Iran J Sci Technol Trans Civ Eng (2019) 43 (Suppl 1):S455–S465
https://doi.org/10.1007/s40996-018-0178-0

RESEARCH PAPER

Fresh, Strength, Durability and Microstructural Properties of Shredded Waste Plastic Concrete

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Received: 25 November 2017 / Accepted: 24 September 2018 / Published online: 1 October 2018

Abstract
The accumulation of waste plastic worldwide creates serious environmental concerns. In the present study, efforts were made to utilize shredded plastic bags as concrete additive materials. Therefore, the workability, density, compressive and flexural strength, water permeability, static and dynamic modulus of elasticity and abrasion resistance properties of concrete were investigated in this study by adding different percentages (0, 0.5, 1, 2, 3 and 5%) of waste plastic bags by weight of concrete. The addition of waste plastic bags decreased the flow ability of fresh concrete and also resulted in loss of hardened concrete properties. The waste plastic concrete samples showed an improved resistance against the abrasion behavior. Microstructure study was also conducted using the optical microscope. The overall results indicated that the waste plastic concrete can be used for non-structural works.

Keywords Waste plastic bag · Waste plastic concrete · Mechanical properties · Water permeability · Abrasion resistance · Microstructural feature

1 Introduction

Currently, the use of plastic is enormous and is being used all over the world. In 1933, polyethylene plastic (a type of plastic) was invented by Eric Fawcett and Reginald Gibson (Trossarelli and Brunella 2003). Plastic is a flexible, durable and cheap material that is being utilized for various applications like packaging ingredients, transporting goods, accumulating household waste, shopping bags, wrapping fabric, fluid containers, industrial products, building fabric and so forth. It is also used for making plastic buckets, plastic glass and plastic furniture (Al-Salem et al. 2009; Rebeiz and Craft 1995). Approximately 50–60% of total plastics are used for packing ingredients (Siddique et al. 2008). After fulfilling its service needs, these plastic packaging substances are rejected as waste and remain non-biodegradable for many years (Hassani et al. 2005; Ismail and Al-Hashmi 2008). The total amount of recycled and non-recycled waste plastic (WP) on a daily basis within the Delhi state of India is around 60% and 40%, respectively (Sharma and Bansal 2016). Though recycling is a possible option for the WP which reduces the environment threat, recycling requires vast manpower and energy (Nikbin et al. 2016; Sadiq and Khattak 2015). There is a need for sustainable and novel approaches for the utilization of WP (Liu et al. 2013; Rahmani et al. 2013). On the other side, the depletion of the natural resources due to the regular increment in the construction industry and growth within the need of concrete industry is a cause for concern (Ramadevi and Manju 2012; Suganthy et al. 2013). The need for an alternative material for concrete industry exists. The exploitation of WP in concrete industry therefore may be the better solution to reduce environment pollution, solve the disposal problem of waste plastic and simultaneously save the natural resources (Akcaozoglu et al. 2010; Foti 2013; Nikbin et al. 2016; Saikia and de Brito 2012; Saikia and de Brito 2014; Sharma and Bansal 2016; Siddique et al. 2008; Verma and Kumar 2016;

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Yesilata et al. 2009). Waste plastic concrete (WPC) in this manner can contribute to sustainable construction.

Ismail and Al-Hashmi (2008) examined the less fluidity of WPC compared to the natural concrete (NC) and came to the conclusion that the possible reason behind this is the presence of irregular shapes of particle. Albano et al. (2009) carried out an experimental study using WP in concrete and reported a decrease in workability with increasing amount and size of waste plastic. Frigione (2010) observed similar workability results of WPC as compared to the NC. The manually cut plastic bags fiber resulted in higher decline of workability as compared to the machine-cut plastic bags fiber (Bhogayata et al. 2012). Al-Hadithi and Hilal (2016) also reported a reduction in workability of self-compacting concrete on the addition to waste polyethylene terephthalate (PET). The same results of workability for WPC were observed by many researchers (Kan and Demirboğa 2009; Marthong and Sarma 2016; Naik et al. 1996; Nibudey et al. 2013; Rahmani et al. 2013; Sabarinathan and Suresh 2016). However, some studies reported that introduction of plastic waste aggregate facilitated the flow of concrete as the smooth texture of plastic reduced the friction between the particles (Ghernouti et al. 2011, 2015).

The systematic decline in density of WPC was observed by Rai et al. (2012) and Ruiz-Herrero et al. (2016) due to the low density of WP as correlated with sand. Marzouk et al. (2007) swapped the WP bottle with fine aggregate in the mortar, and this low-density WP bottle decreased the bulk density of mortar. Al-Hadithi and Hilal (2016) reported the decrease in the density of self-compacting concrete on the addition of waste PET. The reduction in density of WPC has been reported in other studies (Akcaozoglu et al. 2010; Ghernouti et al. 2011; Hannawi et al. 2010; Ismail and Al-Hashmi 2008; Kan and Demirboğa 2009; Liu et al. 2013; Patil et al. 2014; Rahmani et al. 2013; Yang et al. 2015) also.

