PERFORMANCE OF CONCRETE WITH RECYCLED PLASTIC AS A PARTIAL REPLACEMENT FOR SAND

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ABSTRACT:

Environmental concerns have led to severe restrictions on dredging for sand in much of India, including in the state of Goa, leading to direct impacts on the economics of concrete construction. At the same time, waste plastic is rarely recycled across India, with a large proportion of plastic simply exposed of into landfill presenting further environmental concerns.

This paper describes a study seeking a solution to both problems by utilising processed waste plastic as a partial replacement for fine sand in concrete mixes.

This initial work was supported through project funding from the British Council under the UKIERI (United Kingdom India Educational Research Initiative) programme. The compressive strength and performance of concrete mixes with plastic have been tested, and suggestions for suitable replacement percentages are proposed. Parameters including the size and aspect ratio of the plastic particles replacing the san aggregate and effects of chemical treatment are addressed.

Results show that replacing sand with recycled plastic is viable and by using a suitable mix design the impact on the compressive strength of the concrete mix can be kept at acceptably low levels.

Keywords: Sand replacement; Recycled plastic; Mix design; Performance.

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INTRODUCTION

Cement manufacture in India reached 280Mt 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 2010 put a stop to sand dredging [3] and has led to severe supply problems within much of 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 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 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

PLASTIC AS A REPLACEMENT FOR SAND IN CONCRETE

The majority of the research undertaken to date has studied the changes in concrete physical properties attributable to the addition of plastic waste. Variables such as the plastic replacement ratio, the type, size, shape and surface texture of plastic, the concrete mix design and curing conditions all have the potential to modify the concrete properties when plastic is used as a replacement for sand.

Compressive Strength and Bonding Performance

Initial research on the effects of plastic aggregate substitution on concrete compressive strength was undertaken by Al-Manaseer and Dalal [5]. The effect of an increasing proportion of angular waste plastic particles on cylinder strength for three different w/c ratios was explored. It was found that the compressive strength decreased when the plastic aggregate content increased, with the loss in strength attributed to poor bond characteristics between plastic and cement paste. The plastic was seen to pull out of the sample, rather than to split in tension during compressive testing.

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

Albano *et al* [7] tested different sized PET particles for two different w/c ratios over a range of plastic replacement quantities. The PET particles used in the mixes were irregularly shaped, and were all between 2.6mm and 11.4mm in size. 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 all large plastic particles were substantially weaker compared to mixes containing smaller particles. Formation of a honeycomb of cavities and pores was observed and attributed to the low workability affecting the compaction of the concrete.

As the fine aggregate that is used for concrete is normally graded Frigione [8] decided to use granulated PET that was graded very similarly to the siliceous sand that was to be replaced in the mix. It was found that the compressive strength decreased, however, the reduction in compressive strength was only in the order of 0.5 to 2%, when a replacement ratio of 5% was used. However, this is still favourable compared to the 12% loss seen by Saikia and de Brito [6] when 5% sand was replaced with plastic pellets. This indicates that although the use of plastic will cause a decrease in compressive strength because of a poorer bond to the cement compared to the sand, the loss can be limited by appropriate mix design and choice of plastic.

Another possible reason for a lower compressive strength being achieved when plastic is introduced was provided by Ismail and Al-Hashmi [9], when concrete containing a mixture of PET and polystyrene was tested. They explained that the trend can not only be attributed to the decrease in adhesive strength between the surface of the waste plastic and the cement paste, but also because plastic is considered to be a hydrophobic material. Therefore movement of the water required for hydration through the concrete is hindered leaving isolated volumes of unhydrated cement.

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. Coarser plastic aggregate exhibited lower performance, followed by fine particles and then the smooth pellets. The loss of tensile strength was attributed to the characteristics of the plastic, primarily its smooth surface, but also the presence of free water at the plastic surface causing a weak bond to the cement. Microscopic studies of failed specimens revealed that the most common form of failure was de-bonding at the plastic – concrete interface.

