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Research Article

Physio-Mechanical and Thermal Properties of Concrete Produced by Partial Replacement of Sand with Plastic Fines

Khawaja Adeel Tariq[1*], Munib Ul Rehman[2] , Rana Ghafran[3], Ibraheem Kamran[4], and Muhammad Haroon[5]

[1]Department of Civil Engineerinng, The University of Faisalabad, Faisalabad, Pakistan
[2]Department of Architectural Engineering and Design, University of Engineering and Technology Lahore, Pakistan
[3]Engineering Management and Construction Company, Lahore, Pakistan
[4]Structural Engineering Division, National Engineering Services Lahore, Pakistan
[5]Elite Constrution Islamabad, Pakistan

Abstract: Abundant plastic waste is generated around the globe annually and safe management of this waste is crucial for the health of our environment. This study examined the physical and mechanical properties of plastic waste concrete (PWC) formulated by partially replacing natural sand with plastic fines. The sand was substituted by a mixture of two inert and non-recyclable plastics (PVC and polyethylene) in varying replacement ratios (5, 10, and 20% by volume of sand). Fresh and hardened properties of PWC mixes were evaluated. Considering possible degradation in the toughness of plastic particles due to lower melting and softening point, the effect of temperature on PWC was determined simulating heat exposure expected in hot regions of Pakistan. Various concrete specimens were exposed at 65 °C for a day and compressive strength was compared. Plastic fines caused a reduction in the workability of concrete, but it was acceptable at 10% replacement. Concrete density reduced with plastic fines content producing lighter concrete, while, water absorption remained un-affected within 10% replacement. Mechanical strength was reduced with increasing plastic share; about 41.67% and 29% drop in compressive and split-tensile strength was recorded, respectively, for 20% sand replacement; however, within 10% replacement, the properties were favorable. Thermal exposure did not affect much and was hypothesized to have a negligible effect in normal applications. Sand replacement with 10% plastic fines would produce lighter and economical concrete along with resource-conservation and waste reduction benefits.

Keywords: Plastic waste concrete, Plastic aggregates, Thermal exposure, Thermal performance, Sustainable concrete, Splitting tensile strength, Compression strength.

1. INTRODUCTION

In the present century, plastic has secured an integral role in the development of various industries, including construction, packaging, electronics, and automotive; courtesy to its exceptional properties like easy processability, lighter weight, phenomenal strength, durability, and low-cost. In 2012, at a global scale, about 0.29 billion tons of plastic was produced [1] and the demand is further forecasted to observe exponential growth. Out of the bulk plastic generated, only a fraction is recycled and the rest of end-use products are disposed of; studies have reported about 26% [1] and 8.8% [2]effective recycling rates for Europe and USA, respectively. Pakistan produces approximately 1.32 million tons of plastic waste annually [3], the majority of which is left untreated and abandoned in landfills. Plastic waste can have severe impacts on the environment when managed with current practices (landfilling and incineration) due to: non-biodegradable nature, hazardous leaching, and toxic emissions [4]. Safe disposal of plastic waste can be ensured through digestion in construction materials.

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*Corresponding Author: Khawaja Adeel Tariq <khawajaadeel@hotmail.com>

Concrete is the abundantly-used construction material worldwide because of its adequate mechanical performance and durability properties. However, in various regions, the concrete resource materials are over-stressed and facing sustainability issues [5]. Therefore, researchers are constantly exploring alternative materials to replace and provide relief to traditional raw materials of concrete [6].

Concrete, a flexible composite, has been frequently and successfully tested for prospects to digest various municipal and agro-industrial wastes [7-11]. Increasing plastic waste can be effectively and safely recycled in concrete. Various studies have incorporated plastic as a replacement for aggregates in concrete [4]. It is reported that adding plastic aggregates deteriorate mechanical properties slightly, but this drawback can be mitigated by other benefits like safe waste disposal, natural-resource conservation, dead load reduction, better thermal and acoustic insulation, and improved economy of the mixes [12]. Usually, plastics have melting points ranging between 100^{o}C and 200^{o}C [4], and exothermic cement hydration reaction or elevated external temperature may cause softening of plastics leading to bond-degradation between plastic and cement matrix and strength reduction. Existing literature has overlooked the effect of the thermal softening of plastic on the mechanical properties of concrete. Therefore, this study has considered the effect of temperature on the properties of plastic waste incorporated concrete for the first time.