The reduction in compressive strength (CS) of mortar specimens comprising waste polyethylene terephthalate (PET) as fine aggregate substitute was studied by Hannawi et al. (2010). Ismail and Al-Hashmi (2008), Rai et al. (2012) showed a decline in CS of WPC specimens compared to the NC specimens. This reduction may be attributed to weak interfacial transition region (ITR) between WP and cement matrix. The straight/long WP showed higher decrement in CS as related to the deformed/small WP (Borg et al. 2016). Frigione (2010) noticed a minor reduction in compressive strength of concrete samples which contained 5% of waste PET as a replacement of fine aggregate. The reduction in compressive strength of WPC was reported by many authors (Albano et al. 2009; Bhogayata et al. 2012, 2013; Bouziani et al. 2014; Ghernouti et al. 2011; Kan and Demirboğa 2009; Pezzi et al. 2006; Raghatate Atul 2012; Rahmani et al. 2013). However, the increase in compressive strength of WPC has also been available in the literature (Al-Hadithi and Hilal 2016; Ghernouti et al. 2015; Kandasamy and Murugesan 2011; Marthong and Sarma 2016; Yang et al. 2015). This increment is because of the crack arresting behavior of WP fibers which results in higher failure load.

Likewise CS, the same poor interfacial transition region (ITR) factor between WP and concrete matrix was given by Ismail and Al-Hashmi (2008) for reduction in flexural strength (FS) of concrete containing WP. Another cause for decrease in FS was the imbalance of water to cement ratio near the plastic particles causing formation of voids and relatively weaker plastic to cement paste interface (Albano et al. 2009; Ghernouti et al. 2011; Hannawi et al. 2010; Patil et al. 2014; Prahallada et al. 2013; Rahmani et al. 2013; Rai et al. 2012). Few studies have also reported an increase in FS on introduction of plastic waste (in fiber form) as aggregate. The observations drawn suggested that the improvement of FS was due to better anchorage effect and superior stress transfer behavior provided by the WP fibers. (Al-Hadithi and Hilal 2016; Marthong and Sarma 2016; Pešić et al. 2016; Yang et al. 2015).

Liu et al. (2013) obtained the lower modulus of elasticity of WPC with the increase in the amount and size of WP. Marzouk et al. (2007) noticed the reduced modulus of elasticity of mortar comprising waste PET due to low composite bulk density. Hannawi et al. (2010) also obtained the inferior results of modulus of elasticity of mortar containing waste PET as fine aggregate replacement. The inferior results are attributed to the low modulus of elasticity of PET and the lower attachment between the WP and cement matrix. The reason behind the results obtained for the lower modulus of elasticity of concrete specimen consisting of waste PET as fine aggregate replacement by Rahmani et al. (2013) was also the same given by Hannawi et al. (2010). The similar consequences concerning modulus of elasticity of WPC were observed by specific authors (Albano et al. 2009; Ghaly and Gill 2004; Kim et al. 2010; Yang et al. 2015) also.

Little experimental work has been done on the effect of WPB on water permeability and wear and tear of WPC. Islam and Gupta (Islam and Gupta 2016) examined the effect of WP on concrete specimen and got the higher permeability of water through the WPC specimens owing to higher porosity. The reason behind the excessive absorption of water of WPC as observed by Albano et al. (Albano et al. 2009) was also the higher porosity. The increase in water absorption of WPC was observed by some authors (Hannawi et al. 2010; Ruiz-Herrero et al. 2016) also. Saikia and Brito (2014) observed the improved resistance to wear and tear of concrete specimens containing WP as aggregate substitute.

According to the available literature, very few studies are available concerning the incorporation of WPB in concrete. Therefore, this research is carried out to examine the density, workability, compressive and flexural strength, static and dynamic modulus of elasticity of concrete specimens including different percentages (0, 0.5, 1, 2, 3 and 5%) of the WPB by weight. Water permeability, resistance to abrasion and microstructure study of WPC were also conducted.

2 Material and Methodology

2.1 Materials

The ordinary Portland cement (OPC) of 43-grade, fine aggregate (FA), coarse aggregate (CA) and WPB were used in this study. The physical properties of cement are specified in Table 1. The FA (< 4.75 mm) and CA (10 mm and 20 mm size) were procured from the local suppliers as per BIS:383 (1970). The properties of both the aggregates are given in Table 2, while the sieve analysis result of fine aggregate is given in Table 3 and Fig. 1. Water was taken from the same source throughout the study for mixing, casting and curing of the concrete specimen as per BIS:456 (2009).

The WP used in this study consists of WPBs. The WPBs were cut into fiber form (shown in Fig. 2) by shredding machine. The specific gravity of WPB was 0.39. The size of waste shredded plastic bags particle varied between 15 and 30 mm in length and 3–5 mm in width.

2.2 Mixture Proportion

The concrete mixes were designed and prepared as per BIS:10262 (2009) for the control mix (without WPB) and the other mixes incorporating WPB by using constant water to cement (w/c) ratio of 0.45. In this study, a total of 90 concrete specimens of cubes, cylinders and beams were cast with the inclusion of WPB (shown in Fig. 3), modifying from 0 to 5% by weight. The details of mix proportions are represented in Table 4.