Albano *et al* [7] also found that the behaviour under tension was similar to that under compression, and the loss was attributed to the same reasons. It was found that the introduction of waste PET reduced the tensile strength of the concrete, and then when higher proportions were added there was a significant drop due to number of voids present in the concrete. It was therefore noted that when a 50/50 mix of small and large plastic particles were used, a higher tensile strength was recorded compared to when either just small or just large particles were used. Frigione [8] also observed a loss of tensile strength when granulated PET particles were used, and once again, only a very minimal loss in the range of 2% was observed. It was concluded that the loss of compressive strength could be correlated to the loss of tensile strength.

Treatment of Particles

To improve the bond between plastic particles and surrounding matrix, chemical or physical treatment of the plastic prior to concrete mixing has been proposed. Naik *et al* [10] 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 stated that in general plastics do 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.

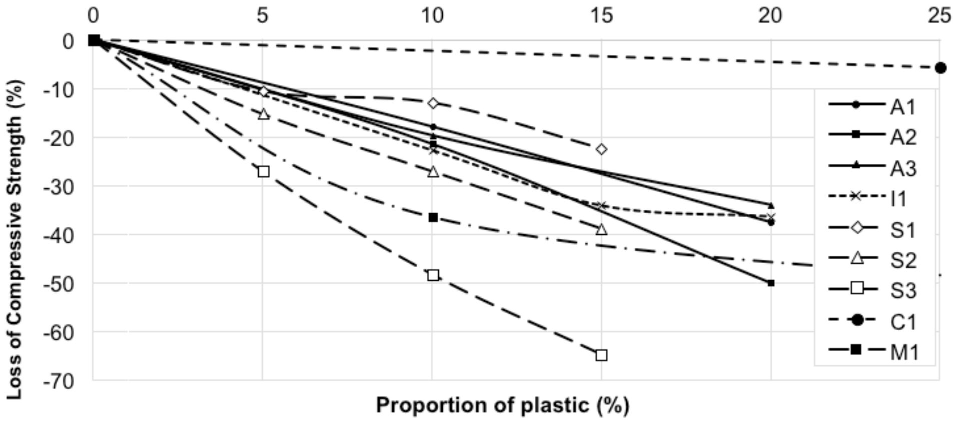
Choi *et al* [11] cut waste PET bottles into fractions in the range of 5-15mm and coated them in ground granulated blast-furnace slag (GGBS) to solidify the surface of the aggregate. This aimed to facilitate the reaction of GGBS to form a pozzolanic material, strengthening the interfacial zone between cement paste and aggregate. It would also improve the workability, the resistance to chemical attack and reduce the heat of hydration. By using a SEM it was shown that hydrates densely covered the surface of the plastic aggregate, which indicates the GGBS on the plastic does react with the calcium hydroxide in the cement to form a chemical bond. It can be seen 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. However, no tests were done by Choi et al. (2005) on concrete containing plastic aggregate that had not been treated, and so it is not possible to make a direct comparison of the effect that the GGBS had. However, it can probably be assumed the addition of the GGBS improves the bonding between the plastic and cement and hence increases the achievable compressive strength.

Summary

The substitution of waste plastic for sand in a concrete mix reduces the compressive strength, and the higher the plastic replacement ratio the greater the loss of strength. The loss of strength is either due to a loss of bonding between the plastic aggregate and the cement paste, the presence of excess water in the mix and hence an increase in voids, or a failure of the plastic. The use of smaller plastic particles reduces 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 before they are added to the concrete stronger bonding between the plastic and cement can be achieved, and hence the loss in compressive strength can be minimised. This treatment can include changing the physical and chemical properties of the surface. The performance of concrete in compression is intrinsically linked to its performance in tension [12] and so if one concrete mix has a lower tensile strength than another, it is likely that it will also have a lower compressive strength. This relationship appears true when plastic is included in the mix.

