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Utilization of plastic waste as replacement of natural aggregates in sustainable concrete: effects on mechanical and durability properties

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Abstract

The study presents the mechanical and durability properties of concrete made up of recycled-waste-polyethylene (PE) and waste-polyethylene-terephthalate (PET)-based aggregate as replacement of natural fine and coarse aggregate, respectively. For this purpose, compressive strength, sorptivity, water permeability, aggressive exposure in acid, base, marine and wastewater, impact resistance, abrasion loss including surface and Cantabro, gas permeability, rapid chloride penetration test (RCPT), elevated temperature and leachability test of microplastic were performed. The experimental works were performed for different volumetric replacement (0–40%) of natural fine and coarse aggregates by PE and PET made aggregate respectively for different curing periods. The experimental results revealed that the sorptivity of PE-based concrete was lowest. Water permeability coefficient signified that with the increase of percentage of PET water permeability increased. In case of aggressive exposure test, the percentage of residual mass and residual strength for all replacement was decreased with the increase in exposure period. Further, impact resistance test result signified that energy absorption increased with the increase of PE and PET percentages. Cantabro and surface abrasion weight loss showed similar trend. Carbonation depth was increased with increasing percentages of PE and PET signified strength decreased with increase of percentages of PE and PET when subjected in CO_2. RCPT test results demonstrated that with increase of PE and PET percentages chloride ion penetrability was reducing. It is observed that below 100 °C temperature, compressive strength of all mix proportions was not affected with elevated temperature. Moreover, the PET-based concrete showed no presence of microplastic in case of leachability test.

Keywords Plastic waste concrete · Recycled polyethylene · Waste polyethylene terephthalate · Volumetric replacement · Compressive test · Durability test · Leachability test

Introduction

The generation of waste plastic has increased day by day worldwide (Gondal et al. 2022; Jadhav et al. 2022). According to UNEP, around 400 million tonnes of waste plastic are produced annually worldwide with a growth of 4.6% per year. As management methods, 9% of all globally generated waste plastic is recycled and 12% is burned (da Luz Garcia et al. 2021). Remaining 79% of waste plastic are either disposed in landfill or in aquatic systems. Indiscriminate disposal and open burning of plastic wastes result in serious environmental problems including emission of toxic and hazardous air pollutants like dioxins, furan and particulate matter, increase in microplastic and heavy metal concentrations in aquatic system through degradation processes and reduction in water permeability and soil fertility of agricultural fields. Voluminous generations of single used plastic have increased significantly worldwide in recent years as the safety equipment to fight against the COVID-19 pandemic. Though Indian Government restricted the use of single use plastic from July 2022 but India alone was reported to generate 5.58 million tons of single use plastic per year. About 20% of the total waste plastic is of polyethylene terephthalate (PET) type, and 29% is made up of items with polyethylene(PE) foundation (Nvironment 2011).

The significant increase in single-use plastic waste (PW) motivates researchers to find effective, safe, low-cost and

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sustainable methods to manage it in urgent basis (Zhang et al. 2023). The desired characteristics like low water adsorption capacity, corrosion resistance, low electrical and thermal conductivity and high impact resistance capacity of waste plastic suggest the material may be one of the potential eco-friendly and effective alternatives of natural coarse and fine aggregate in cement concrete production and includes PW in circular economy. Life cycle assessment (Zhang et al. 2023) of plastic waste also proves that recycling of PW can improve environment by reducing global warming (Tian et al. 2020) potential and human toxicity. Around 60–80% of concrete is made up of aggregate (Naderi and Kaboudan 2021). To achieve this requirement, aggregate usage worldwide is around 13.12 billion tonnes per year (Islam and Shahjalal 2021).

Extraction of natural aggregates from quarry is a highly environmentally negative activity led to subsequent energy use and related greenhouse gas (GHG) emissions, degradation of landscape and land stability, pollution of water resources, pollution of the atmosphere due to particulate matter, societal impacts due to vandalism, etc.

