

Performance of structural concrete with recycled plastic waste as a partial replacement for sand

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HIGHLIGHTS

- Eleven concrete mixes tested with plastic as partial replacement for sand.
- Target compressive strength of 54 MPa to replicate structural concrete.
- Control of particle size distribution minimises change in compressive strength.
- PET fragments graded as sand can be used at a replacement ratio of 10%.
- Save 820 Mt sand per year by replacement with waste plastic.

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ABSTRACT

Environmental concerns arising from the over-dredging of sand have led to restrictions on its extraction across India, with direct economic impacts on concrete construction. A suitable environmentally friendly alternative to sand must be found to match the huge demand from the concrete construction industry. At the same time, waste plastic is rarely recycled in India, with as much as 40% left in landfill. The dumping of such materials which degrade at extremely low rates meaning they persist in the environment is a long-term environmental concern.

To tackle both issues, it is proposed to process waste plastic to create a partial replacement for fine sand in a novel mix for structural concrete. In this paper eleven new concrete mixes are evaluated to study five plastic material compositions, three groups of particle sizes, three different aspect ratios, and two chemical treatments and establish an appropriate choice of material to act as partial replacement for sand.

The results show that replacing 10% sand by volume with recycled plastic is a viable proposition that has the potential to save 820 million tonnes of sand every year. Through suitable mix design the structural performance of concrete with plastic waste can be maintained. This preliminary work was supported through funding from the British Council under the UKIERI (United Kingdom India Educational Research Initiative) programme for the project 'Development of structural concrete with the help of plastic waste as partial replacement for sand'.

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1. Introduction

Cement manufacture in India reached 280 Mt in 2014 [1], second only to China. India exports only small volumes of cement, with internal demand for concrete being driven by a growing economy, growing population, and rising living standards [2]. Mass extraction of sand, usually via river dredging, has been a problem

in India for a number of years and is mainly fed by construction demand. A high court ruling in 2011 has virtually eliminated sand dredging [3] with the consequence of supply problems within India.

The Indian central pollution control board (CPCB) reported in 2008 that approximately 15,000 tons of plastic waste is dumped every day in India [4]. Non-biodegradable plastic waste is inert and breaks down very slowly once buried in landfill. Even if all of this plastic could be recycled, by-products of the recycling

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process such as polyethylene terephthalate (PET) sand are still required to be sent to landfill.

A solution to both of these problems is proposed by substituting fine sand in concrete mixes with processed waste plastic, which would otherwise remain as waste in landfill. This would not only encourage the collection and use of waste, but would provide alternative sources of fine material in place of sand in novel concrete mixes

2. Plastic as a replacement for sand in concrete

Initial research on the effects of plastic aggregate substitution on concrete compressive strength was undertaken by Al-Manaseer and Dalal [5], who explored the effect of an increasing proportion of angular waste plastic particles on cylinder strength for three different water to binder ratios. It was found that compressive strength decreased with an increase in plastic aggregate content, with this loss in strength attributed to poor bonding between the plastic and cement paste (Fig. 1). The plastic was able to pull out, rather than to split in tension, during compressive testing of the concrete.

Saikia and de Brito [6] tested concrete mixes containing three different sized and shaped particles: 1) large (10–20 mm length) particles; 2) shredded flaky fine particles (2–5 mm length); and 3) cylindrical pellet shaped particles (3 mm length). Each of these was tested over a series of replacement ratios, ranging from 0% to 15% of the sand. It was found that the higher the replacement ratio, the lower the concrete's compressive strength, attributed to the lack of interaction between the PET aggregate and cement paste (Fig. 1). This study concluded that the interfacial transition zone in concrete containing PET aggregate is weaker than that of standard concrete.

Albano et al. [7] used irregularly shaped PET particles between 2.6 mm and 11.4 mm in replacement quantities of 10% and 20% with two different w/c ratios (0.50 and 0.60). It was found that

the compressive strength reduced with increases in the proportion of plastic, implying that plastic particles acted as defects within the internal structure of the concrete. Mix designs containing only larger plastic particles were substantially weaker compared to mixes containing only smaller PET particles, as illustrated in Fig. 1. The formation of a honeycomb of cavities and pores was observed and attributed to the low workability affecting the compaction of the concrete.