Considering this background, the major aim of this study is to re-use plastic waste in producing sustainable concrete, which will help both in reducing waste and relieving stress on natural raw materials. This study has undertaken to investigate fresh and hardened properties of concrete designed using plastic waste as a replacement to fine aggregates. Plastic fines sourced from dead, non-recyclable, and thermoset polyvinyl chloride (PVC) and polyethylene (PE) wastes were used to replace a proportion of natural sand in the concrete mixes. Different properties of various concrete mixtures were investigated including workability, density, water absorption, and mechanical strength. The effect of the internal heat of hydration and the external atmospheric temperature was also investigated on the compressive strength of concrete comparing normal and post heat-exposure results.

2. MATERIALS AND METHODS

2.1. Materials

The Portland cement, ASTM Type I [13], was used in this work; the fineness and specific gravity of cement were 3250 cm^2/g and 3.15 g/cm^3, respectively. The oxide-based composition of cement is reported in Table 1 as provided by the manufacture. Uniformly graded sand, sourced from River Chenab outskirts, was used as fine aggregates having fineness modulus (FM) of 2.54. A mixture of two non-recyclable plastic wastes (PVC and PE, sourced from electric wires insulation) was used as a partial replacement of sand. The FM of plastic fines was 3.52. Coarse aggregate was sourced from the Sargodha quarry and its maximum size was 19 mm. Potable water was used during concrete mixing. Physical properties of different aggregates

Table 1. Composition of oxides in cement

Oxide	Weight (%)
Silica (SiO_2)	20.3
Iron oxide (Fe_2O_3)	2.8
Alumina (Al_2O_3)	4.9
Lime (CaO)	63.6
Magnesia (MgO)	2.2
Sulfur trioxide (SO_3)	2.8
Sodium oxide(Na_2O)	0.4
Potassium oxide (K_2O)	0.7
Chloride	0.01
Loss on ignition (LOI)	2.5
Moisture content	<1

Table 2. Physical properties of different aggregates used in this work

Property	Aggregate Type		
	Sand	Plastic Fines	Coarse Aggregate
Density (kg/m^3)	1441	366	1500
Water Absorption (%)	2.1	0.1	0.14
Fineness Modulus	2.54	3.52	-
Maximum Size (mm)	4.75	4.75	19

were measured and are provided in Table 2.

2.2 Concrete Production

Concrete mixtures were designed in two categories: control concrete (without plastic fines) and plastic waste concrete, PWC (with the varying dosage of plastic fines). Three PWC mixtures were designed by replacing sand with plastic fines in the following volume percentages, 5%, 10%, and 20% considering the density of both materials. All the concrete mixes were designed with a fixed water/cement ratio of 0.52 following the design guidelines of ACI 211.1 [14]. All other constituents were the same for all mixes except variation between sand and plastic. The mix proportions for concrete are presented in Table 3.

Concrete proportioning and casting was performed following ACI guidelines [14]. After mixing and homogenization, concrete was cast in standard concrete cylinders (150 mm x 300 mm). Specimens were de-molded after 24 h of initial stay period and then kept in a water tank for curing in laboratory ambient condition (23 ± 5 ºC) until testing age.

2.3. Testing on Concrete

2.3.1. Physical Properties

The workability of fresh concrete mixes was assessed through a slump test within half an hour of casting; the procedure of ASTM 143 was adopted for the test [15]. Concrete density was determined after 7 days of curing. Water submerged cylinders were oven-dried at 50 ºC for a day and then oven dry weight was calculated; thus partially simulating ASTM C1585 [16], the concrete density was recorded. Fig. 1 displays an overview of the testing scheme adopted in this work.

For water absorption measurement, the concrete specimens were oven-dried at 50 ºC for a day and then placed in water for the next 24 h. After 24 h, the oven-dried weight was determined to calculate the water absorption.

2.3.2. Mechanical Properties

Compressive strength test was performed on cylinders after designated curing age as per ASTM C39 [17]. Before the test, the concrete cylinders were brought out of the curing tank and were placed in the laboratory for 24 h to dry; afterward, they were tested under 1000 kN UTM applying strain-controlled conditions (2.5 mm/min). To account for the effect of temperature on strength, a set of PWC specimens were also exposed to a sustained temperature of 65ºC for 24 h, and the strong results were compared for exposed and un-exposed specimens. This temperature was achieved in an oven within 10 minutes, sustained for 24 h, and then dropped to zero within 10 minutes of the

