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Surface Modified Synthetic Plastic Aggregate for Concrete – Experimental and Analytical Studies

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To reduce the plastic waste accumulation, and also to decrease the consumption volume of natural resources for concrete production, in this paper, an attempt is made to produce novel lightweight coarse aggregate using Polyethylene Terephthalate (PET) based plastic waste. The aggregates were manufactured manually by processing the PET waste that included cleaning, shredding, melting and moulding. The use of plastic aggregate normally reduces the strength of concrete primarily due to smoother surface and poor bonding with adjacent cement matrix. Towards improving the bonding characteristics with cement matrix, different surface treatment procedures employing dispersion of sand and ceramic waste particles were tried. The experimental study consisted of using different percentages of plastic aggregate as a partial replacement for conventional coarse aggregate. The mechanical properties of concrete such as workability, density, compressive strength and flexural-tensile strength were determined. Correlations studies to predict the concrete strength based on a percentage of replacement, and equations relating compressive and flexural-tensile strengths of the concrete were also conducted. The studies indicated that it is possible to improve the bonding property of plastic aggregate for achieving strength and integrity similar to that of control concrete.

Keywords: recycling, plastic waste, PET, aggregate, concrete.

1. INTRODUCTION

Concrete is considered to be one of the most used materials in the World, next to the water. In the context of mostly used materials, plastic also proves itself to be dominant in the market. Both concrete and plastic can be moulded into different shapes. Besides several advantages, the usage of these two materials has adverse effects on the environment. Concrete requires huge volumes of natural resources for obtaining raw materials and causes degradation of natural resources. Whereas, the use of plastic generates huge volumes of non-degradable wastes. Industrial by-products such as fly ash, blast furnace slag, etc. can be used as replacements for cement and aggregates. Results of several research studies that investigated the use of alternate materials in concrete production have been conducted and are available in the public domain. For disposing the plastic wastes, there are only a few options left, and they are (i) incineration, (ii) segregation and dumping on vacant lands, and (iii) recycling. Incineration releases huge volumes of toxic gases into the atmosphere and causes threats to living things. Dumping on vacant lands again leads to environmental degradation. The last available option is recycling, which can be considered a viable one.

Centre for Science and Environment has reported [1] that India is generating nearly 9200 metric tonnes of plastic waste per day, and out of the total plastic waste generated, only 9 % is recycled [1]. A typical picture of plastic waste dumped in a compost yard is shown in Fig. 1. Researchers [2, 3] have developed plastic aggregates for replacing conventional aggregates in concrete production. Alqahtani and Zafar [4] proposed lightweight aggregate by combining plastic waste and other local materials. Shredding, granulating and powdering were employed in the study. Test results showed that the addition of plastic aggregate improved the thermal conductivity of concrete. Coppola et al. [5] proposed polymeric aggregate for replacing sand. The results showed that the interfacial transition zone (ITZ) was similar to that present in conventional concrete. More roughness of plastic aggregate surface improved the interlocking mechanisms with the adjoining cement matrix.

Fig. 1. Disposed plastic waste in compost yard

The use of plastic aggregates decreased the pores [6]. Choi et al. [7] proposed PET aggregates coated with slag. The authors [8] also have proposed aggregates produced using PET waste coated with river sand. Studies by Castillo et al. [9] showed that lightweight concrete with strength up to 20 MPa can be achieved. Haghighatnejad et al. [10]

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studied the influence of curing condition on strength of concrete containing plastic aggregate. Senhadji et al. [11] observed that strength of concrete with plastic aggregates can be improved by using higher strength of cement. Kou et al. [12] proposed concrete with clay aggregate and plastic aggregate. Internal bleed water around the plastic aggregates decreased the strength of concrete. Górak et al. [13] proposed plastic aggregates similar to Choi et al. [7] with modified surface characteristics. Sabau and Vargas [14] have used 40 – 60 % of e-plastic waste in concrete and observed that the use of e-plastic waste decreased the strength. Ashok et al. [15] conducted research on activated recycled plastic waste aggregate in concrete.