Frigione [8] used granulated PET that was graded very similarly to the siliceous sand that was to be replaced in the mix. It was found that while the compressive strength of the mix decreased, the reduction was less than 2% when a replacement ratio of 5% was used. This is favourable when compared to the 12% loss seen by Saikia and de Brito [6] when 5% sand was replaced with larger plastic pellets. This indicates that although the use of plastic may cause a decrease in compressive strength because of a poorer bond to the surrounding matrix when compared to sand, the loss can be limited by appropriate mix design and choice of plastic.

Ismail and Al-Hashmi [9] tested concrete with a mixture of PET and polystyrene as sand replacement. Subsequent reductions in compressive strength were attributed to a decrease in adhesive strength between the surface of the waste plastic and the cement paste as plastic is a hydrophobic material (Fig. 1). Therefore movement of the water required for cement hydration is hindered, leaving isolated volumes of unhydrated cement within the bulk volume.

Albano et al. [7] demonstrate that both larger particles, and higher replacement percentages, cause significant reductions in tensile strength due to an increase in voids present within the concrete. This is supported by Frigione [8], where 5% replacement by volume of sand using granulated PET led to only a 2% loss in tensile strength.

Saikia and de Brito [6] found that as with compressive strength, there was a loss of tensile performance when plastic aggregate was introduced into the concrete, and the more plastic added, the greater the loss. The loss of tensile strength was attributed to the

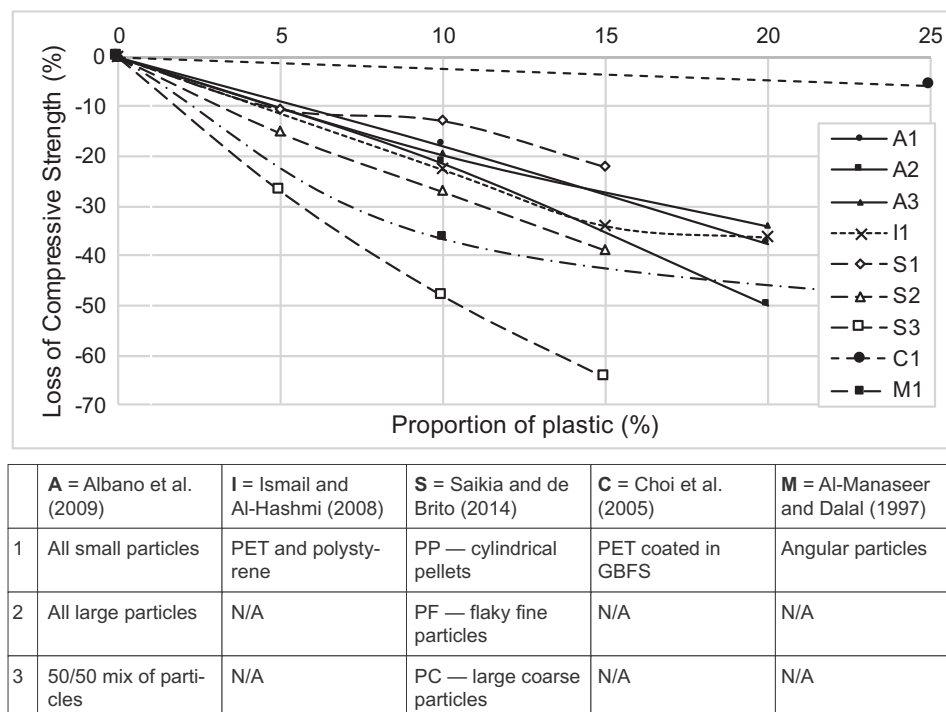


Fig. 1. The relationship between plastic replacement and loss in compressive strength.

characteristics of the plastic, primarily its smooth surface, but also the presence of free water at the plastic surface causing a weak bond with surrounding cement paste. Microscopic studies of failed specimens revealed that the most common form of failure was debonding at the plastic-concrete interface.