Figure 1 shows a combination of the compressive strength results obtained by each of the pieces of research studied in the literature review. As they all had different mix designs, the compressive strength of the reference concretes were all different. For this reason the proportion of plastic has been plotted against strength loss. The spread of results is attributed to the number of variables, and hence differences there are between the mixes. These include the w/c ratio, and the type, size, shape, surface texture and treatment of the plastic. To balance substituting significant volumes of sand with plastic , while not having a considerable loss of compressive strength, this research will use a replacement ratio of 10%.



References

A1, A2, A3	[7]
I1	[9]
S1, S2, S3	[6]
C1	[11]
M1	[5]

Figure 1: The relationship between plastic replacement and loss in compressive strength in different pieces of literature

TEST METHODOLOGY

This experimental research compares different forms of plastic, and attempts to identify the optimum form or shape that provides the most efficient performance in terms of strength. A number of different mixes will be made, each containing a different plastic sample as the only changing variable, and then tested for both compressive and tensile strength.

Characterisation of materials

A total of 5 different plastics were used in the test regime, referenced in Table 2 and described below:

1. Recycled polyethylene terephthalate (PET) drinks bottles, washed, shredded and blended. The plastic is ungraded, with particles ranging from 15mm to 0.05mm in diameter. Fourier transform infrared spectroscopy (FTIR) was used to confirm the type of plastic by sampling a random selection of particles;
2. Virgin 3mm diameter smooth finished spherical high density polypropylene (PP) pellets;
3. Recycled, high-density polyethylene (HDPE) carrier bags shredded into plates between 500mm^2 and 5mm^2;
4. Virgin polypropylene multifilament fibres, 20mm length, diameter 0.05mm;
5. Virgin polypropylene strips, 20mm long, 3mm wide, triangular in cross section.

Mix Design

A concrete mix was designed according to [13]. Coarse Aggregate was angular, maximum 10mm diameter crushed gravel; Fine Aggregate was uncrushed, mixed coarse and fine sand, graded, percentage finer than 0.6mm was 30% and density was 1.66g/cm^3. For the concrete with plastic, 10% by volume of the fine sand in the reference mix was replaced with plastic materials, as shown in Table 1 (10% by volume of sand in this case is 0.047m^3).

Table 1: Mix designs per m^3

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

Ten mixes with plastic were used, with a replacement volume of $0.047m^3$. One reference mix (R1) was cast. The description of each mix is given in Table 2. All preparation, mixing and casting was undertaken in accordance with BS EN 12390-2:2009 [14].

Table 2: Mix descriptions

Mix Number	Base mix design	Plastic type	Mix description
1	R1	NA	None – Reference mix
2	P1	1	PET bottle fragments graded to match the sand replaced
3	P1	2	Smooth spherical pellets uniform in size and shape
4	P1	3	Shredded carrier bags passing through a 4mm sieve
5	P1	4	Virgin polypropylene fibres (aspect ratio 400)
6	P1	5	Plastic strips (aspect ratio 6.7)
7	P1	1	PET bottle fragments between 2 and 4mm in size and treated with sodium hydroxide and sodium hypochlorite
8	P1	1	PET bottle fragments between 2 and 4mm in size
9	P1	1	PET bottle fragments between 0.5 and 2mm in size
10	P1	1	PET bottle fragments between 2 and 4mm in size and treated with sodium hydroxide and sodium hypochlorite and washed
11	P1	4	0.64% substitution of sand with virgin polypropylene fibres

Testing

Three 100mm concrete cubes were tested 14 days after casting in compression for each mix listed in Table 2. Compressive testing was performed in accordance with BS EN 12390-3:2009 [15]. Three 100mm diameter concrete cylinders for each mix listed in Table 2 were tested in a split cylinder following BS EN 12390-6:2009 [16] 14 days after casting.