Recycling of waste plastic as replacement of natural aggregates can be a hopeful approach to reduce the number of environmental hazards, social issues and health risks associated with extraction of natural aggregates (Jain et al. 2022). In past, several research works were conducted on the determination of strength (Sim and Park 2011; Gu and Ozbakkaloglu 2016) of waste plastic aggregate-based concrete. However, very few studies are available on the durability properties (Zega and Di Maio 2011) of waste plastic aggregate-based concrete. Akçaözoğlu et al. (2010) reported that mortar specimens with 100% PET aggregates had more water absorption values than a mortar with PET and sand aggregate. Choi et al. (2009) found sorptivity coefficient of mortars by replacing the 25–75% finer portion of natural aggregates (NA) with lightweight aggregate (LWA), which was made by coating sand with PET at a temperature of 50 °C in an airtight mixer. It was evaluated that by adding 25% of the PET aggregate sorptivity increased up to 52%. Further, Ohemeng and Ekolu (2019) obtained 31% drop of sorptivity coefficient when 75% of natural fine aggregates (FAs) were replaced by low-density polyethylene (LDPE) (Frigione 2010). Majeed et al. (2019) explored that up to 12% CA can be replaced beneficially by high-density polyethylene (HDPE) in terms of water adsorption capacity. He further added that additional 6% of HDPE resulted 75% increase in water adsorption capacity. Silva et al. (2013) demonstrated that the permeability of the flaky particles is greater than that of the PET-pelleted particles in concrete. Saxena et al. (2018) suggested that for concrete containing

coarse and fine PET particles, liquid permeability is more due to higher void content. Lee et al. (2019) found out that the water penetration rate decreases due to modification of microstructure pore system and bond qualities of PET. Jain et al. (2020) observed that there is a decrease of water penetration depth of concrete with fine aggregate (FA) partially replaced by LDPE granules made from plastic bag waste.

According to the investigation carried out both by Janfeshan Araghi et al. (2015) and by Nikbin et al. (2016), degradation rate of weight increases and load sustain decreases of concrete specimens with PET immersed for 60 days in 5% sulphuric acid solution. Saxena et al. (2018) and Jain et al. (2020) established that PET-based concrete performs better when it is exposed to low-velocity impact loads as it has enhanced energy absorption capacity. Jain et al. (2020) evaluated that the abrasion resistance in terms of the loss in thickness was decreased by 50% when 20% of FA was replaced using HDPE. Alqahtani et al. (2018) found out a reduction in abrasion values ranging from 29 to 58%, for the replacement levels of CA from 25 to 100% using LDPE by volume. Galvão et al. (2011) examined mass loss for concrete samples containing 0%, 2.5% and 5% PET aggregates under erosion and abrasion and reported that the concrete with 5% PET aggregates had greater resistance to abrasion than the control mix. Furthermore, according to Ferreira et al. (2012), abrasion resistance of concrete increased by using PET as FA and CA in concrete. Saikia and de Brito (2014) also opined that PET aggregates in concrete tend to enhance abrasion resistance, when replacement levels were increased by 10% flaky aggregates.

According to the research conducted by Sim and Park (2011) and Mercante et al. (2018), penetration gases, such as carbon dioxide or other suspended ions, may have an unfavourable impact on the durability of embedded steel reinforcement and composite materials. According to the research outcome of Akçaözoğlu et al. (2010), the mortars having both sand and PET had deeper carbonation levels than mortars carrying only 100% PET. Furthermore, Silva et al. (2013) found that the carbonation depth (Sim and Park 2011) increased in concrete containing 15% PET aggregates than control concrete due to the increase in porosity of the mix. According to the research performed by Gavela et al. (2013), no carbonation was observed in any specimens exposed up to 240 days, which were prepared by adding polypropylene (PP) and HDPE in concrete. Almeshal et al. (2020) reported chloride ion penetration (Sim and Park 2011) increased with increase of plastic waste aggregate in concrete. Further, Silva et al. (2013) determined that chloride penetration coefficient increased up to 57% by substitution of 15% fine aggregate (FA) with flaky PET particles in