The influence of three different curing conditions for concrete with plastic waste aggregates on its mechanical performance was explored by Ferreira et al. [10] who found that the dominant effect on performance was not curing conditions but percentage replacement.

Safi et al. [11] examined the use of waste plastic bags in the production of self compacting mortar mixes. Replacement levels of 0–50% were tested, with reductions in strength being related to the percentage replacement. At 30% substitution, average strength reductions of 15% were recorded at 28 days. The reductions in strength are attributed to poor bond between the plastic and surrounding cement paste, a conclusion supported by the majority of the research in the literature.

Choi et al. [12] heated PET fragments of 5–15 mm in size to create rounded aggregate particles for use in mortar mixes. Replacing all the large aggregate in the mix with the new particles results in reductions in strength of 42% at 28 days. The round shapes of the new PET particles were attributed to improvements in workability of the mixes with replacement materials. Hassani et al. [13] replaced up to 20% of coarse aggregate by volume with PET granules in concrete-asphalt mixes with moderate impact on the material resistance to deformation and creep. Batayneh et al. [14] propose the combined use of ground glass and plastic as replacement materials, and show moderate reductions in strength of up to 13% in a 20% aggregate replacement mix.

In addition to waste plastic, many other materials have been trialled as replacement materials in concrete mixes, including recycled electrical cable rubber [15] waste polystyrene [16,17], and scrap-tire rubber [18,19]. In addition to sand and aggregate alternatives, Gesoglu et al. [20] replace 5–25% of cement by weight with plastic waste powder, however the resulting concrete had, as expected, a linear reduction in strength with increasing cement replacement.

Comprehensive review papers by Siddique et al. [21] and Saikia and de Brito [22] and Sharma and Bansal [23] illustrate many of the variables associated with using plastic as an aggregate replacement, and demonstrate the key finding that as the replacement percentages increase, so the concrete compressive strength reduces. It is therefore a key challenge in this paper to minimise as far as possible this loss in strength in order that a concrete for structural use can be proposed.

2.1. Treatment of particles

A key reason for premature failure of concrete containing waste plastic is the reduced bond between the plastic and surrounding matrix. To improve this bond, chemical or physical treatment of the plastic prior to concrete mixing has been proposed. Naik et al. [24] subjected shredded high-density plastic waste to treatment with (i) 5% Hypochlorite Solution and (ii) 5% Hypochlorite Solution + 4% Sodium Hydroxide in an attempt to improve bonding with the cementitious matrix. It was expected that plastics would not form chemical bonds with cementitious materials, only physical bonds. However, by being treated with oxidising chemicals or treatments the polymer chains would react with the chemicals modifying the surface functional groups. Rather than having fairly stable hydrogen ions bonded to the carbon, hydroxide and oxygen ions would be bonded as well. As these ions are more unstable it is easier for the calcium in the cement matrix to bond with them to create calcium oxides or calcium hydroxide. Hence, a partial chemical bonding between cement and plastic could be possible. It was found that compared to the concrete containing untreated plastic,

both mixes had an increased compressive strength, however, the alkaline bleach was the strongest and therefore the most effective at reducing the loss of compressive strength.

Choi et al. [12] cut waste PET bottles into fractions in the range of 5–15 mm and coated them in ground granulated blast-furnace slag (GGBS) to solidify the surface of the aggregate, aiming to facilitate the reaction of GGBS to form a pozzolanic material, strengthening the interfacial zone between cement paste and aggregate. Using scanning electron microscopy (SEM) it was shown that hydrates densely covered the surface of the plastic aggregate, which indicates the GGBS on the plastic reacted with the calcium hydroxide in the cement to form a chemical bond. It can be seen (Fig. 1) that the percentage loss of strength in the concrete containing the GGBS is considerably smaller than the loss of strength found by other researchers who didn't use GGBS to coat their plastic, even though large sized particles were used. Choi et al. [12] did not test concrete containing untreated plastic aggregate, and so it is not possible to quantify the effect of the GGBS coating.