RESULTS, ANALYSIS AND DISCUSSION

A summary of test results for each mix is provided in Table 3, with each mix being described in detail in Table 2. Figure 2 summarises the percentage changes in compressive and tensile strength for each mix. Figure 3 and Figure 4 show the mean average strength for each concrete mix in either compression or tension. The range of results obtained from the samples tested can be seen by the error bars, which show the highest and lowest recorded results.

Table 3: Summary of test results for tensile and compression testing

Mix No.	Average Density (kg/m3)	Average Compressive Strength (N/mm2)	% Change in Compressive Strength	Average Tensile Strength (N/mm2)	% Change in Tensile Strength
1	2300	53.8	-	3.26	-
2	2273	54.4	+1.2	4.07	+25.0
3	2244	47.0	-12.5	3.05	-6.3
4	2242	45.6	-15.1	3.77	+15.8
5	2111	33.5	-37.7	3.77	+15.7
6	2266	52.2	-2.9	2.41	-26.0
7	1861	11.8	-78.1	1.55	-52.4

Mix No.	Average Density (kg/m3)	Average Compressive Strength (N/mm2)	% Change in Compressive Strength	Average Tensile Strength (N/mm2)	% Change in Tensile Strength
8	2282	51.6	-4.1	3.31	+1.5
9	2272	51.8	-3.7	3.70	+13.7
10	2269	52.7	-1.9	2.88	-11.5
11	2288	54.5	+1.5	4.04	+24.0

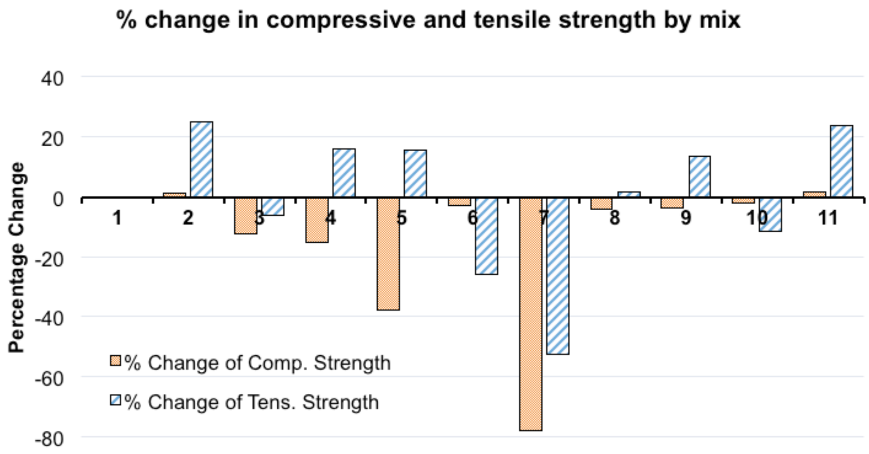


Figure 2: Percentage change in strength of each mix compared to the reference mix

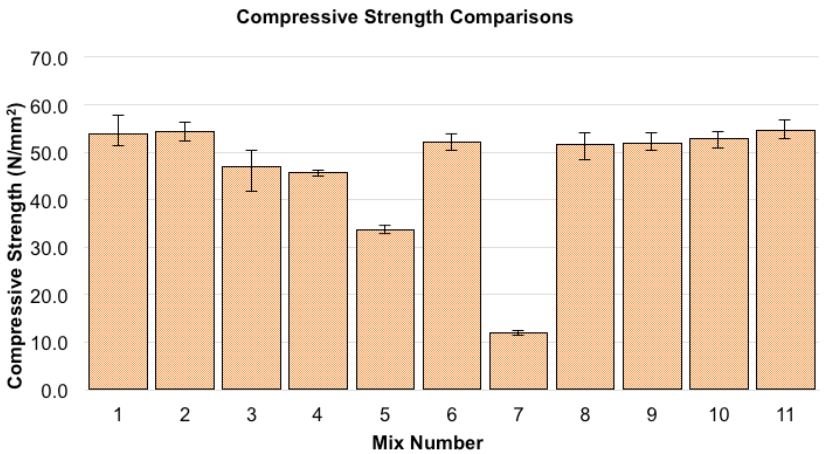


Figure 3: Comparison between the average compressive strength achieved with each mix after 14 days