Table 1 Physical properties of cement

Properties	Results
Consistency	32%
Initial setting time	130 min
Final setting time	213 min
Specific gravity	3.13
7-day compressive strength	34.95 Mpa
28-day compressive strength	45.29 Mpa

Table 2 Properties of fine aggregate and coarse aggregate

Properties	Results
Specific gravity of FA	2.63
Specific gravity of CA	
(i) 10 mm size	2.70
(ii) 20 mm size	2.78
Fineness modulus of FA	2.83
Fineness modulus of CA	
(i) 10 mm size	6.29
(ii) 20 mm size	7.06
Water absorption of FA	0.4%
Water absorption of CA	
(i) 10 mm size	0.5%
(ii) 20 mm size	0.7%

Table 3 Sieve analysis of FA

Sieve size (mm)	% Passing
4.75	98
2.36	93.7
1.18	71
0.600	36.1
0.300	17.1
0.150	1.1

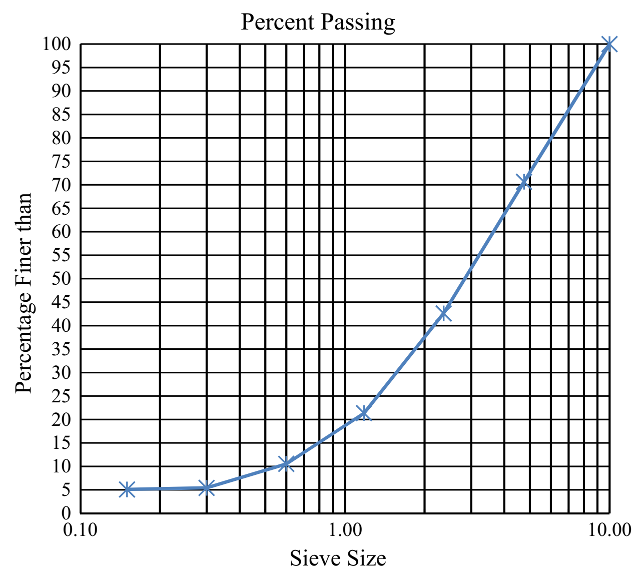

Fig. 1 Sieve analysis of fine aggregate

Fig. 2 Shredded plastic bags

Fig. 3 Testing specimens

3 Testing Procedure

Compaction factor (C.F.) test was conducted for finding the workability of fresh concrete mix with the guideline of BIS:1199 (1959). Compressive strength and flexural strength were evaluated on 100-mm cubic specimen and 500 mm × 100 mm × 100 mm beam specimen, respectively, as per the BIS:516 (1959). Compressive strength tests were conducted on 7 and 28 days cured specimens. The loading rate for the test was 140 kg/cm^2. Flexural strength test was conducted at the age of 28 days on cured specimens with four-point bending system as shown in Fig. 4.

Static modulus of elasticity test was conducted at the age of 28 days on cured cylindrical specimens (300 mm height and 150 mm diameter) with the guidelines of ASTM:C469 (1994). The 300-ton capacity of automatic compression testing machine (shown in Fig. 5) was used to evaluate the modulus of elasticity with the aid of the following expression:

$$K_s = \frac{(A_2 - A_1)}{(\varepsilon_2 - 0.000050)}, \quad (1)$$

where K_s = modulus of elasticity (MPa); A_2, A_1 = stress at 40% of ultimate load and longitudinal strain of 50 millionths (MPa), respectively; and ε_2 = longitudinal strain corresponding to stress A_2.

Portable ultrasonic pulse velocity tester was utilized to assess the dynamic modulus of elasticity of 150-mm cubic specimen after 28 days of curing as per the ASTM:C597 (2009). After finding the velocity, the subsequent expression (Eq. 2) given by Rahman et al. (2012) was used to assess the dynamic modulus of elasticity:

$$E_d = \frac{\rho V^2}{g \times 100}, \quad (2)$$

where E_d = dynamic modulus of elasticity, ρ = density of concrete specimen (kg/m^3), V = velocity (km/s) and g = acceleration due to gravity (m/s^2).

For water permeability, the 150-mm cubic specimens were subjected to water pressure of 5 kg/cm^2 for 3 days (shown in Fig. 6) as per the DIN:1048 (1991). In this process after 3 days, the depth of water penetration was calculated by splitting the specimen into two parts in compression testing machine. The resistance to abrasion of 100-mm cubic concrete specimens was calculated as per the BIS:1237 (2012). The resistance to abrasion was

Table 4 Details of mix proportion

WPB fraction	w/c ratio	Cement	Fine aggregate	Coarse aggregate	
				10 mm	20 mm
0% (control mix)	0.45	1	1.54	1.10	1.66
0.5%	0.45	1	1.54	1.10	1.66
1%	0.45	1	1.54	1.10	1.66
2%	0.45	1	1.54	1.10	1.66
3%	0.45	1	1.54	1.10	1.66
5%	0.45	1	1.54	1.10	1.66

Fig. 4 Flexure strength testing machine

Fig. 5 Automatic compressive testing machine

Fig. 6 Water permeability testing machine

calculated in terms of thickness loss of specimen using the following expression:

$$t = \frac{(P_1 - P_2) \times V_1}{P_1 \times A}, \quad (3)$$

where t = thickness loss (mm), P_1 = initial weight (g), P_2 = weight after abrasion (g), V_1, A = initial volume (mm^3) and area of the specimen (mm^2), respectively.

The microstructure attributes of WPC were also evaluated using the optical microscope (OM) having 1000 × maximum magnification capacity.