Some of the favourable results of using plastic aggregates in concrete as reported in the literature are lower density, increased ductility, lower drying shrinkage, higher resistance to chloride ion penetration, increased workability, decreased thermal conductivity, better abrasion resistance and high durability (in terms of water absorption and chloride permeability). Some of the negative effects of using plastic aggregates are decreased strength and increased drying shrinkage. A critical review of the literature indicated that many studies used scrapped/grounded plastic wares in concrete. Synthetic aggregates by using plastic wastes are found to be very limited. Some available studies that used synthetic plastic aggregates are reported by Alqahtani and Zafar [4], Coppola et al. [5] and Castillo et al. [9]. Only a very few researchers have tried modifying the surface conditions of plastic aggregate for achieving better bonding properties with the adjoining cement matrix. In this paper, an attempt has been made to produce plastic aggregate from PET waste. The surface characteristic of plastic aggregate was modified by the addition of sand or ceramic particles during the production process. This was done to improve the bonding properties with the cement matrix. The compressive strength of the produced plastic aggregate was determined. The produced plastic aggregate was used in concrete specimens for determining their mechanical properties. In this paper, experiments were conducted to determine the workability, compressive strength, flexural tensile strength and ultrasonic pulse velocity (UPV) of the concrete specimens containing the proposed PET-based aggregate. Correlation studies were also made to determine the relationship between the compressive strength and the percentage of replacement.

2. EXPERIMENTAL DETAILS

The experimental study consisted of the production of plastic aggregate from PET wastes and, the casting and testing of concrete specimens. Different percentages (10 %, 20 % and 30 %) of the proposed plastic aggregate were used as replacements for coarse aggregate. The workability of concrete was determined using the slump cone test as per IS-1199 [16]. Compressive strength and flexural strength of the concrete specimens were determined as per IS-516 [17] after a curing period of 28 days by immersion in water. The compressive strength of concrete was determined on 100mm cube specimens and flexural strength on 500 × 100 × 100 mm prism specimens.

2.1. Manufacturing of plastic aggregates

The production of plastic aggregate involved the collection of PET waste, cleaning, shredding, melting and moulding. The flow chart given in Fig. 2 shows the production process. All three types of plastic aggregates are shown in Fig. 3. Aggregate P consisted of only plastic, aggregate PS consisted of plastic and sand particles, and aggregate PC consisted of plastic and ceramic particles.

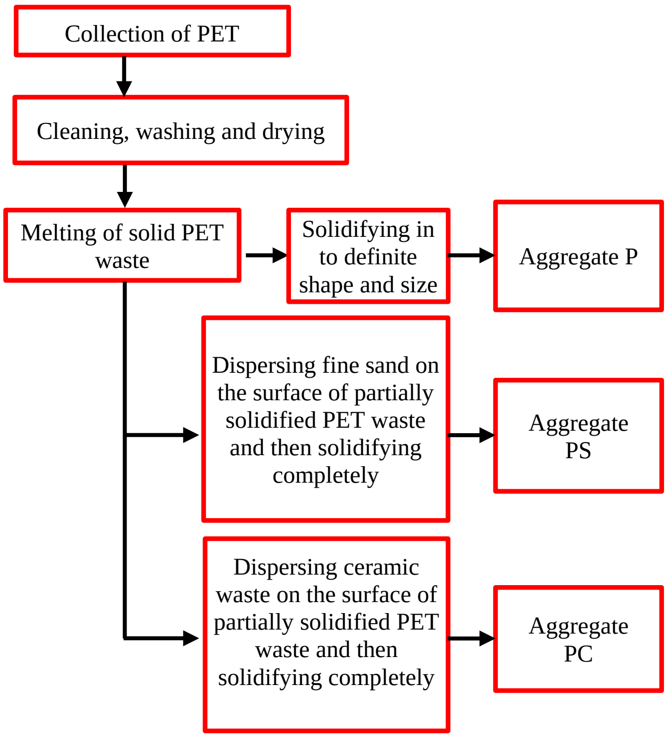

Fig. 2. Flowchart showing the production process of plastic aggregates

Fig. 3. Picture of proposed plastic aggregates

2.2. Properties of plastic aggregates

The specific gravity of the produced plastic aggregates was determined as per ASTM D792[18], and was determined to be 0.889, 0.895 and 1.157 for aggregates P, PS and PC. Particle size distribution of the aggregates was determined as per IS-2386 (Part 3) [19]. In IS-2386, two different types of coarse aggregates have been defined, and they are (i) single-sized aggregate, and (ii) graded aggregate. Sieve analysis of the proposed plastic aggregates was conducted and the results are given in Table 1.