Fig. 1 summarises the results from Albano [7], Ismail [9], Saikia [6], Choi [12] and Al-Manaseer [5], plotting strength loss (%) against plastic replacement by volume. The spread of the results is explained by the number of variables between each set of tests, including w/c ratio, and the type, size, shape, surface texture and treatment of the plastic.

2.2. Summary

The volumetric substitution of waste plastic for sand in concrete reduces its density and compressive strength, with higher replacement ratios causing greater strength losses. This may arise from a poor bond between the plastic and surrounding matrix, excess water due to the hydrophobic plastic surface causing an increase in voids, or a failure of the plastic in tension. All failure modes in concrete under everyday design situations are a consequence of tensile failure [25] and controlling the tensile strength can be a method to limit losses in compressive strength.

The use of smaller plastic particles appears to minimise the loss of compressive strength in comparison to large particles. However, grading the size of the particles to include some small and some large can be equally effective as more efficient packing of the particles can be achieved. By treating the plastic particles to improve the physical and chemical bonding with the concrete matrix losses in compressive strength can be minimised.

3. Experimental methodology

To identify suitable candidate materials to be used as sand replacement, experimental tests were undertaken on eleven novel concrete mixes with the type of plastic being the only experimental variable. Considering the results in Fig. 1, and balancing the need to substitute a sufficient volume of sand with plastic to see a change while minimising potential strength losses, a constant replacement ratio of 10% by volume was used in all but one of the mixes.

3.1. Mix design

A reference concrete mix (R1) was designed with a 14 day target mean strength of 53 MPa [26], Table 1. The target strength was chosen to give a realistic structural concrete to determine if plastic can be an appropriate sand replacement for such mixes and as such have wider use beyond non-structural concretes. Mixes with plastic replaced 10% by volume of the fine material.

Table 1
Mix designs per m³.

Mix reference	Cement CEM I 42.5R (kg)	Water (kg)	Fine aggregate ¹ (kg)	Coarse aggregate ² (kg)	Plastic (m ³)	Plastic (%)
R1	550	220	780	780	0	0
P1	550	220	702	780	0.047	10

Notes: ¹uncrushed mixed coarse and fine sand graded with percentage finer than 0.6 mm 30% and density of 1.66 g/cm³; ² angular, maximum 10 mm diameter crushed gravel.

3.2. Replacement materials

Five plastics were used as sand replacement, as described in Table 2. Grading curves for PET particles are given in Fig. 2 and compared to the fine sand used in the mix. Ten mixes with plastic (see Table 1) were cast along with the reference mix (R1) without plastic. The description of each mix is given in Table 3. All preparation, mixing and casting was undertaken in accordance with BS EN 12390-2:2009 [27].

3.3. Strength testing

Three 100 mm concrete cubes were tested in compression in accordance with BS EN 12390-3:2009 [28], and three 100 mm diameter concrete cylinders were subject to a split cylinder test following BS EN 12390-6:2009 [29], 14 days after casting of each mix listed in Table 3.

3.4. Scanning electron microscopy

A JEOL SEM6480LV scanning electron microscope (SEM) was used to identify bonding between elements, distribution of plastic, and proportion and sizes of voids. A selection of images were taken, on both fracture surfaces and resin impregnated polished sections. Imaging was undertaken 28 days after casting, and was primarily used to aid qualitative analysis.

4. Results

A summary of strength test results for each mix is provided in Table 4. Fig. 3 summarises the percentage changes in compressive and tensile strength for each mix. Figs. 4 and 5 show the mean strength for each mix in compression and tension, with the range of results indicated by error bars.

Table 2
Plastic types.