4 Result and Discussion

The results obtained for compressive strength, split tensile strength, flexure strength and static modulus of elasticity are presented in Table 5.

4.1 Workability

The workability of concrete mix containing WPB in terms of C.F. is shown in Fig. 7. It can be seen that the C.F. for the control mix achieved was 0.91, while 0.65 C.F. was achieved with 5% addition of WPB.

The C.F. decreased insignificantly from 0.91 for the control mix to 0.87 for concrete mix containing 0.5% WPB, while the significant reduction in the C.F. was examined with the inclusion of 3% and 5% WPB which was 0.71 and 0.65, respectively. Therefore, more water or superplasticizer is required to make the concrete mix workable with 5% WPB inclusion in the concrete. The workability of WPC was reduced by 7.69% with 1% inclusion of WPB, and it reduced by 28.57% with 5% inclusion of WPB.

In the present study, the decrease in the workability may be due to the larger size of WP particle which may result in huge voids, less fluidity and influencing the compaction. The irregular and soft shape of shredded plastic can create pockets of air during the casting process which can lead to poor compaction of concrete.

Bhogayata and Arora (2017) detected up to 25% reduction in workability for the 2% inclusion of food-packaging polythene pieces. The earlier study done by Ismail and Al-Hashmi (2008) also found substantial reduction up to 95.33% in workability on 20% replacement of fine aggregates by WP containers.

4.2 Density

The density of concrete specimens (average of three) containing WPB at 28 days of curing is shown in Fig. 8. It can be noticed that the density of concrete specimen

Table 5 Results for properties for various concrete mixes showing mean, standard deviation (SD) and coefficient of variation in percentage (COV)

Property		0% WPB	0.5% WPB	1% WPB	2% WPB	3% WPB	5% WPB
Density (Kg/m^3)[28 Days]	Mean	2408.82	2397.06	2355.88	2267.65	1932.35	1708.82
	SD	59.11	63.23	55.78	58.32	51.45	56.43
	COV	2.45%	2.63%	2.36%	2.57%	2.66%	3.30%
Compressive strength (MPa)	Mean	17.8	17.2	16.5	10.9	4.6	1.9
[7 Days]	SD	0.7	1.3	0.8	0.87	0.41	0.098
	COV	3.93%	7.56%	4.85%	7.98%	8.91%	5.16%
Compressive strength (MPa)	Mean	26.7	26.1	22.9	15.7	7.5	4.1
[28 Days]	SD	1.9	1.5	0.7	0.9	0.5	0.32
	COV	7.12%	5.75%	3.06%	5.73%	6.67%	7.80%
Flexural strength (MPa)	Mean	3.55	3.4	3.07	1.89	1.08	0.63
[28 Days]	SD	0.35	0.4	0.35	0.13	0.11	0.0075
	COV	9.86%	11.76%	11.40%	6.88%	10.19%	11.90%
Static modulus of elasticity (MPa)	Mean	26,100	25,861	24,229	20,811	12,798	8169
[28 Days]	SD	1054.84	1076.87	1560.32	1163.87	521.54	605.76
	COV	4.04%	4.16%	6.44%	5.59%	4.07%	7.41%
Dynamic modulus of elasticity (GPa)	Mean	52.89	48.15	42.26	30.49	14.92	4.24
[28 Days]	SD	2.2	1.7	1.8	2.0	1.2	0.37
	COV	4.16%	3.53%	4.26%	6.56%	8.04%	8.73%
Water permeability (mm)	Mean	24	33	64	98	123	150
[28 Days]	SD	0.6	1.1	1.8	1.8	1.7	0
	COV	2.50%	3.33%	2.81%	1.84%	1.38%	0%
Depth of Wear (mm) [28 Days]	Mean	0.42	0.40	0.37	0.36	0.36	0.22
	SD	0.02	0.03	0.034	0.028	0.026	0.013
	COV	4.76%	7.50%	9.19%	7.78%	7.22%	5.91%