Table 1 indicated that the proposed plastic aggregate satisfied the single-sized aggregate specifications.

Table 1. Particle size distribution

Sl. No.	IS Sieve mesh size, mm	Percentage passing			
		P	PS	PC	Control
1	20	100.0	100.0	100.0	100.00
2	16	2.93	2.86	8.28	73.00
3	12.5	0.15	2.20	7.96	32.00
4	10	0.03	1.96	7.76	5.00
5	4.75	0.00	1.96	4.36	0.00
6	Pan	0.00	0.00	0.00	0.00

The compressive strength of the proposed plastic aggregate ‘P’ was determined by testing individual aggregate particle. Two ends of the plastic aggregate particle were cut to produce an even and horizontal surface for enabling uniform loading and stability of the specimen during testing. The picture of plastic aggregate particles used for compression testing is shown in Fig. 4.

Fig. 4. Plastic aggregate particle for compression testing

The compression testing was conducted in a Compression Testing Machine (CTM) of 1000 kN capacity. The loading rate was kept as 0.5 kN/sec. The picture of tested specimens is shown in Fig. 5. During testing, it was observed that the plastic aggregate particle did not fail by crushing (Fig. 5). The plastic aggregate continued to deform as the compressive loading was increased. The loading was stopped as soon as the applied loading reached 10 kN. The test results are given in Table 2. It was observed from Table 2 that the plastic aggregate particle resisted a maximum compressive stress of about 28 MPa.

Fig. 5. Tested plastic aggregate particle under compression

DSC analysis was conducted on the plastic aggregate, and it was found that the softening point, melting point and boiling point of the plastic were 120.82 °C, 252.29 °C and 379.95 °C respectively.

2.3. Details of specimens cast and tested

M20 grade concrete was considered for casting the specimens. The mix proportion for concrete was arrived based on IS-10262 [20]. Ordinary Portland Cement of 43 grade was used. River sand was used as fine aggregate. Gravel was used as conventional coarse aggregate. The water-cement ratio of all the mixes was fixed at 0.5. The mix proportions of the specimens considered are given in Table 3. The proposed plastic aggregates were used to replace 10, 20 and 30 % (by volume) of conventional coarse aggregate. Pictures of coarse aggregate replaced and the corresponding plastic aggregate (P) used as replacement and their mass (in gm) are shown in Fig. 6 for comparison.

Table 2. Plastic aggregate particle tested under compression

Sl. No.	Sample No.	Weight, g	Cross-sectional area (approx.), mm^2	Maximum load applied, kN	Maximum stress applied (approx.), MPa	Length before testing, mm	Length after testing, mm	Percentage of axial deformation, %
1	P-1	10.0	351.83	10	28.4	32	20	62.5
2	P-2	9.6	353.43	10	28.3	34	21	61.7
3	P-3	9.9	365.21	10	27.4	31	19	61.3

Table 3. Mix proportions of specimens

Sl. No.	Mix ID	Cement, kg/m^3	Fine aggregate, kg/m^3	Coarse aggregate, kg/m^3	Replacement, vol%	Remarks
1	Control	383	574.5	1149.0	0	Conventional coarse aggregate
2	P-10			1120.3	10	Plastic aggregate based on PET waste (P)
3	P-20			1091.6	20	
4	P-30			1062.8	30	
5	PS-10			1120.3	10	Plastic aggregate based on PET waste containing river sand on their surface for improving bonding properties (PS)
6	PS-20			1091.6	20	
7	PS-30			1062.8	30	
8	PC-10			1120.3	10	Plastic aggregate based on PET waste containing ceramic waste on their surface for improving bonding properties (PC)
9	PC-20			1091.6	20	
10	PC-30			1062.8	30	

Fig. 6. Coarse aggregate replaced and the plastic aggregate used as a replacement