Plastic material	Description
PET	Recycled polyethylene terephthalate (PET) bottles, washed and shredded. The plastic is ungraded, with particles ranging from 0.05 to 15 mm in diameter. Fourier transform infrared spectroscopy (FTIR) was used to confirm the type of plastic by sampling a random selection of particles
HDPP	Virgin 3 mm diameter smooth finished spherical high density polypropylene (HDPP) pellets
HDPE	Recycled, high-density polyethylene (HDPE) carrier bags shredded into thin plates of between 5 and 500 mm ² . The material was washed with tap water prior to casting.
PPF	Virgin polypropylene multifilament fibres, 20 mm length, diameter 0.05 mm
PPS	Virgin polypropylene strips, 20 mm long, 3 mm wide, triangular in cross section

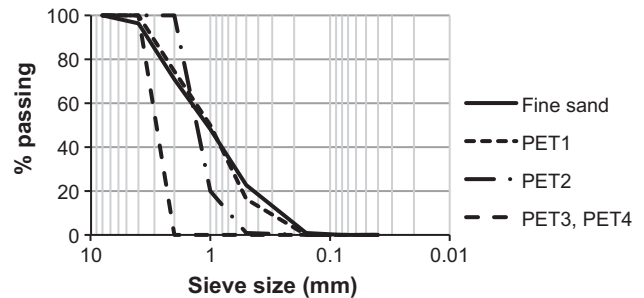


Fig. 2. Particle size distribution of PET fragments and fine sand.

Table 3
Test mixes.

	Mix code	Base mix design	Mix description
1	Ref	R1	Reference mix
2	PET1	P1	PET fragments graded to match the sand replaced
9	PET2	P1	PET fragments between 0.5 and 2 mm in size
8	PET3	P1	PET fragments between 2 and 4 mm in size
7	PET4	P1	PET fragments between 2 and 4 mm in size and treated with sodium hydroxide and sodium hypochlorite
10	PET5	P1	PET fragments between 2 and 4 mm in size and treated with sodium hydroxide and sodium hypochlorite and washed
3	HDPP1	P1	Smooth spherical polypropylene pellets 3 mm diameter
4	HDPE1	P1	Shredded high-density polyethylene carrier bags passing through a 4 mm sieve
6	PPS1	P1	Virgin polypropylene strips (aspect ratio 6.7)
5	PPF1	P1	Virgin polypropylene fibres (aspect ratio 400)
11	PPF2	P1	0.64% substitution of sand with virgin polypropylene fibres

5. Analysis and discussion

The results show that with an appropriate choice of plastic particle size and grading, it is feasible to produce structural grade concrete mixes with 10% sand replacement.