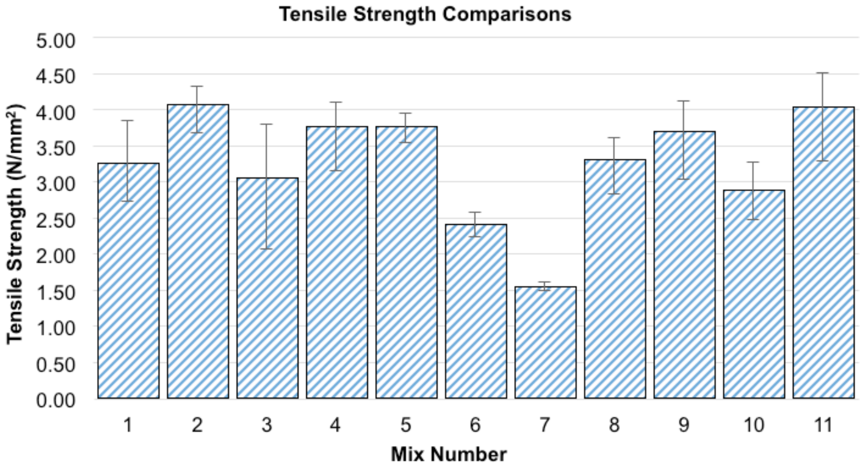


Figure 4: Comparison of the average tensile strength achieved with each mix after 14 days

Mixtures containing PET bottle fragments (Mixes 2, 8, and 9)

Mix numbers 2, 8 and 9 had different plastic size distributions (Table 2). The three mixes gave compressive strengths that were very close in value (Table 3). Mix 2, 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 negligible effect on the concrete strength achieved. Mixes 8 and 9 achieved almost identical performance in compression, showing that particles up to 4mm in size can feasibly be used as replacement aggregates. The loss in compressive strength shown by Mix 8 (4.1%) is less than that reported seen in the literature for similar sized particles. All mixes performed well in tension, with Mix 2 achieving a 25% increase, proving the addition of this type of plastic improves the tensile properties of the concrete. This may also explain why the concrete achieved better compression results than expected.

Mix containing spherical 3mm diameter pellets (Mix 3)

Mix 3 contained smooth spherical pellets, whereas the plastic used in Mix 8 was approximately the same size but had a more irregular surface geometry. It can be seen that Mix 3 achieves a significantly lower compressive strength than Mix 8, and the same trend is seen for tensile strength. These results confirm that a smoother surface and more regular shape of plastic aggregate create a weaker bond between the cement and plastic. The weaker the bond between the particles and cement, the lower the strength of the concrete.

Mixture containing shredded plastic bags (Mix 4)

Mix 4, which utilises shredded plastic carrier bags, had a 15% lower compressive strength than the reference mix, whilst the tensile strength was 15% higher. During tensile testing, failure was more gradual compared to Mixes 1 or 2. HDPE, which the carrier bags are made from, has a very low ultimate tensile strength compared to either PP or PET, however, it can elongate up to 500% before failing completely, compared to around 100% for the other two types of plastic used. Therefore, rather than the sudden failure observed with samples from Mix 2, where at a particular load the bond between particles and cement fails, in this mix the plastic reaches its yield point before a load sufficient enough to cause de-bonding is reached. The plastic then continuously deforms until the point of fracture. Hence, this concrete had a different failure mechanism to previous mixes, as the plastic failed rather than its bonding.