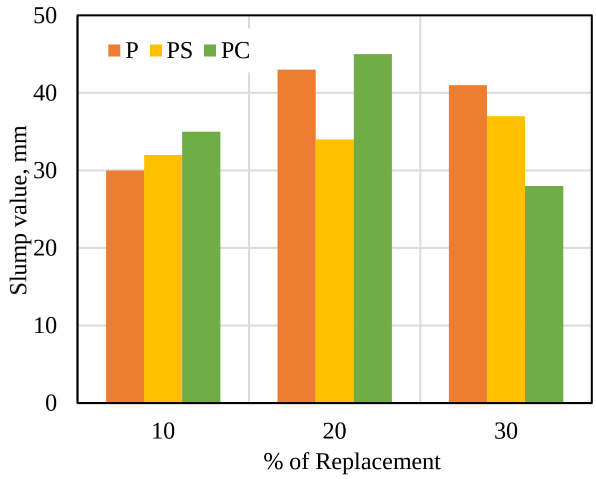

Fig. 7. Slump value of different concrete mixes

3. RESULTS AND DISCUSSION

3.1. Workability

The results of slump cone tests are shown in Fig. 7. The test results indicated that the workability of concrete increased with the addition of plastic aggregate P, PS and PC as compared to control concrete. The slump value of control concrete was 26 mm. For all the plastic aggregates (P, PS and PC) considered, the workability increased with an increase in the replacement content by up to 20 %. As the replacement percentage was increased from 20 % to 30 %, the workability of concrete mix with plastic aggregate 'P' and 'PS' did not show appreciable change and the behaviour was similar to that of the concrete mix containing 20 %. However, the test results showed that, for the concrete mix containing plastic aggregate 'PC', the workability decreased as the replacement percentage was increased from 20 % to 30 %. An increase in the workability of concrete (as compared to the control mix) due to the addition of plastic aggregate (up to 20 %) can be attributed to the following major reasons: (i) smoother surface of plastic aggregate as compared conventional coarse aggregate, and (ii) hydrophobic nature of plastic aggregate particles causing increased free water availability. The decreased workability of the mix containing 30 % of plastic aggregate 'PC' was attributed due to the 'interlocking' action provided by the protruding ceramic waste particles with the mortar.

3.2. Compressive strength

The results of compressive strength tests are given in Table 4. The average compressive strength of three cube specimens is given in Table 4. The compressive strength variation is shown graphically in Fig. 8. Test results showed that the replacement of conventional coarse aggregate with the proposed plastic aggregate influenced the compressive strength of the concrete. Each type of plastic aggregate produced different effects on the compressive strength of concrete. In general, it was observed that, the replacement of conventional coarse aggregate with plastic aggregates (P, PS and PC) decreased the compressive strength of concrete. Also, test results showed that the increase in the percentage of replacement decreased the compressive strength of concrete. The compressive strength of concrete with plastic aggregate 'P' was 15 %, 20 % and 28 % less than that of control concrete for 10 %, 20 % and 30 % replacement levels, respectively.

The compressive strength of concrete with plastic aggregate 'PS' was 8 %, 14 % and 20 % less than that of control concrete for 10 %, 20 % and 30 % replacement levels, respectively. The compressive strength of concrete with plastic aggregate 'PC' was 31 %, 39 % and 50 % less than that of control concrete for 10 %, 20 % and 30 % replacement levels respectively. A decrease in the compressive strength of concrete with the usage of plastic aggregate 'P' could be attributed due to poor bonding characteristics with the adjoining cement matrix and the hydrophobic nature of plastic aggregate [4, 10].

Table 4. Compressive strength of specimens

Sl. No.	Mix ID	Compressive strength, MPa	Flexural strength, MPa	Compressive strength ratio	Flexural strength ratio
1	Control	30.7	2.80	1.00	1.00
2	P-10	26.2	2.40	0.85	0.86
3	P-20	24.5	2.35	0.80	0.84
4	P-30	22.1	2.29	0.72	0.82
5	PS-10	28.2	2.52	0.92	0.90
6	PS-20	26.5	2.43	0.86	0.87
7	PS-30	24.6	2.38	0.80	0.85
8	PC-10	21.2	2.18	0.69	0.78
9	PC-20	18.6	1.98	0.61	0.71
10	PC-30	15.2	1.62	0.50	0.58