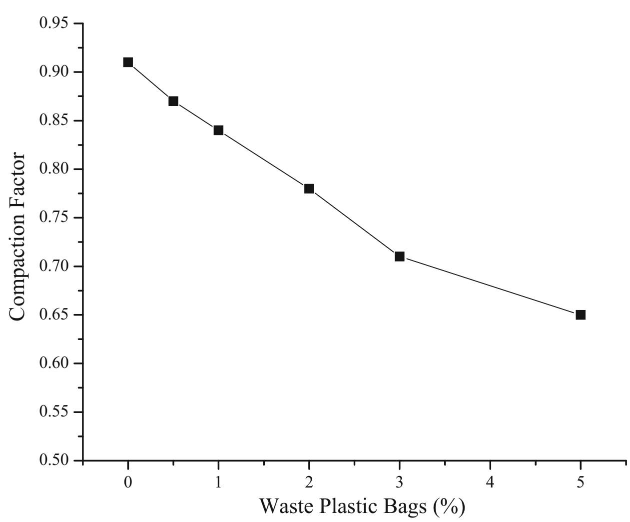

Fig. 7 Compaction factor of concrete containing WPB

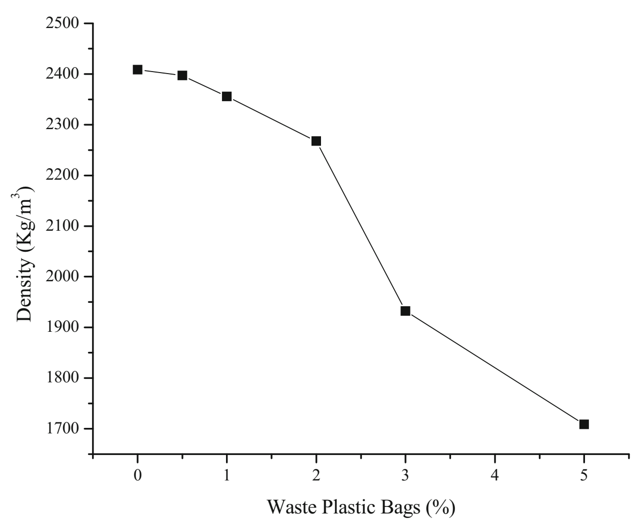

Fig. 8 Density of concrete containing WPB

declined with the incorporation of WPB. The density of WPC was reduced by 2.20% and 29.06% with 1% and 5% incorporation of WPB, respectively.

The reason for this decrement can be because of the low specific gravity of WPB, i.e., 0.39, compared to cement, fine aggregate and coarse aggregate that have specific gravity 3.13, 2.63 and 2.78, respectively. The same reason for the decrement of density of WPC was also given by many authors (Akcaozoglu et al. 2010; Hannawi et al. 2010; Ismail and Al-Hashmi 2008; Liu et al. 2013; Patil et al. 2014; Rahmani et al. 2013; Yang et al. 2015). The reduction in density up to 30% was also reported by Ruiz-Herrero et al. (2016) on the incorporation of WP in concrete.

4.3 Compressive Strength

The compressive strength (CS) of concrete specimens containing WPB at 7 days and 28 days of curing is represented in Fig. 9. Though the CS of the concrete specimens increases with increase in curing age, the general trend of the CS decreased with the incorporation of WPB.

The CS of control concrete (without WP) after 7 days of curing was observed as 17.8 MPa which reduced to 1.9 Mpa at 5% addition of WPB. The 28 days CS of cube specimens was observed as 26.7 MPa, 26.1 MPa, 22.9 MPa, 15.7 MPa, 7.5 MPa and 4.1 MPa at 0, 0.5, 1, 2, 3 and 5% addition of WPB, respectively. The CS of WPC after 28 days of curing of specimens was reduced by 14.23% at 1% inclusion of WPB, and it reduced by 84.64% at 5% inclusion of WPB.

In the present work, the primary cause for this decrement in CS may be because of (1) the weak ITR between the surfaces of WP and cement paste, (2) the large particle size of the WP, which resulted in pores and cavities in the concrete, and (3) the low workability. This same effect was noticed by other researchers (Albano et al. 2009; Bhogayata et al. 2012, 2013; Borg et al. 2016; Bouziani et al. 2014; Frigione 2010; Pezzi et al. 2006; Raghatate Atul 2012; Rahmani et al. 2013) also. In previous study, the same behavior was reported by Bhogayata and Arora (2017) on the addition of food-packaging polythene pieces in concrete. They detected up to 11% decrement in CS for 1% fraction of WP.

4.4 Flexural Strength

The flexural strength (FS) of concrete specimens containing WPB at 28 days of curing is shown in Fig. 10. The general trend of the FS decreased with the incorporation of WPB. The FS after 28 days of curing of beams (average of three) was observed as 3.55 MPa, 3.40 MPa, 3.07 MPa, 1.89 MPa, 1.08 MPa and 0.63 MPa at 0, 0.5, 1, 2, 3 and 5% of addition of WPB, respectively. The FS of WPC was reduced by 13.52% with 1% of WPB, and it reduced by 82.25% with 5% of WPB.

The test results showed that the value of flexural strength decreases with the increase in WPB content. The decrement in FS values was probably due to the similar reasons as compressive strength. Other authors realized a similar decrement in FS for the incorporation of WP (Albano et al. 2009; Ghernouti et al. 2011; Hannawi et al. 2010; Ismail and Al-Hashmi 2008; Prahallada et al. 2013; Rahmani et al. 2013; Rai et al. 2012). The decline in FS of concrete specimens was also obtained by Bhogayata and Arora (Bhogayata and Arora 2017) for the addition of food-packaging polythene pieces.

4.5 Static Modulus of Elasticity

The static modulus of elasticity of concrete specimens (average of three) containing WPB at 28 days of curing is presented in Fig. 11. The results of static modulus of elasticity after 28 days of curing of cylinder specimens