concrete. Alqahtani et al. (2018) suggested that the chloride permeability in concrete may be significantly reduced by using recycled synthetic aggregates in concrete. Islam et al. (2022) conducted elevated temperature test and found that at high temperatures, compressive strength decreased by 10.8% and 34% at 100 °C and 200 °C respectively. Saxena et al. (2018) reported that residual compressive strength of concrete subjected to temperatures at 300° and 600 °C were reduced when both FA and CA were replaced with 5–20% PET aggregates by volume. In another study, Correia et al. (2014) observed decrease in residual compressive strength when PET flakes and pellets were used in concrete and heated to 600° and 800 °C. Sojobi and Owamah (2014) found that the residual compressive strength of concrete heated to 500 °C was greater when up to 15% of FA (by weight) was replaced by LDPE. LDPE demonstrated greater performance than PET aggregates in concrete for durability study conducted by Galvão et al. (2011).

The different studies in the literature that have explored the use of waste plastic aggregate (WPA) as a replacement of natural fine aggregate (NFA) and natural coarse aggregate (NCA) in cement concrete have largely focused on its impact on mechanical properties. Past literature signifies that limited durability study was conducted for cement concrete by replacing NCA and NFA by WPA made from single use PET and PE respectively. Thus, to fill the gap in the literature related to using waste plastic aggregate as a replacement of NCA and NFA in concrete, this study was conducted to examine the effects of incorporating WPA on the mechanical property (compressive strength) and durability of concrete before recommending WPA as replacement of natural aggregates. The durability tests include sorptivity test, water permeability test, aggressive exposure test of acid, base, marine and municipal waste water, impact resistance test, abrasion loss test including surface and Cantabro, gas permeability test, rapid chloride penetration test (RCPT), elevated temperature test and leachability of microplastic test. To evaluate the microstructural change due to addition of plastic waste-based aggregates, optical microscope tests were also performed for all concrete mixtures at 28 days

of curing period. This research will fill an important gap between practice and the literature related to durability of WPA-based concrete.

Materials and methods

Material

In the present study to prepare concrete mix, locally available Portland pozzolanic cement of 43-grade comply to IS-part-I (1489)(Table 1) was used. Clean river sand having dry compacted bulk density of 1600 kg/m³ and fineness modulus of 2.84 with specific gravity 2.66 was employed as fine aggregate (Table 2). As coarse aggregate, naturally obtained crushed stone having specific gravity of 2.76, maximum particle size of 20 mm and dry compacted bulk density of 1650 kg/m³ was used (Table 2). The sieve analysis revealed that the coarse aggregate and the fine aggregate were in grading zone II according to IS 383 (1970) (Fig. 1b). To enhance the workability of concrete while utilizing lower water-cement ratios, a super plasticizer (CONPLAST SP 430 DIS admixture) confirming (ASTM C494-19 2019) was applied. Natural fine aggregate (NFA) and natural coarse aggregate (NCA) were
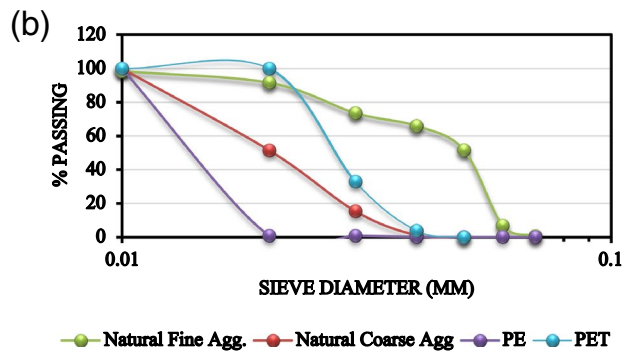
Table 2 Properties of natural coarse and fine aggregate

Properties	Coarse aggregate	Fine aggregate
Specific gravity (oven dry condition)	2.6	2.3
Specific gravity (saturated surface dry condition))	2.76	2.66
Bulk density (kg/m³)	1650	1600
Water absorption (%)	0.70	1.10
Fineness modulus (%)	6.6	2.9
Los Angeles abrasion, LAA (%)	30	–
Aggregate impact value, AIV (%)	32	–
Aggregate crushing value, ACV (%)	30	–