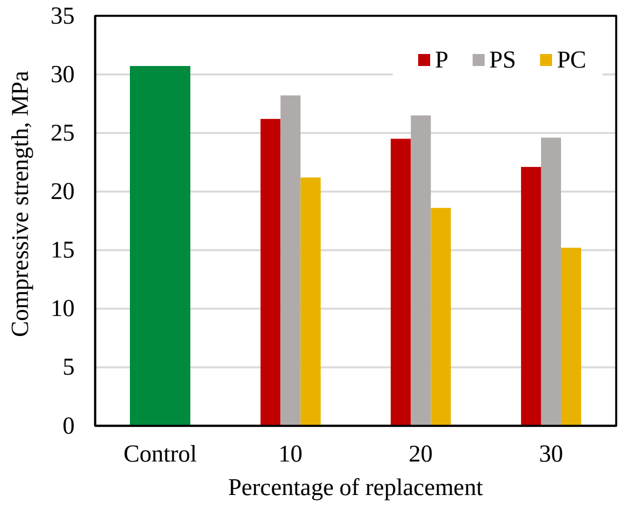

Fig. 8. Compressive strength variation

As compared to the performance of plastic aggregate 'P', the plastic aggregate 'PS' behaved better due to improved bonding characteristics due to the presence of sand particles on their surface. However, when compared to the use of plastic aggregate 'P' and 'PS', test results showed that the compressive strength of concrete was adversely affected when the plastic aggregate 'PC' was used. This could be due to the following reasons: (i) the ceramic waste particles that were bonded to the plastic aggregate could not ensure good bonding characteristic with the adjoining cement matrix, and (ii) as the compressive load is applied, the ceramic waste particles partially or completely lost its bond with the plastic aggregate and decreased the strength of concrete. These observations indicated that plastic aggregate 'PS' performed better as compared to the other two plastic aggregates 'P' and 'PC'.

3.3. Flexural tensile strength

The average flexural-tensile strength of the concrete specimens tested is shown graphically in Fig. 9. Comparison of Fig. 8 and Fig. 9 indicated that the variation of flexural tensile strength of the concrete mixes followed a similar trend as that of compressive strength.

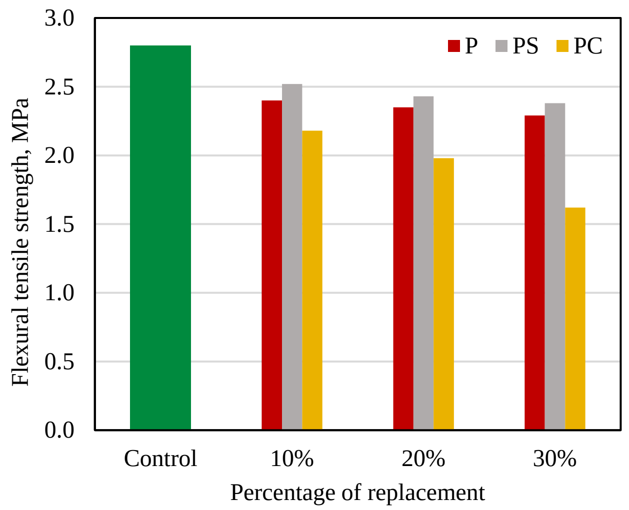

Fig. 9. Flexural strength variation

The flexural tensile strength of concrete containing plastic aggregate was found to be less than that of control concrete. The flexural tensile strength of concrete with plastic aggregate 'P' was 14 %, 16 % and 18 % less than that of control concrete for the replacement levels 10 %, 20 % and 30 %, respectively. The flexural tensile strength of concrete with plastic aggregate 'PS' was 10 %, 13 % and 15 % less than that of control concrete for the replacement levels 10 %, 20 % and 30 %, respectively.

The flexural tensile strength of control concrete with plastic aggregate 'PC' was 22 %, 29 % and 42 % less than that of control concrete for the replacement levels 10 %, 20 % and 30 %, respectively. The flexural tensile strength of concrete mixes with plastic aggregate 'PC' was significantly lower than that of concrete containing plastic aggregates 'P' or 'PS'.

3.4. Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) of the concrete specimens was examined just before testing under compression and the results are given in Table 5. In Table 5, the average UPV values of three specimens are reported.

