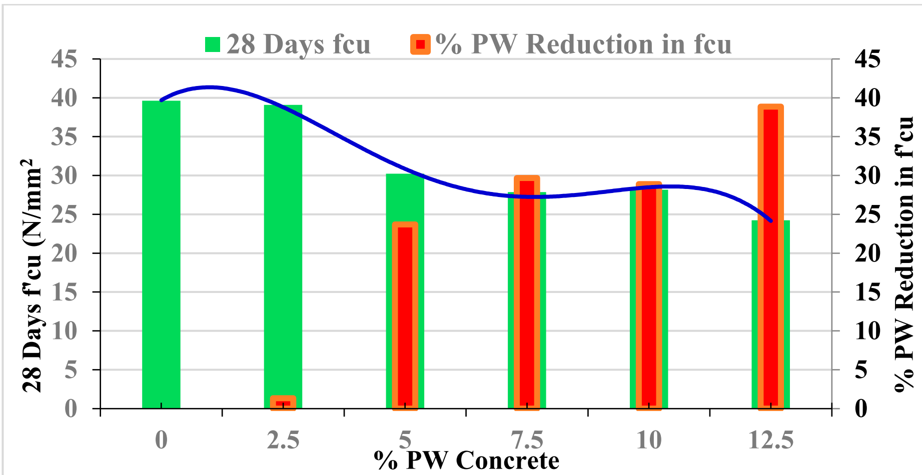

Figure 9. Percentage reduction in compressive strength (f_{xu}) at 28 days due to % PW. The blue line illustrates the trend of compressive strength reduction as coarse aggregates are replaced.

4.3.3. Splitting Tensile Strength

From Figure 11, it is obvious that concrete's splitting tensile strength decreases significantly and steadily when aggregates are replaced with PW by more than 2.5%. The reduction in splitting tensile strength by increasing the percentage of PW in concrete was mentioned by many researchers, such as Al-Manaseer and Dalal [27], Choi et al. [28], and Siddique et al. [29]. This is due to the weak adhesion strength of plastic waste particles with the cement paste of the concrete mixture. This explains what was seen and observed about how the samples failed when conducting tests, where the failure took on a ductility mode and not a brittle mode, as is the case for CC. This confirms the conclusion of Al-Manaseer and Dalal [27].

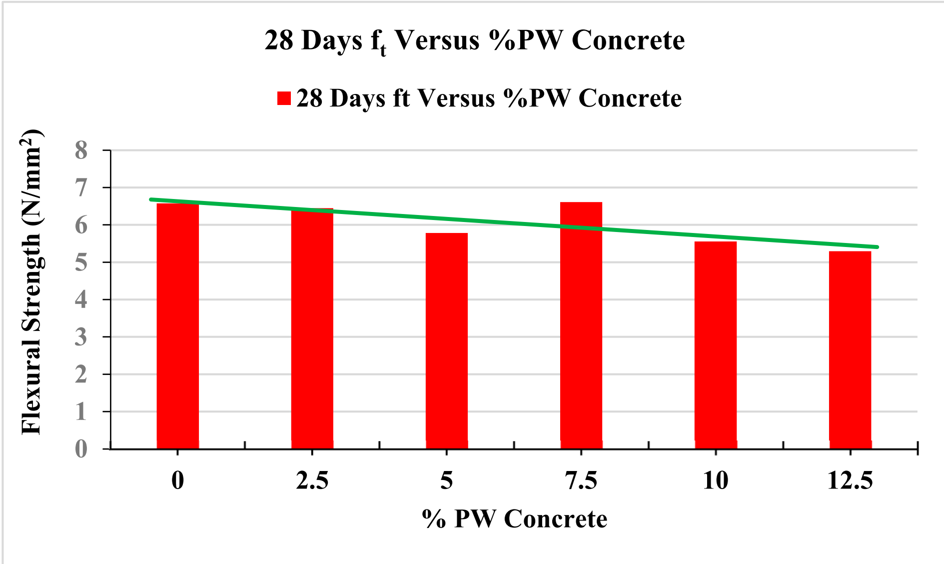

Figure 10. Flexural strength vs. percentage of PW in concrete. The green line represents the trend of flexural strength reduction as coarse aggregates are replaced.