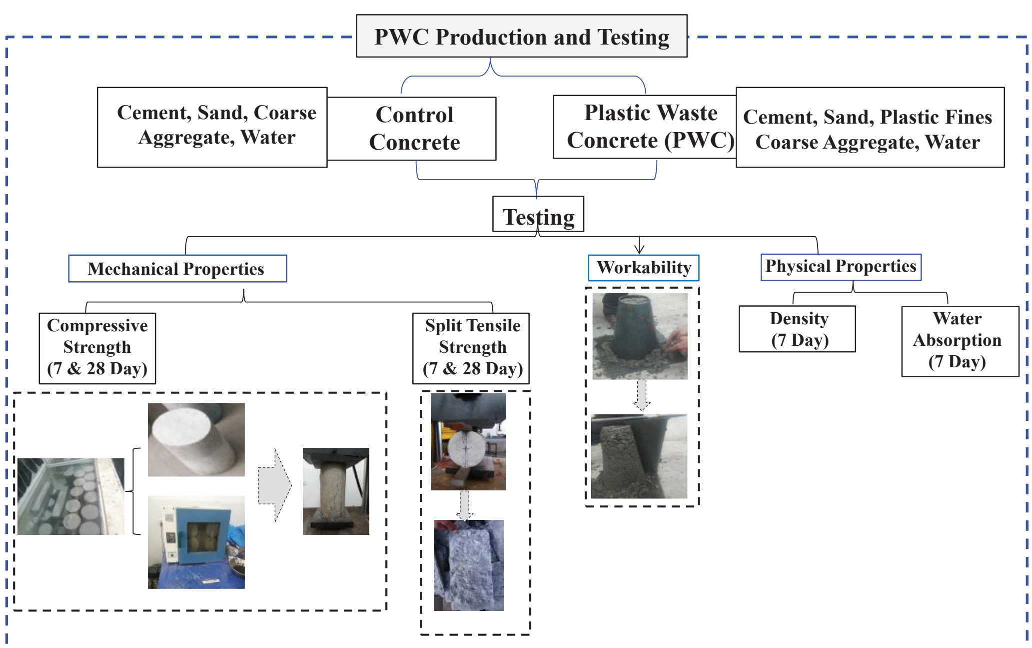


Fig. 1. Graphical summary of the testing scheme.

recession period. The average of three cylinders was reported as compressive strength in this paper. To estimate tensile strength, the split-tensile strength of concrete cylinders was examined under UTM following ASTM C496 [18].

3. RESULTS AND DISCUSSION

3.1. Workability

The workability of different concrete mixtures is displayed in Fig. 2. Slump decreased as the plastic fines were increased in the mixture. At maximum replacement of sand (20% plastic fines), the slump of the concrete was reduced by 52% relative to the control mixture. Another study [19] reported a 50% decline in workability with 20% replacement. The slump reduces plastic waste addition due to various reasons including the irregular shape of plastic particles [4], water absorption, and enhanced surface area (fineness) [20]. The plastic was finer than sand (considering FM from Table 2), which required more water to be wet and flowable due to increased surface area and thus caused a drop in slump value. The shape effect of irregular morphology of particles also produced lesser slump. However, with 10% plastic fines, the slump was adequately good, and it reduced significantly on 20% replacement of sand making replacement beyond 10% less desireable.

3.2. Density

The density of 7-day concrete specimens is presented in Fig.3. Approximately, linear drop in the density was observed with plastic fines content (Fig. 3). After 20% replacement of sand with plastic fines, the density dropped by 11% approximately compared with control specimens. The reduction in the density was because of the significantly lesser unit weight of plastic fines compared to sand (Table 2). Although the density of plastic fines was almost one third that of sand, the decline in concrete density was not exactly aligned; this is due to the fineness and filler effects of plastic fines. Plastic fines better filled the voids to make a denser packing of constituents and thus avoided a significant reduction in unit weight. Literature has evidenced about an 8% to 16% reduction in density due to plastic fines [20]. Particle size and fineness of plastic aggregate greatly influence density, as about 30% lighter concrete has been developed using plastic coarse aggregate [4]. PWC of this study can be used for a wide range of applications from structural to non-structural to insulation walls. Another study reported density reduction from 2400 kg/m^3 to 1620 kg/m^3 on 20% addition of a similar type of plastic as a coarser fraction [12]. The concrete transitioned from structural to lightweight concrete. The density reduction can offer various indirect benefits, including optimized design dimensions, reduced transportation, and reduced on-site handling costs.