Table 5. UPV test results

Sl. No.	Mix ID	UPV, km/s		
		10 %	20 %	30 %
1	Control	4.718		
2	P	4.509	4.476	4.388
3	PS	4.517	4.491	4.362
4	PC	4.461	4.315	4.306

It was observed from Table 5 that the UPV of concrete specimens containing the proposed plastic aggregates was less than that of control concrete. As compared to control concrete, the maximum percentage decrease in the UPV value of concrete due to the use of plastic aggregate PC (at 20 % and 30 % replacement levels) was found to be only 9 %. Test results showed that the increase in the percentage use of plastic aggregates slightly decreased the UPV. However, the percentage decrease was found to be ≤ 3.0 %. These observations indicated that the use of plastic aggregate did not significantly influence the integrity of concrete, and hence, concrete with integrity similar to that of control concrete could be achieved by using plastic aggregate. As per IS-13311 [21], the quality grade of control concrete was found to be 'Excellent' (with UPV > 4.5 km/s). The quality grade of concrete with plastic aggregate P and PS up to 10 % replacement level was also found to be 'Excellent'. For other concrete specimens, the quality grade was found to be 'Good' (with UPV > 3.5 km/s and < 4.5 km/s).

4. CORRELATION STUDIES

4.1. Relation between compressive strength and percentage of replacement

Regression analysis was carried out on the experimental results to determine strength predictive equations relating the compressive strength of control concrete and the percentage use of plastic aggregates 'P', 'PS' and 'PC'. The different equation was determined for each type of plastic aggregate. The results of the regression analyses are pictorially shown in Fig. 11.

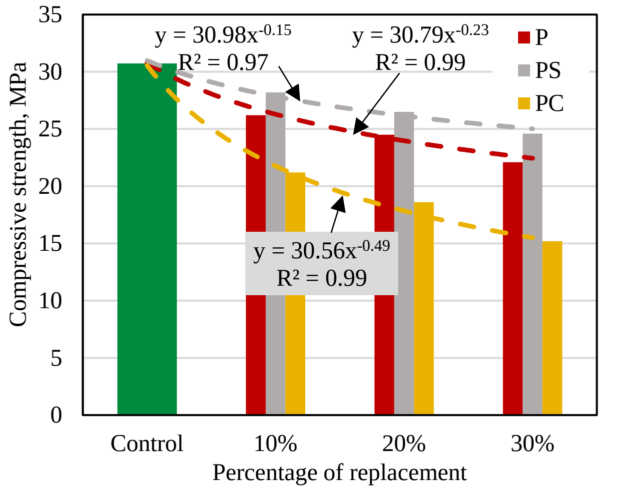

Fig. 10. Regression analysis

Fig. 10 indicated that the compressive strength of concrete decreased non-linearly with the increase in the percentage use of the proposed plastic aggregates ‘P’, ‘PS’ and ‘PC’. The compressive strength of concrete can be represented by a general form as a function of different variables.

$f_{sc} = f_n$ (f_{ck} is the percentage of replacement and a numerical factor that depends on the type of plastic aggregate used as replacement)

$$f_{sc} = f_{ck} \cdot x^{-y}, \tag{1}$$

where f_{sc} is the compressive strength of sustainable concrete with plastic aggregate, MPa; f_n is the function of f_{ck}; f_{ck} is the compressive strength of control concrete, MPa; x is the percentage of replacement, %; y is the numerical factor that depends on the type of plastic aggregate used as replacement.

The values of numerical factor (y) as obtained from the regression analyses are 0.15, 0.23 and 0.49 for the plastic aggregate ‘PS’, ‘P’ and ‘PC’ respectively. The results indicated that the numerical factor (y) value was higher for aggregate ‘PC’. The value of numerical factor (y) was the least for aggregate ‘PS’. As compared to that of ‘PS’, the numerical factor (y) was 53 % more for ‘P’, and it was 3.26 times more for ‘PC’. This observation indicated that the value of the numerical factor could be correlated against the strength decrease of concrete. Higher the numerical factor value, the higher the decrease in the strength of concrete.

4.2. Correlation between compressive strength and flexural-tensile strength

In this section, correlations between the compressive and flexural-tensile strengths of concrete with plastic aggregate are made. Regression analysis was used to determine the correlation function, and the result is graphically shown in Fig. 11.

The relationship between the compressive and flexural-tensile strengths of concrete mixes considered is expressed as follows:

$$f_{tsc} = 0.26\, f_{sc}^{0.69}, \tag{2}$$

The experimental and predicted flexural-tensile strengths (based on Eq. 2) of the concrete mixes are given in Table 6. It was observed that the predicted flexural-tensile strength was closer to the experimental values.