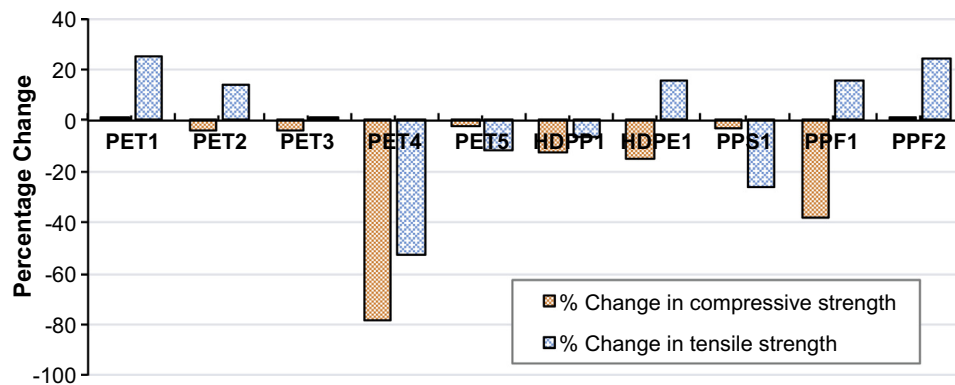
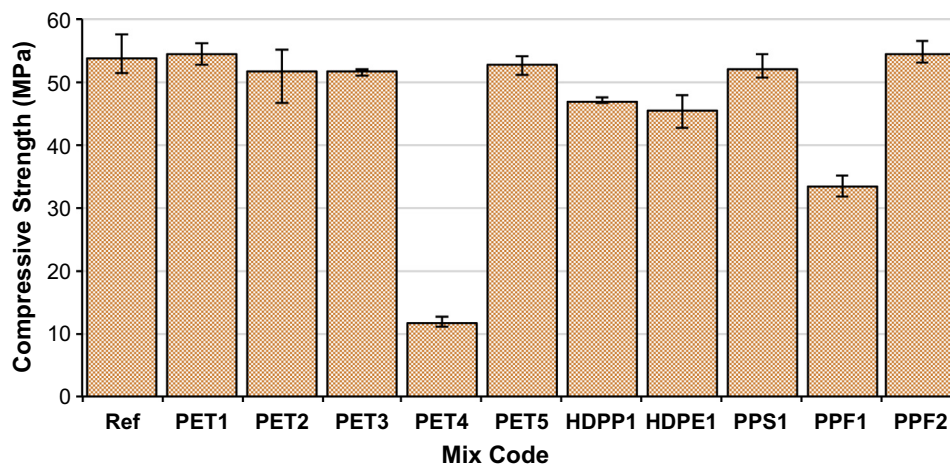
The effect of particle size is seen by comparing results from PET1, PET2, and PET3 (Table 4). The three mixes gave compressive strengths that were very close in value. PET1 containing plastic graded according to the sand it replaced) achieved the best performance + 1.2%). The improved packing in such a situation supports work by Albano et al. [7] and shows that a 10% replacement has a negligible effect on the concrete strength achieved.

PET2 and PET3 mixes achieved almost identical performance in compression, showing that particles up to 4 mm in size could feasibly be used in structural concrete. Mix PET3, with particles up to 4 mm in size, saw a loss of compressive strength of 4.1%, which is less than reported in the literature for other similar mixes. Mix HDPP1 contained particles of a similar maximum dimension as PET3, but with a smooth spherical surface, which resulted in a significantly lower compressive and tensile strength compared to PET3 (Table 4).

Table 4

Summary of test results for tensile and compression testing.

	Mix code ¹	Average Density (kg/m ³)	Average Compressive Strength (N/mm ²)	% Change in Compressive Strength compared to Mix 1	Average Tensile Strength (N/mm ²)	% Change in Tensile Strength compared to Mix 1
1	Ref	2300	53.8	–	3.26	–
2	PET1	2273	54.4	+1.2	4.07	+25.0
9	PET2	2272	51.8	–3.7	3.70	+13.7
8	PET3	2282	51.6	–4.1	3.31	+1.5
7	PET4	1861	11.8	–78.1	1.55	–52.4
10	PET5	2269	52.7	–1.9	2.88	–11.5
3	HDPP1	2244	47.0	–12.5	3.05	–6.3
4	HDPE1	2242	45.6	–15.1	3.77	+15.8
6	PPS1	2266	52.2	–2.9	2.41	–26.0
5	PPF1	2111	33.5	–37.7	3.77	+15.7
11	PPF2	2288	54.5	+1.5	4.04	+24.0

Notes: ¹See Table 3.**Fig. 3.** Percentage change in strength of each mix compared to the reference mix.**Fig. 4.** Mean 14-day compressive strength.

PET1, PET2, and PET3 mixes performed well in tension, with PET 1 achieving a 25% increase in tensile strength when compared to the reference mix. However, the high variability in tensile strength test results must be considered if such results are to be used in design. In all cases, the plastic was debonded from the surrounding matrix at failure, Fig. 6.

Mix HDPE1, which utilises shredded plastic carrier bags, had a 15% lower compressive strength than the reference mix, while the tensile strength was 15% higher. During tensile testing, failure was more gradual compared to both the Reference and PET1 mixes. While high-density polyethylene has a very low ultimate tensile strength compared to either polypropylene or PET, it can elongate

up to 500% before failure [30]. Rather than the brittle failure observed with samples using mix PET1 in HDPE1 samples the plastic was able to yield before a load sufficient to cause debonding was reached. The plastic then continuously deforms until the point of concrete failure.