3.3. Water Absorption

Water absorption values of concrete specimens are reported in Fig. 4. As observed, up to 10% replacement, plastic fines had a negligible effect on water absorption. However, beyond 10%, and at a 20% replacement level, the water absorption of PWC increased by about 9% relative to control concrete. Up to 10%, the filler effect, and better packing might have allowed less penetration of water, and further addition of plastic caused internal-segregation and mixing incompatibility

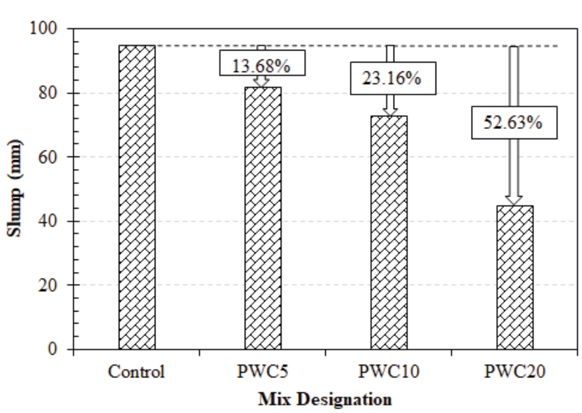


Fig. 2. Variation of the slump with plastic fines.

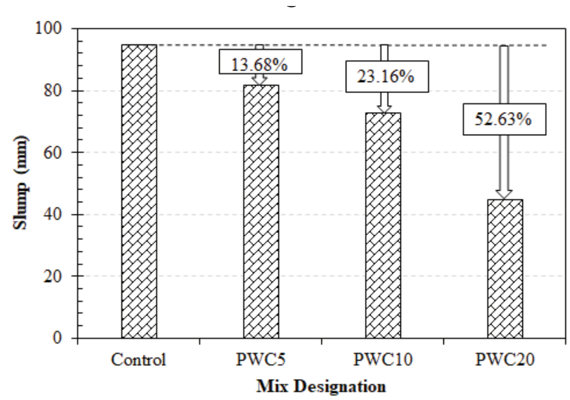


Fig. 3. The density of concrete with varying plastic-fines dosage.

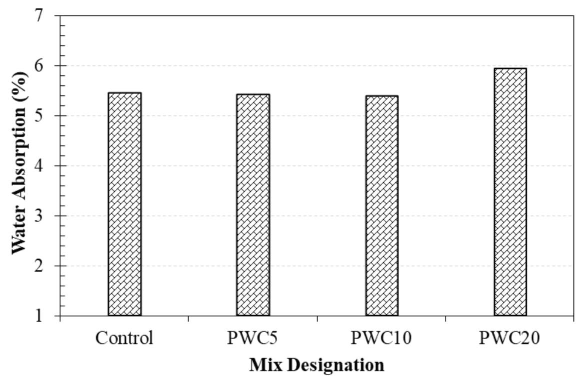


Fig. 4. Water absorption of control and PWC specimens.

between conventional and plastic aggregates leading to more porous concrete [4].

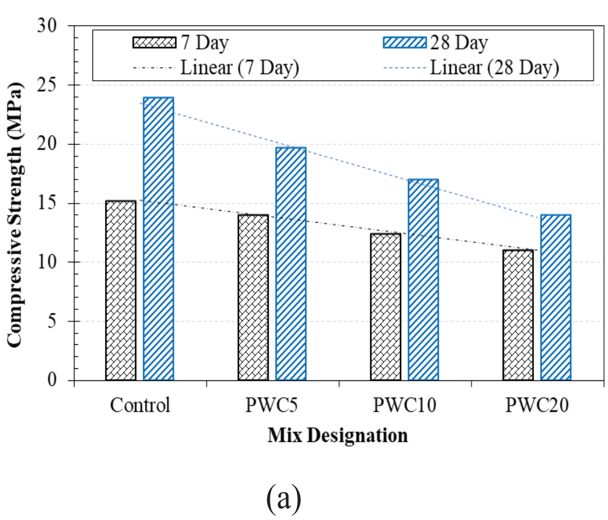
3.4. Compressive Strength

Compressive strength results of concrete specimens are displayed in Fig. 5. Compressive strength decreased with plastic fines content; an approximately linear decrease in strength was observed at both curing ages. However, the drop in strength was more prominent at 28 days curing as evident from the slope of the trend-line (Fig. 5a). The strength of specimens containing 20% plastic fines was about 27.30% and 41.67% lesser than corresponding control specimens after 7 and 28-day curing, respectively. The strength deterioration can be attributed to the low toughness of plastic aggregates, the weak bond between plastic fines and cement paste [20], and increased porosity of PWC [4] (Fig. 6). The density of concrete also plays an important role; the decline in the density of concrete with more plastic fines also contributed to lower strength as evident from Fig. 5b.