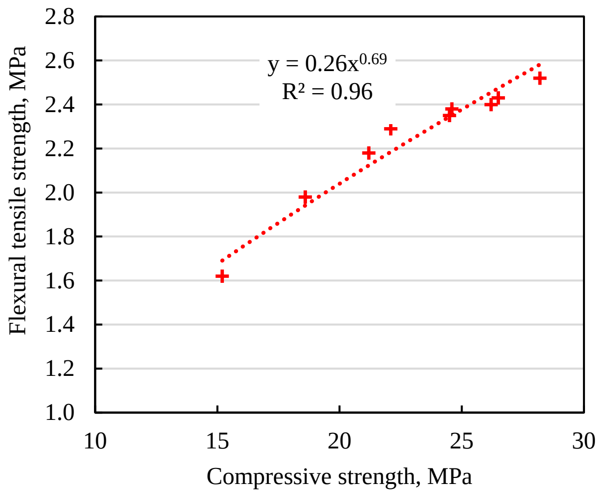

Fig. 11. Correlation between compressive and flexural strength

5. SUMMARY AND CONCLUSIONS

In this paper, research studies on the properties of concrete containing innovative plastic aggregate based on PET waste are presented and discussed. Plastic aggregates with different surface characteristics are proposed. Compressive and flexural-tensile strengths of concrete with different types of plastic aggregates were determined.

Table 6. Experimental and predicted flexural strength

Sl. No.	Mix ID	Experimental		Predicted
		Compressive strength, f_{sc_exp}	Flexural-tensile strength, f_{tsc_exp}	Proposed Eq. 2, f_{tsc_2}
1	CA1-10	26.2	2.40	2.46
2	CA1-20	24.5	2.35	2.35
3	CA1-30	22.1	2.29	2.18
4	CA2-10	28.2	2.52	2.59
5	CA2-20	26.5	2.43	2.48
6	CA2-30	24.6	2.38	2.35
7	CA3-10	21.2	2.18	2.12
8	CA3-20	18.6	1.98	1.93
9	CA3-30	15.2	1.62	1.68

Regression analyses to determine the relationship between the compressive strength and percentage of replacement, and the relationship between the compressive and flexural-tensile strengths were carried out. The results are summarized below.

1. Reduced dumping of PET waste can be achieved by using them for producing aggregates.
2. The proposed plastic aggregate did not fail by crushing.
3. The bonding properties of plastic aggregate particles could be improved by dispersing sand particles and that increased the strength of concrete.
4. Concrete with UPV > 3.5 km/s and grading quality 'Good' can be achieved by using plastic aggregate up to a replacement level of 30 %.
5. The proposed equation can be used to predict the strength of concrete as a function of the percentage of replacement.
6. Investigations on behaviour of concrete under elevated temperature, and durability studies may be considered as future scope of the research.