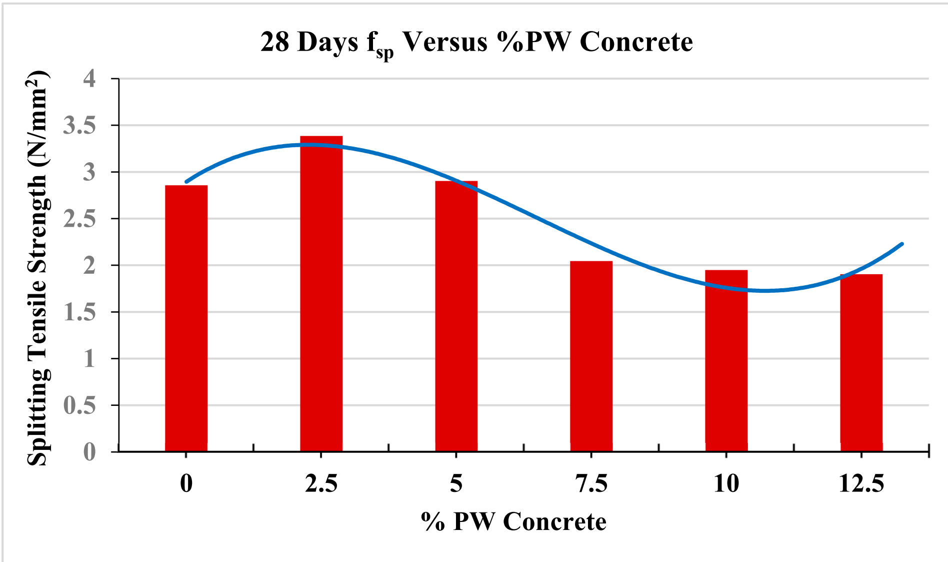

Figure 11. Splitting tensile strength ($f_{\gamma}{}^{P}$) vs. percentage of PW of concrete at 28 days. The blue line illustrates a significant and steady decrease in splitting tensile strength of concrete as the aggregate is replaced with plastic waste (PW).

5. Conclusions and Recommendations

In this research, to develop sustainable concrete, the effect of partially replacing the coarse aggregate of conventional concrete with PW was studied. Concrete mixtures were made with partial replacement weight ratios of 2.5%, 5%, 7.5%, 10%, and 12.5% PW for coarse aggregate. The physical and mechanical properties, including slump, densities, compressive strength, flexural strength, splitting tensile strength, and UPV, of the concrete produced from the above-mentioned mixtures were investigated. The results obtained in this study can be concluded and summarized as follows.

1. The decrease in the slump value of fresh concrete increases as the percentage of PW partially replaced by the coarse aggregate increases, as the drop values for the CC and 12.5% PW concrete were 100 mm and 10 mm, respectively;

2. The value of the decrease in the density of concrete increases with the increase in the proportion of coarse aggregate replaced by PW. The dry density of 2.5% PW concrete decreased by 1% from the density of CC, while the maximum decrease in density was 11% for the 12.5% PW concrete. There is no significant difference between the dry density and bulk density of concrete produced at all of its age stages, regardless of the percentage of PW that replaces the aggregate and regardless of the age stage;
3. The compressive strength of the produced concrete decreases as the percentage of aggregates replaced with PW increases. It was found that the decrease in strength does not exceed 1% for concrete with 2.5% PW compared to the strength of CC, while the strength of concrete with 5% PW decreases by 24%;
4. Replacing aggregates with any amount of PW reduces concrete's flexural strength. In any case, this decrease is consistent with the results of previous studies. However, the flexural strength is not significantly affected when replacing coarse aggregate with PW up to 2.5%;
5. The splitting tensile strength of concrete decreases significantly and steadily when the aggregate is replaced with PW, by more than 2.5%. Otherwise, the tensile strength of the concrete will be enhanced;
6. Therefore, PW concrete can maintain its strength when PW is used in small quantities (up to 2.5%) and is suitable for structural applications. However, beyond this limit, it is more appropriate for non-structural uses;
7. To predict the strength of concrete according to the % PW replacement of coarse aggregate for a given age, it is recommended to derive a mathematical model to achieve this.

This study can be generally summarized as follows. The physical properties of concrete (in both its fresh and hardened states) are only slightly affected when part of the coarse aggregate is replaced with PW in small quantities (up to 2.5%). The concrete can maintain its strength and, therefore, is suitable for non-structural applications. Additionally, no significant difference was observed in the dry density or bulk density of the concrete at any age stage, regardless of the percentage of PW used to replace the aggregate.

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