To examine the effect of temperature on plastic fines' softening and later on compressive, the concrete specimens were exposed to 65 °C for a day. Fig. 7 compares the compressive-strength of heat-exposed and un-exposed concrete specimens. Thermal exposure slightly impacted concrete strength; the strength reduction was higher for 7 day cured specimens relative to 28 day cured ones: possibly because after 7 days, the concrete is not strong enough due to incomplete hydration and strength gain. After thermal exposure, the control concrete strength fell by 5.17% and 2.61% for 7 and 28-day cured specimens, respectively; whereas, PWC observed a 2.96-7.26% and 3.84-6.85% strength decline for 7 and 28-day curing, respectively. The results support the safe use of PWC in all the regions of Pakistan where the temperature usually remains below 55 °C. It is further hypothesized that the effect of environmental temperatures will be negligible once PWC is fully matured after months of curing and strength gain in actual applications.

3.5. Split Tensile Strength

Split-tensile strengths of the concrete specimen without heat exposure are drawn in Fig. 8. Split-tensile strength dropped with increasing plastic fines at both curing ages; though many consistent results were observed for specimens cured for 28



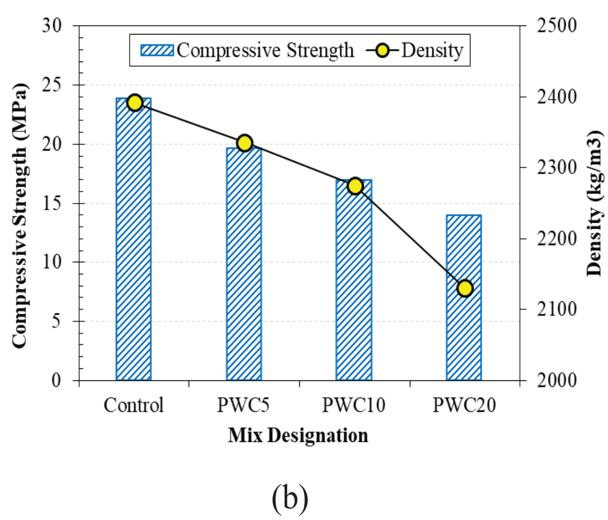


Fig. 5. Variation of: (a) concrete compressive strength with plastic fines content, (b) compressive strength and density of concrete.

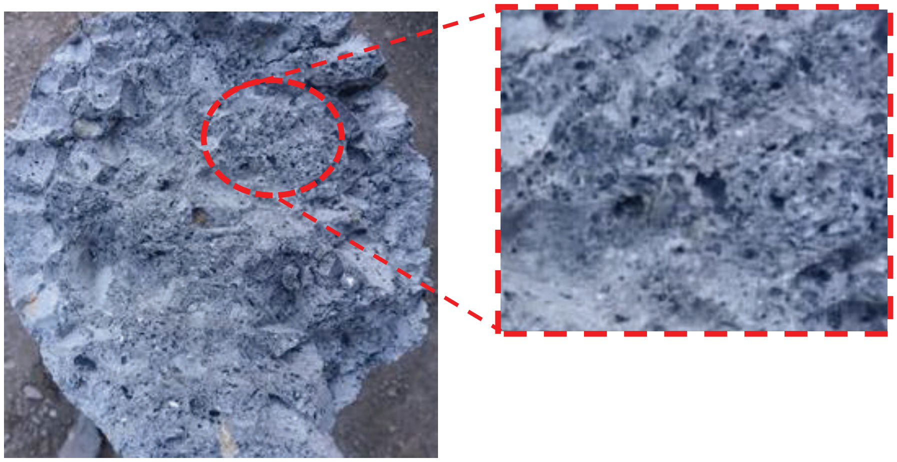


Fig. 6. Fractured PWC20 specimens exhibiting a porous matrix inside.