Mixtures containing plastic fibres and strips (Mixes 5, 6, and 11)

Mixes 5, 6, and 11 used plastic strips with a higher aspect ratio than in other mixes (Table 2). The fibres used in Mix 5 resulted in a 38% loss in compressive strength, but a 16% improvement in tensile strength. The large drop in compressive strength is attributed to the large volume of the fibres used, which made the mix unworkable and resulted in numerous voids. During tensile testing, a gradual failure mode was again noted caused by the presence of the fibres crossing the failure plane. The high drop in compressive strength led to a new mix design, Mix 11, which used the same fibres as Mix 5 but in a reduced replacement quantity of just 0.64%, following the work of Bayasi and Zeng [17]. As seen in Table 3, this improved the performance of the mix, but the small volume of fibres used represents only a very small reduction in sand use, negating the aim of the research. These fibres would also be difficult to manufacture from recycled plastic. Mix 6 used 3mm diameter plastic strips in an attempt to mimic the same tensile strength improvements that the fibres had, while being of a size that shouldn't reduce workability as much. Mix 6 saw a loss of compressive strength of only 2.9% compared to the reference, a considerable improvement on Mix 5. However, there was a large decrease in tensile strength between the fibres and the strips.

Mixture containing PET bottle fragments treated with chemicals (Mixes 7 and 10)

Mix 7 used the same plastic as Mix 8 (Table 2) but was undertaken to investigate methods to improve bond between PET bottle fragments and the cement matrix through the use of chemical treatment. The PET in Mix 7 was treated with a solution of sodium hydroxide and sodium hypochlorite before being dried. However, it can be seen in Table 3 that it performs very badly in both compression (-78%) and tension (-52%) when compared to the reference concrete. It is proposed that after the plastic was subjected to the chemical solution and dried, excess solution on the surface of the plastic crystallised. When the plastic was added to the concrete mix these crystals reacted with the water and cement to produce oxygen bubbles. It can be seen in Table 3 that the average density of Mix 7 after 14 days is significantly lower than all other mixes, due to the large number of voids present in the concrete. A modified method (Mix 10) of chemical washing was then utilised, in which the plastic was washed first in bleach and sodium hydroxide, and then in water, before being dried. The results show that Mix 10 achieved a compressive strength only 1.9% lower than the reference mixture, but perhaps more importantly 2.1% higher than Mix 8, which used the same, but untreated, plastic.

CONCLUSIONS

This research was undertaken to explore the potential for using recycled waste plastic in a concrete mix. If this could work on a commercial level then vast quantities of waste plastic could be used in situations where recycling is not yet practical, rather than being disposed of in landfill. This would reduce sand demand from the construction industry, and as a result provide environmental benefits through a reduction in sand dredging. It is generally seen that substituting plastic into a concrete mix causes a decrease in compressive and tensile strength due to a reduction in bond strength between the plastic and cement. This paper has investigated several ways in which this loss of strength could be limited, including size, shape, grading, and treatment of the plastic. 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.

A reduction in strength when plastic is added to a concrete mix is generally due either to the de-bonding of the plastic from the cement matrix, or a failure of the plastic itself. This failure mode is dependent on the shape, type and texture of the plastic. High aspect ratio fibres perform well, but are more difficult to produce from waste material. Random cut or fragmented particles are more likely to fail by de-bonding from the surrounding matrix and large plate like particles introduce failure planes. The performance of concrete with partial replacement of sand using plastic could also be improved through chemical treatment of the plastic aggregate to promote the formation of chemical bonding with the cement. An improved bond will mitigate against failure by premature de-bonding, and as a result lead to an increase in compressive strength of the concrete.

By testing different forms of plastic, it has been easy to see 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. Concrete strength can also potentially be further enhanced by the treatment of the plastic to improve the bond to the cement. The results strongly indicate that no significant reduction in strength will occur (Table 3) and small increases in strength can be achieved.

RECOMMENDATIONS FOR FUTURE WORK

Further investigations are needed before plastic can be considered for use in structural concrete on a commercial level. More investigation is required to understand the bond performance with the plastic, the potential for higher replacement percentages beyond 10%, effect on bonding with steel reinforcement, different mix designs and cement types, and the effect that plastic has on durability, workability, fire performance, and construction cost.

Acknowledgements

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