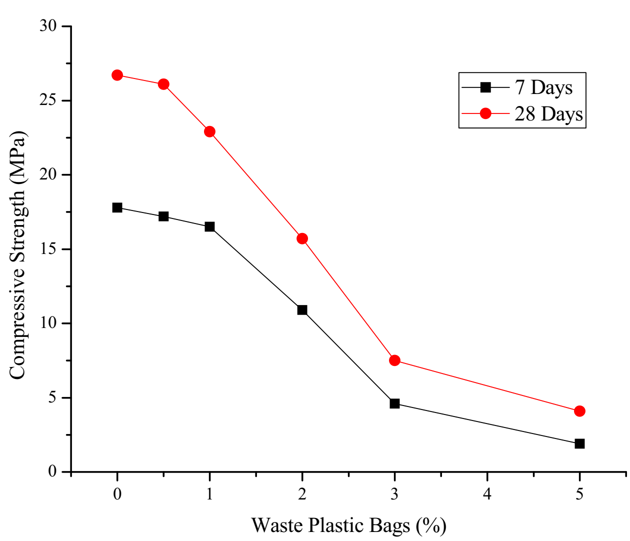

Fig. 9 Compressive strength of concrete containing WPB

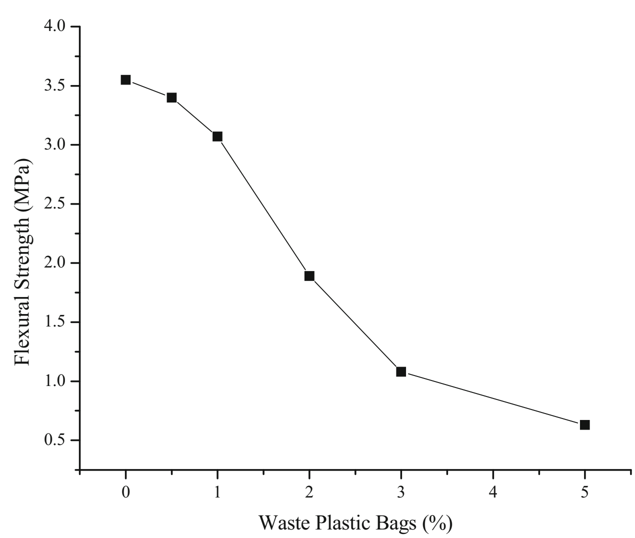

Fig. 10 Flexural strength of concrete containing WPB

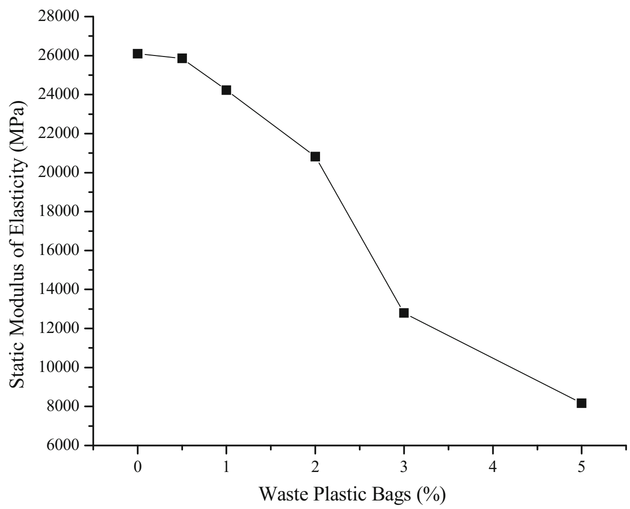

Fig. 11 Static modulus of elasticity of concrete containing WPB

were observed as 26,100 MPa, 25,861 MPa, 24,229 MPa, 20,811, 12,798 MPa and 8169 MPa at 0, 0.5, 1, 2, 3 and 5% addition of WPB, respectively. The modulus of elasticity of WPC was reduced by 7.17% on 1% of WPB, and it reduced by 68.70% on 5% of WPB.

The results of testing indicated the reduction of modulus of elasticity with the rise in WPB content. This was probably due to the low modulus of elasticity of plastic bags and also due to the weak bonding between WPB and cement matrix. Previous authors (Albano et al. 2009; Ghaly and Gill 2004; Hannawi et al. 2010; Kim et al. 2010; Marzouk et al. 2007; Rahmani et al. 2013; Yang et al. 2015) also observed the same results. Earlier research done by Liu et al. (Liu et al. 2013) also observed up to 40% reduction in modulus of elasticity on 20% replacement of fine aggregates by WP.

4.6 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity of concrete specimens containing WPB at 28 days of curing is presented in Fig. 12. The results of dynamic modulus of elasticity after 28 days of curing of cubes (average of three) were found as 52.89 GPa, 48.15 GPa, 42.26 GPa, 30.49 GPa, 14.92 GPa and 4.24 GPa at 0, 0.5, 1, 2, 3 and 5% addition of WPB, respectively. The dynamic modulus of elasticity of WPC was reduced by 20.09% and 91.98% with 1% and 5% of WPB, respectively.

The test results indicated the reduction of dynamic modulus of elasticity with the rise in WPB content. This is probably the cause of low bulk density of composite and also higher porosity which resulted in reduced wave velocity (Marzouk et al. 2007). The above-mentioned observations were also reported by Rahman et al. (2012).