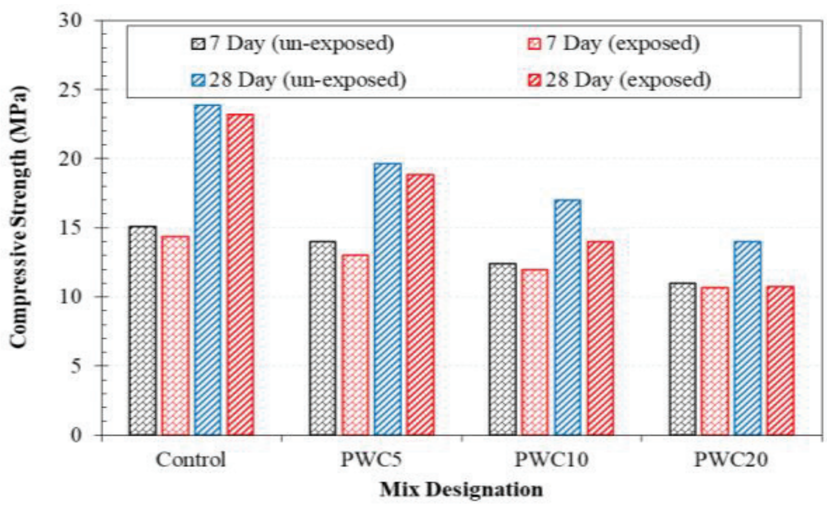


Fig. 7. Comparison of compressive strength for control and PWC concrete before and after thermal exposure.

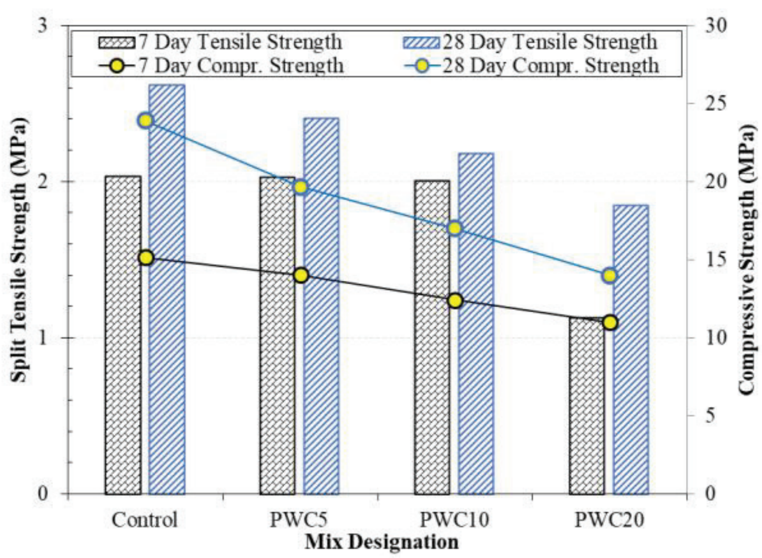


Fig. 8. Variation of split-tensile and compressive strengths with plastic fines content.

days. PWC strength was short of control specimens by 8.28% and 29.39% for 5% and 20% substitution ratios, respectively. Overall, as evident from Fig. 8, the split-tensile strength results were aligned with those of compressive strength.

4. CONCLUSION

The current study investigated the physical, mechanical, and thermal performance of concrete (PWC) in which sand was replaced by plastic fines in varying percentages. To confirm the stability of PWC under the hottest climate of Pakistan, the specimens were exposed to an exaggerated representative temperature and the strength under compression was compared for both exposed and un-exposed specimens. Following conclusions were drawn from the experimental results:

- The workability of concrete decreased with increasing plastic fines content due to more fineness, enhanced surface area, and water absorption of plastic particles. Slump reduced by 52% at 20% replacement level; however, the slump was acceptable within 10% sand replacement.
- The density of concrete fell by about 11% on adding 20% plastic fines due to the lower unit weight of the plastic. Water absorption approximately remained unaffected up to 10% replacement, but at 20% replacement, water absorption increased by 9% relative to control concrete possibly due to porosity created in the vicinity of plastic particles due to loose bonding with cement paste.
- The mechanical performance of the concrete was degraded by adding plastic fines. Compressive strength dropped by 41.67%, and split-tensile strength fell by about 29% on 20% plastic fines content for 28-day cured specimens. The strength deterioration is attributed to the weak bond between plastic and cement paste, reduced density of concrete, and enhanced porosity of the matrix.
- Thermal exposure did not severely impact the strength of PWC possibly due to the encapsulation of plastic fines in cement paste, and the effect was reduced with curing age. The strength reduction for PWC20 was merely 4% more than control concrete for 28-day testing. The authors hypothesized that for the actual application, the concrete will be more stable due to prolonged hydration due to months of curing and adequate strength gain.

Based on the test results and analysis, 10% replacement of sand with plastic fines is recommended. The higher plastic content will lead to severe degradation in concrete quality.

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