Mixes PPS1, PPF1, and PPF2 used replacement materials with a much higher aspect ratios than any other plastic used in this study (Table 2). PPF1 saw a 38% loss in compressive strength, but a 16% improvement in tensile strength, compared to the reference mix. The significant drop in compressive strength is attributed to the poor workability of this mix, where the large volume of long fibres became entangled and the resulting concrete was of low density

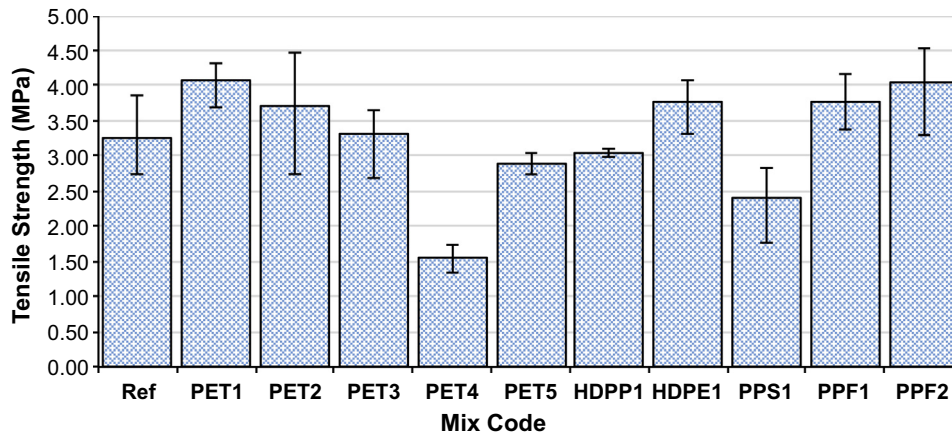


Fig. 5. Mean 14-day tensile strength.



Fig. 6. SEM image of PET3 showing debonding of plastic particle on split cylinder surface.

with significant porosity (Table 4). During tensile testing of PPF1, a gradual failure mode was again noted caused by the presence of the fibres crossing the failure plane. Fig. 7 shows the fibre mixing and air voids in the sample which led to the reduced compressive strength.

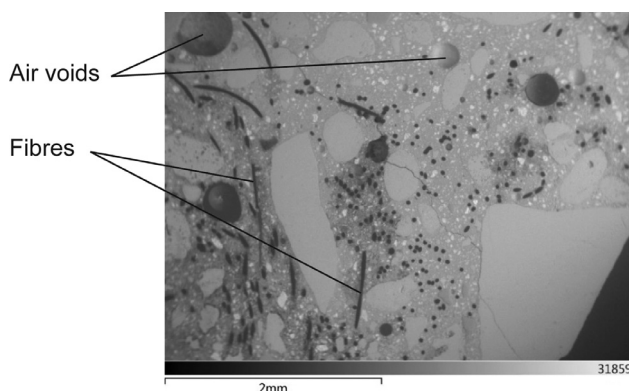


Fig. 7. Fibre dispersal and air voids in mix PPF1.

Mix PPF2 was cast to address the poor workability of PPF1 and was unique in this study in having a replacement percentage of only 0.64%, following the work of Bayasi and Zeng [31]. As seen in Table 4, this improved the performance of the mix, but the small volume of fibres used provides only a small source of sand replacement and these fibres would be difficult to manufacture from recycled plastic.

To try and achieve the tensile strength improvements of PPF1, but maintain the workability of PPF2, a third mix with strips of plastic was tested using 20 mm long, 3 mm diameter plastic strips. The larger volume of these strips reduced the number required, preventing the entanglement seen in PPF1. PPS1 saw a loss of compressive strength of only 2.9% compared to the reference, a considerable improvement on PPF1. However, there was a large decrease in tensile strength of the mix when compared to the reference sample. The 3 mm diameter strips used in PPS1 have a much higher axial stiffness than the thin strips used in PPF1, being much larger in cross section. In PPF1 the strips elongated significantly before failure, whereas in PPS1 they did not reach a yield load and debonded from the matrix causing a sudden failure. The presence of the rather large and triangular strips in PPS1 may also have contributed to this premature failure, as seen in the lower density of this mix compared to the reference (Table 4).