Table 1 Physical and mechanical properties of cement

	Test	Average	Limitation (IS-part-I, 1489)
Physical tests	Normal consistency (%)	34	–
	Initial setting time (min)	120	Min 30
	Final setting time (min)	300	Max 600
	Soundness (mm)	2	Max 10
	Cement fineness (cm²/gram)	350	Min 300, Max 450
Compressive strength test	7 days (MPa)	25	
	28 days (MPa)		
		25	Min 22
		42.85	Min 33

replaced by PE- and PET-made aggregate, respectively. Cutting PET bottles into small bits that can pass through a 20-mm screen and be retained in a 10-mm sieve were allowed for the creation of coarse aggregates. Despite being flaky, they were employed as a partial replacement of natural coarse aggregate because of their hardness. On the other hand, melting PE and cutting it into beads were used to create fine aggregates with a diameter of 1 to 5 mm. Table 3 illustrates the characteristics of PET- and PE-based aggregates used in the present study. Both

Table 3 Properties of PET- and PE-based aggregates

Property	PET	PE
Specific gravity	0.8–0.9	0.7–0.9
Water absorption %	0.44	0.005
Melting point (°C)	130–180	100–150
Impact strength (J/m)	120	10–200
Young's modulus (MPa)	1800	800
Fineness modulus (%)	6.5	2.6

types of aggregates were gathered from a nearby recycling facility. The flowchart of processing of the PET and PE aggregates utilized in the present research is presented in Fig. 1a. The aggregates were heated with natural sand to improve the binding strength between cementitious matrix and plastic aggregates and decrease the gap at the interfacial transition zone (ITZ). Figure 1b depicts the gradation of plastic aggregates used, which were obtained from sieve analyses.

Experimental methods

Mix design

Mix designs for concrete of the M30 grade were carried out in the current experiment following (IS 10262 (Revised) 2019). For 0% replacement level (Control mix) and constant water–cement (W/C) ratio 0.37, the quantities of water (IS-456:2000) cement, natural fine aggregate (NFA), natural coarse aggregate (NCA) and chemical additive (superplasticizer) for M30 grade concrete were determined as 165 kg, 410 kg, 690 kg, 1170 kg, and 4.08 kg per cubic meter of concrete, respectively. The quantity of chemical additive was determined based on the workability of the fresh concrete mixture from trial–error process to ensure the good quality of the concrete mixture. In this investigation, to evaluate the effects of replacing NFA and NCA by PE- and PET-made aggregates on mechanical and durability properties

of concrete, three trials each having four mixtures were prepared keeping W/C ratio constant (0.37) (Table 4). In the first trial, PE-made aggregate was employed to replace NFA at different volumetric replacement percentages, including 10%, 20%, 30%, and 40%, and denoted as PE10, PE20, PE30, and PE40, respectively (Table 4). Only naturally occurring coarse aggregates (NCAs) were swapped out with PET-made aggregates in the second trial and were denoted as PET10, PET20, PET30, and PET40, respectively (Table 4). In the third trial, both PET- and PE-made aggregates were used in place of the coarse and fine aggregates, respectively, that were naturally obtained and were denoted as WPA10, WPA20, WPA30, and WPA40, respectively (Table 4). All the mixtures were made triplicate, and average of the test results was reported. Table 4 contains the mix proportions for 4 replacement levels for all trials keeping W/C ratio same and same chemical admixture.