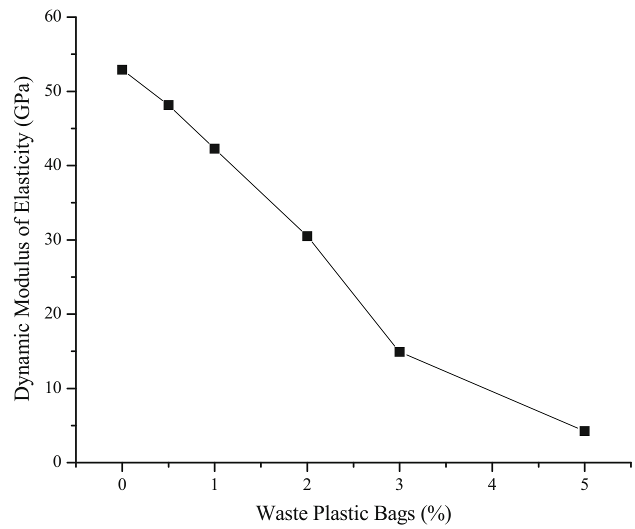

Fig. 12 Dynamic modulus of elasticity of concrete containing WPB

4.7 Water Permeability

Water permeability of concrete specimens comprising WP is measured in terms of depth of water permeation. The depth of water penetration of concrete containing WPB at 28 days of curing is presented in Fig. 13. The depth of water penetration after 28 days of curing of cubes (average of three) was observed as 24, 33, 64, 98, 123 and 150 mm at 0, 0.5, 1, 2, 3 and 5% of addition of WPB, respectively. The testing results exhibited the higher variation in depth of water permeation with the incorporation of WPB.

This variation can be due to a substantial number of voids and also poor ITR in the structure of concrete due to the irregular shape of WP and less adhesion with cement matrix. The significant penetration of water for concrete specimen with and without WPB can be clearly

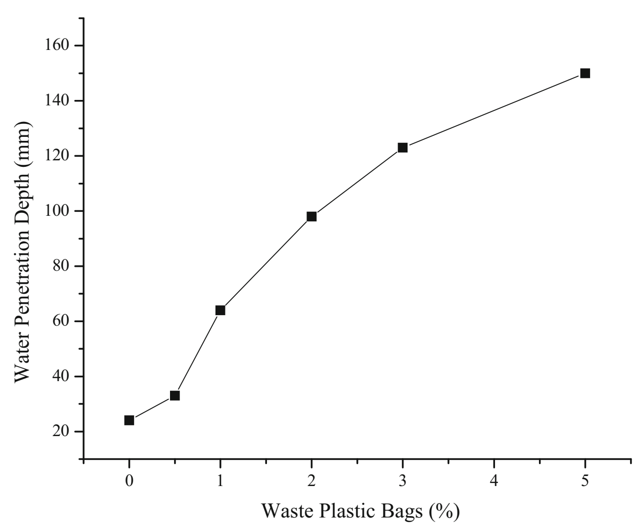

Fig. 13 Water penetration depth of concrete containing WPB

differentiated through Fig. 14. Previous investigation done by Islam and Gupta (Islam and Gupta 2016) also obtained the higher depth of water penetration with the addition of polypropylene fiber in concrete because of poor microstructure.

4.8 Abrasion Resistance

The abrasion resistance of concrete specimens having WPB is shown in Fig. 15, and it was calculated in terms of depth of wear. The testing results showed the wear of the depths 0.42, 0.40, 0.37, 0.36, 0.36 and 0.22 mm with the addition of 0, 0.5, 1, 2, 3 and 5% WPB, respectively. The depth of wear of WPC was reduced by 11.90% with 1% of WPB, and it reduced by 47.62% with 5% of WPB. The outcomes of testing indicated improved abrasion resistance of specimens.

The increase in abrasion resistance may be due to the high toughness and good abrasion behavior of WP compared to the natural aggregate. This same behavior was observed by Saikia and Brito (2014) on partial substitute of natural aggregate by waste plastic. From the results of testing, it can be inferred that the concrete specimens containing WPB fall into the category of general-purpose concrete tiles (limit of depth of wear < 3.5 mm) and heavy duty application (limit of depth of wear < 2 mm) as per BIS:1237 (2012).

4.9 Microstructure Analysis

The optical images of WPC are shown in Fig. 16a, b that were taken at 100 × and 200 × magnification, respectively. These images clearly expose the gap as well as poor connection between the concrete matrix–WPB interfaces. The red line in Fig. 16 points to the ITR between concrete matrix and WPB. In the present work, the poor connection of concrete matrix with WPB was the rationale for the fall of compressive strength, flexural strength and modulus of elasticity of WPC. The poor microstructure also led to the higher penetration of water through concrete specimens consisting of WPB. Similar poor interface characteristics of WPC were also detected by Hannawi et al. (2010), Yang et al. (2015).

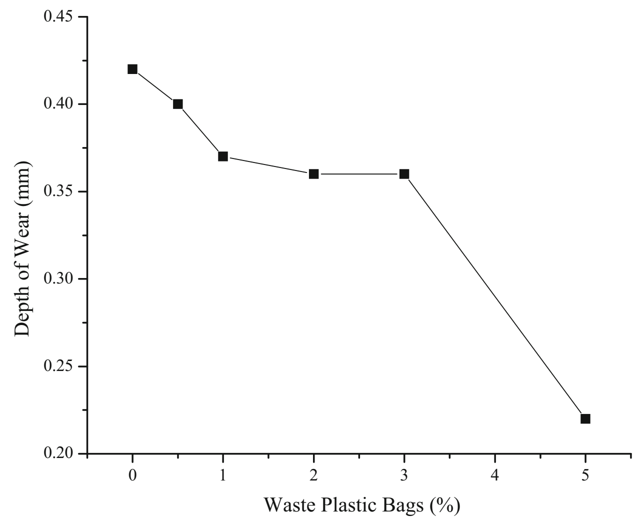

Fig. 15 Abrasion resistance of concrete containing WPB

5 Conclusion

The workability, density, compressive and flexural strength, static and dynamic modulus of elasticity, water permeability and abrasion resistance properties of concrete specimens consisting of waste plastic bags were found in this study for the w/c of 0.45. Based on test findings, the results are listed below:

1. The workability of waste plastic concrete (WPC) decreased with the increase in the percentage of WPB. The large and irregular size of plastic waste aggregate results in loss of fluidity. However, by introducing

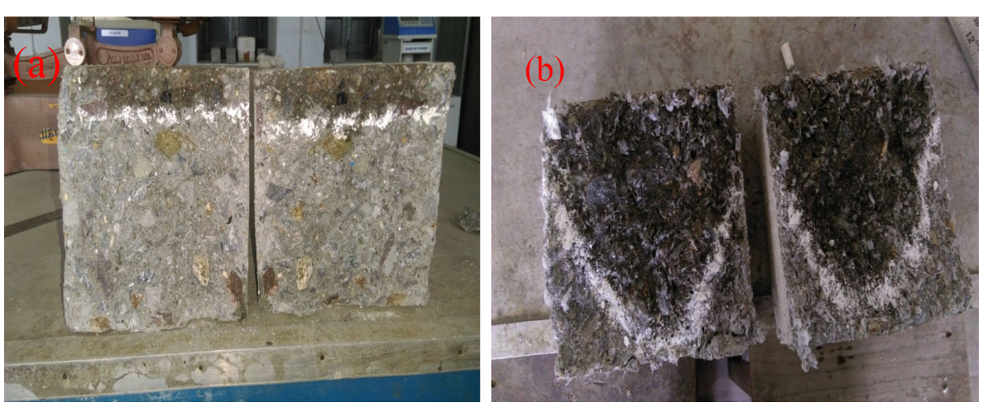

Fig. 14 Concrete specimen after mid-section splitting showing water penetration **(a)** without WPB and **(b)** with WPB

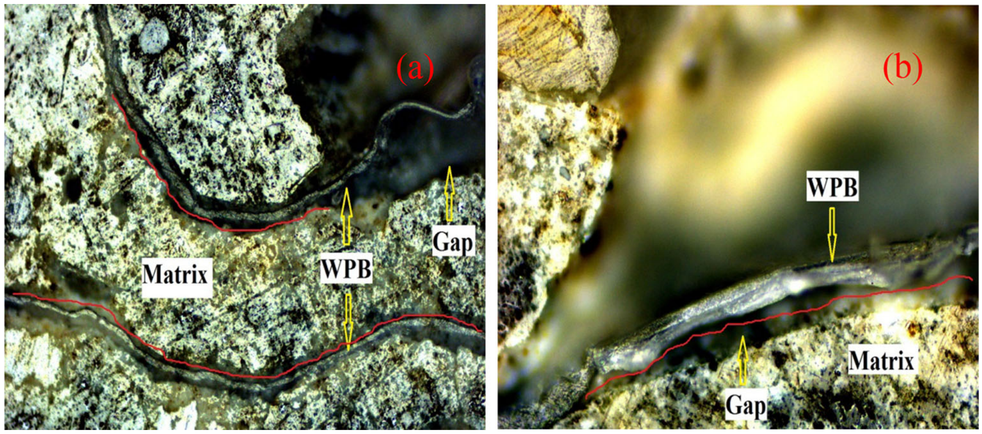

Fig. 16 Microstructure of WPC (**a**) 100 × magnification and (**b**) 200 × magnification

adequate dosages of superplasticizer, the workability performance of WPC can be improved.

2. The mechanical properties of WPC decreased with the increment in the percentage of WPB. The improper bonding between plastic aggregate and cement paste along with the formation of voids is the primary reason for loss in strength performance of WPC.
3. There was the significant increase in the water penetration of WPC with the increment in the percentage of WPB. The voids and weak ITR zones facilitate the penetration of water into concrete mix.
4. There was a higher abrasion resistance against rubbing and scraping effect of WPC as compared to the nominal concrete. The brush-like action of plastic waste provided resistance against the abrasive force.
5. Microstructure study revealed the poor interface of concrete–plastic bag matrix. This poor bonding is the prime cause for the reduction of mechanical properties as well as significant increase in permeation of water of WPC.
6. For future studies, the effects of various mineral admixtures and fillers can be investigated to improve the properties of WPC.

Based on the outcomes of this study, WPB can be suggested for use in concrete for non-structural works. Such modified concrete would appear to provide a very environment-friendly method of WPB disposal and minimize the depletion of natural resources. This modified concrete can be used accordingly in situations which require lightweight and low-strength construction work such as park benches, stone curbs, temporary structures, driveways, walkways, concrete barriers. This modified concrete can also be used to repel freeze–thaw action.

Durability studies can be carried out in the future for carbonation test, chloride test, and freeze and thaw action and shrinkage test of waste plastic concrete.

Acknowledgements The authors would like to acknowledge the Department of Science and Technology, New Delhi, for financial support of this study (No. DST/SSTP/Rajasthan/331).

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