Investigations to assess the effect of chemical surface treatments were undertaken with mixes PET4 and PET5. In mix PET 4, the plastic was treated using common household bleach (sodium hypochlorite) with caustic soda (sodium hydroxide). The plastic was immersed in the solution for one hour, before being drained and dried using heaters so as to not wash off any of the surface solution. The results show that this method was unsuccessful, as PET4 performs very badly in both compression (−78%) and tension (−52%) when compared to the reference mix.

It is proposed that after the plastic was subjected to the chemical solution and dried, compounds originally dissolved precipitated on the surface of the plastic forming crystals. When the plastic was added to the concrete mix these crystals dissolved in the water and decomposed in the high pH environment of the cement forming oxygen. It can be seen in Table 4 that the average density of mix PET4 after 14 days is significantly lower than all other mixes at 1861 kg/m³, due to the large number of voids present in the concrete.

A modified method was utilised in mix PET5, where the plastic was washed first in bleach and sodium hydroxide, and then in water, before being dried. The results show that PET5 achieved a compressive strength only 1.9% lower than the reference mixture, but perhaps more importantly was 2% higher than Mix 8, which used the same, but untreated, plastic. This difference is potentially within the margins for error of both samples and therefore should

be viewed as a neutral result. The use of treatment to the plastic adds a step in the manufacturing process, and should therefore only be used if the improvement in mechanical performance is significant.

The results may further be compared to those reported in the literature (Fig. 1) where reductions in compressive strength of between 10 and 50% are reported at a replacement ratio of 10%. The results here perform well by comparison, with some notable exceptions as outlined above. By careful control of the mix design, strength changes can be carefully controlled, see for example Mix PET1, to ensure that the resulting concrete can be used in a structural context. It should be noted that there is scatter within the test results. Further data from a larger test program is required to fully identify the patterns of behaviour outlined in this pilot study.

6. Conclusions

This paper has demonstrated the potential for using recycled waste plastic in structural concrete mixes. At a replacement ratio of 10% by volume, this has the potential to save 820 millions tonnes of sand every year from being used in concrete mixes [1]. This is equivalent to approximately 5% of total global annual sand consumption. A further benefit is to add value to waste plastic, helping to reduce the volumes sent to landfill in some countries. A reduction in sand demand from the construction industry would further support efforts to limit the effects of sand dredging in countries such as India and China, where significant sand volumes are extracted every year.

It is generally seen that substituting plastic into a concrete mix causes a decrease in compressive and tensile strength due to the poor bond between the plastic and surrounding matrix. Since failure in concrete propagates in tension, the poor bond around plastic particles leads to a reduced compressive and tensile strength. The use of a graded PET plastic matched to the size of the sand particles it replaces, and at a replacement of 10% by volume, gave the most promising overall performance. This material is furthermore cost effective to produce and comes widely available as a waste material in many markets. This paper has shown that simply shredding a PET material is sufficient processing to provide a viable alternative to sand.

Testing different forms of plastic has demonstrated that the most efficient plastic aggregate used in a concrete mix should have a rough surface, be irregular in shape, and be sufficiently small so as to not create a significant failure surface, but also be graded similar to the sand it replaces. The results indicate that through appropriate mix design reductions in strength can be minimised to acceptable levels.

7. Recommendations for Future work

Further investigations are needed before plastic can be considered for widespread use in moderate- to high-strength structural concrete include 1) understanding the underlying bond between matrix and plastic, 2) investigating methods to improve this bond through chemical treatment; 3) investigating replacement percentages beyond 10%, 4) bond with steel reinforcement, 5) alternative cement types, and 6) the effect that plastic has on durability, workability, fire performance, and construction cost.

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