Casting and curing of sample specimen

All the constituents of concrete were measured with 0.005 g accuracy. At first, all the constituents of concrete were mixed thoroughly to achieve homogeneous mixture by hand on a waterproof frame. The mixture was then carefully added with tap water (IS-456:2000) and chemical additives to ensure that no water was wasted during mixing. The compaction of the sample was improved using a vibrating instrument. 100 mm × 100 mm × 100 mm cubes and cylinders with

Table 4 Mix proportions for different trials

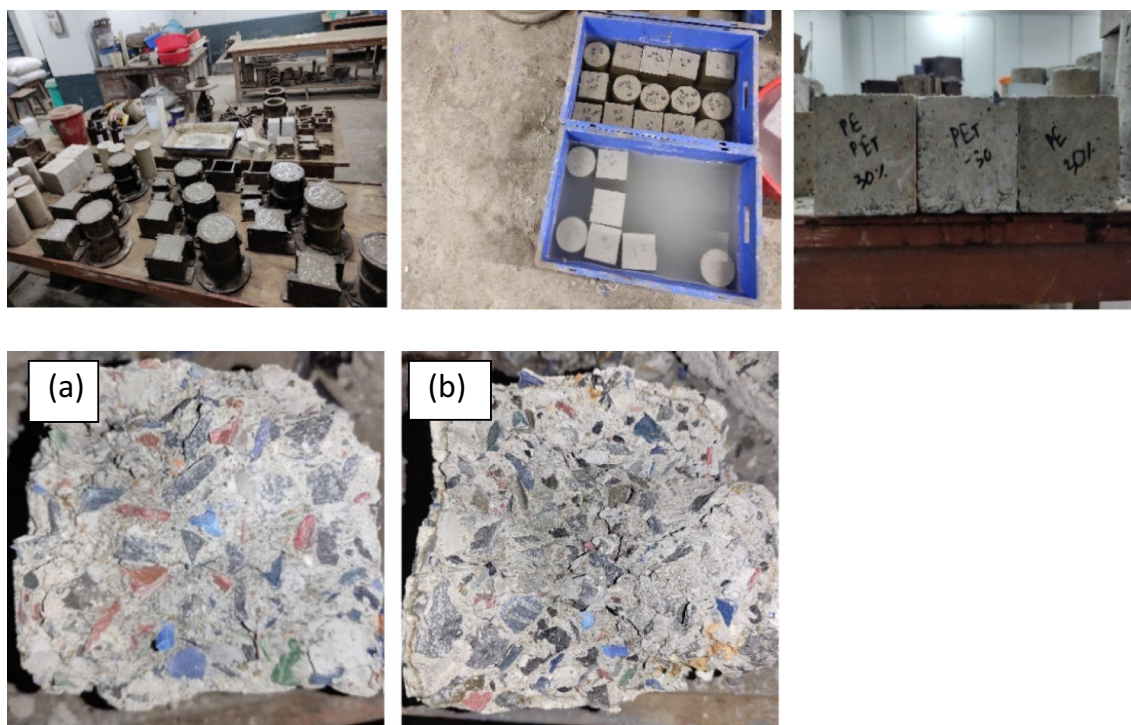| mix name	Percentage replaced by waste plastic	Quantity of cement in kg/m^3	Quantity of water in kg/m^3	Quantity of fine aggregate in kg/m^3	Quantity of coarse aggregate in kg/m^3	Chemical Admixture in kg/m^3	Quantity of PE aggregate in kg/m^3	Quantity of PET aggregate kg/m^3
Control	0	410	165	690	1170	4.08	0	0
First trial								
PE10	10	410	165	610.83	1170	4.08	22.09	0
PE20	20	410	165	542.96	1170	4.08	44.18	0
PE30	30	410	165	475.09	1170	4.08	66.27	0
PE40	40	410	165	407.22	1170	4.08	88.34	0
Second trial								
PET10	10	410	165	690	1083.238	4.08	0	43.60
PET20	20	410	165	690	962.88	4.08	0	87.22
PET30	30	410	165	690	842.52	4.08	0	130.82
PET40	40	410	165	690	722.16	4.08	0	174.43
Third trial								
WPA 10	10	410	165	654.01	1131.38	4.08	26.17	9.30
WPA 20	20	410	165	626.76	1059.16	4.08	52.33	18.60
WPA 30	30	410	165	599.52	986.95	4.08	78.5	27.90
WPA 40	40	410	165	572.26	914.73	4.08	104.66	37.21

Fig. 2 Sample preparation and curing of test specimens. Cross-sectional views of **a** PET- and **b** WPA-based concrete

a diameter of 100 mm and heights of 200 mm, respectively, were cast to examine subsequent mechanical and durability qualities. After casting, the samples were initially cured under ambient conditions at 27 °C and 90% relative humidity for the first 24 h, after which they were demoulded and immersed in normal water in the curing tank until testing. Sample preparation and curing of test specimens are depicted in Fig. 2.