REFERENCES

1. **Centre for Science and Environment**. Managing Plastic Waste in India – Challenges and Agenda, New Delhi, India, 2020.
2. **Phillips, P., Richards, G.** The Use of Mixed Polymer Waste Products to Produce Paving Grade Asphalt *In: Proceeding of 3rd Eurasphalt and Eurobitume Congress* 2004: pp. 1171 – 1180.
3. **Dunster, A.M., Moulinier, F., Abbott, B., Conroy, A., Adams, K., Widyatmoko, D.** Added Value of Using New Industrial Waste Streams as Secondary Aggregates in Both Concrete and Asphalt *R & D Report* Banbury, Oxon, United Kingdom, 2005: pp. 1 – 13.
4. **Alqahtani, F.K., Zafar, I.** Characterization of Processed Lightweight Aggregate and its Effect on Physical Properties of Concrete *Construction and Building Materials* 230 2020: pp. 116992. https://doi.org/10.1016/j.conbuildmat.2019.116992
5. **Coppola, B., Courard, L., Michel, F., Incarnato, L., Di, L.** Investigation on the Use of Foamed Plastic Waste as Natural Aggregates Replacement in Lightweight Mortar *Composites Part B* 99 2016: pp. 75 – 83. https://doi.org/10.1016/j.compositesb.2016.05.058.
6. **Coppola, B., Courard, L., Michel, F., Incarnato, L., Scarfato, P., Di, L.** Hygro-thermal and Durability Properties of a Lightweight Mortar Made with Foamed Plastic Waste Aggregates *Construction and Building Materials* 170 2018: pp. 200 – 206. https://doi.org/10.1016/j.conbuildmat.2018.03.083
7. **Choi, Y., Moon, D., Chung, J., Cho, S.** Effects of Waste PET Bottles Aggregate on the Properties of Concrete *Cement and Concrete Research* 35 2005: pp. 776 – 781. https://doi.org/10.1016/j.cemconres.2004.05.014
8. **Choi, Y., Moon, D., Kim, Y., Lachemi, M.** Characteristics of Mortar and Concrete Containing Fine Aggregate Manufactured from Recycled Waste Polyethylene Terephthalate Bottles *Construction and Building Materials* 23 (8) 2009: pp. 2829 – 2835.
9. **Castillo, R., Almesfer, N., Saggi, O., Ingham, J.M.** Lightweight Concrete with Artificial Aggregate Manufactured from Plastic Waste *Construction and Building Materials* 265 2020: pp. 120199. https://doi.org/10.1016/j.conbuildmat.2020.120199
10. **Haghighatnejad, N., Mousavi, S.Y., Khaleghi, S.J., Tabarsa, A., Yousefi, S.** Properties of Recycled PVC Aggregate Concrete under Different Curing Conditions *Construction and Building Materials* 126 2016: pp. 943 – 950. https://doi.org/10.1016/j.conbuildmat.2016.09.047
11. **Senhadji, Y., Escadeillas, G., Benosman, A.S., Mouli, M., Khelafi, H., Kaci, S.O.** Effect of Incorporating PVC Waste as Aggregate on the Physical, Mechanical, and Chloride Ion Penetration Behavior of Concrete *Journal of Adhesion Science and Technology* 4243 2015: pp. 1 – 16. https://doi.org/10.1080/01694243.2014.1000773
12. **Kou, S.C., Lee, G., Poon, C.S., Lai, W.L.** Properties of Lightweight Aggregate Concrete Prepared with PVC Granules Derived from Scraped PVC Pipes *Waste Management* 29 (2) 2009: 621 – 628. https://doi.org/10.1016/j.wasman.2008.06.014
13. **Górak, P., Postawa, P., Trusilewicz, L.N., Łagosz, A.** Lightweight PET based Composite Aggregates in Portland Cement Materials – Microstructure and Physicochemical Performance *Journal of Building Engineering 34* 2020: pp. 101882. https://doi.org/10.1016/j.jobe.2020.101882
14. **Sabau, M., Vargas, J.** Use of E-Plastic Waste in Concrete as a Partial Replacement of Coarse Mineral Aggregate *Computers and Concrete* 21 (4) 2018: pp. 377 – 384. http://dx.doi.org/10.12989/cac.2018.21.4.377
15. **Ashok, M., Jayabalan, P., Saraswathy, V., Muralidharan, S.** A Study on Mechanical Properties of Concrete Including Activated Recycled Plastic Waste *Advances in Concrete Construction* 9 (2) 2020: pp. 207 – 215. http://dx.doi.org/10.12989/acc.2020.9.2.207
16. **IS 1199.** Methods of Sampling and Analysis of Concrete. *Bureau of Indian Standards*, 1959.
17. **IS 516.** Method of Tests for Strength of Concrete. *Bureau of Indian Standards, New Dehli*, 2018. https://doi.org/10.3403/02128947
18. **ASTM D729.** Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement. *American Society for Testing and Materials*, 6, 2008. https://doi.org/10.1520/D0792-20.2
19. **IS 2386- Part III.** Method of Test for Aggregate for Concrete. Part III- Specific gravity, density, voids, absorption and bulking. *Bureau of Indian Standards, New Delhi*, (Reaffirmed 2002), 1963.
20. **IS 10262**. Concrete Mix Proportions – Guidelines. *Bureau of Indian Standards, New Delhi*, 2019.

IS 13311-Part I. Non-Destructive Testing Method of Concrete – Methods of Test: Ultrasonic Pulse Velocity. *Bureau of Indian Standards, New Delhi*, 2004.