Testing procedures

As mechanical property of concrete, the compressive strength test was performed according to IS:516-1959 (1959) using compression testing machine. The cross-sectional views of concrete mix samples are presented in Fig. 2a, b.

The durability properties of concrete were investigated using the sorptivity test, the water permeability test, exposure test in different adverse medium like acid, alkaline, marine and municipal wastewater, resistance to impact loads, resistance to abrasion, gas penetration test, chloride ion penetration test and elevated temperature effect test. Different information related to the size of the testing sample and details of curing periods are presented in Table 5 regarding the mechanical and durability study. The sorptivity test was carried out according to ASTM C1585 (2013) by measuring the $Ca(OH)_2$ solution absorption rate due to capillary action with respect to the cross-sectional area of concrete specimen cured at various times exposed to the $Ca(OH)_2$ solution up to 2 mm height from the base at various time as 3, 6, 9, 12, 15, 20, 30, 45, 60, 75, and 120 min (Fig. 3a–c). To maintain the
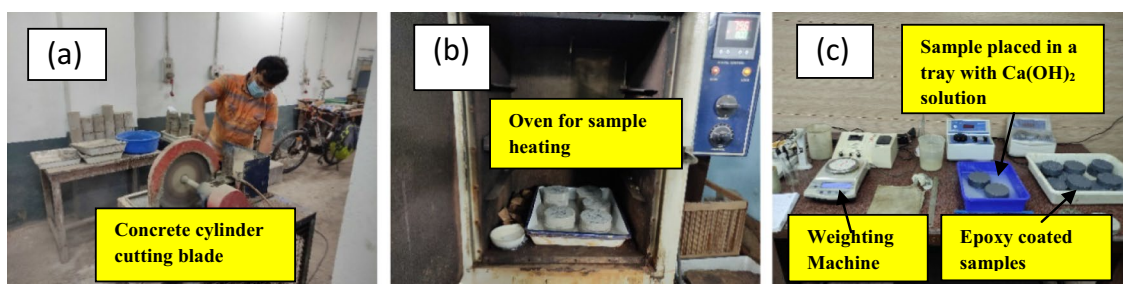

Fig. 3 **a** Iron cutter machine for slice of specimen, **b** inside view of test specimens in oven and **c** sorptivity test set-up

Table 5 Details of sample dimensions and curing period for all tests regarding mechanical and durability study

Name of the test	Curing (days)	Testing inventory (days)	Types of sample	Size of original sample (mm×mm×mm)	Sample size to be tested (mm×mm×mm)
Compressive strength	28	28	Cube	100×100×100	100×100×100
Sorptivity test	28	7,28,56 and 90	Cylinder	200×100(dia)	30×100(dia)
Acid resistance test (H$_2$SO$_4$) and (HNO$_3$)	28	7,28,56	Cube	100×100×100	100×100×100
Marine water exposure test	28	7,28,56	Cube	100×100×100	100×100×100
Waste water exposure test	28	7,28,56	Cube	100×100×100	100×100×100
Alkaline water exposure test	28	7,28,56	Cube	100×100×100	100×100×100
Impact test	28	28	Cylinder	200×100(dia)	200×100(dia)
Cantabro abrasion test	28	28	Cylinder	200×100(dia)	50×100(dia)
Surface abrasion test	28	28	Cube	25×25×25	25×25×25
Water permeability test	28	28	Cube	100×100×100	100×100×100
Gas permeability test	28	28	Cube	100×100×100	100×100×100
RCPT test	28	28	Cylinder	200×100(dia)	50×100(dia)
Elevated temperature test	28	28	Cube	100×100×100	100×100×100
Leachability test	28	28	Cube	Dust	Pure dust < 5 mm
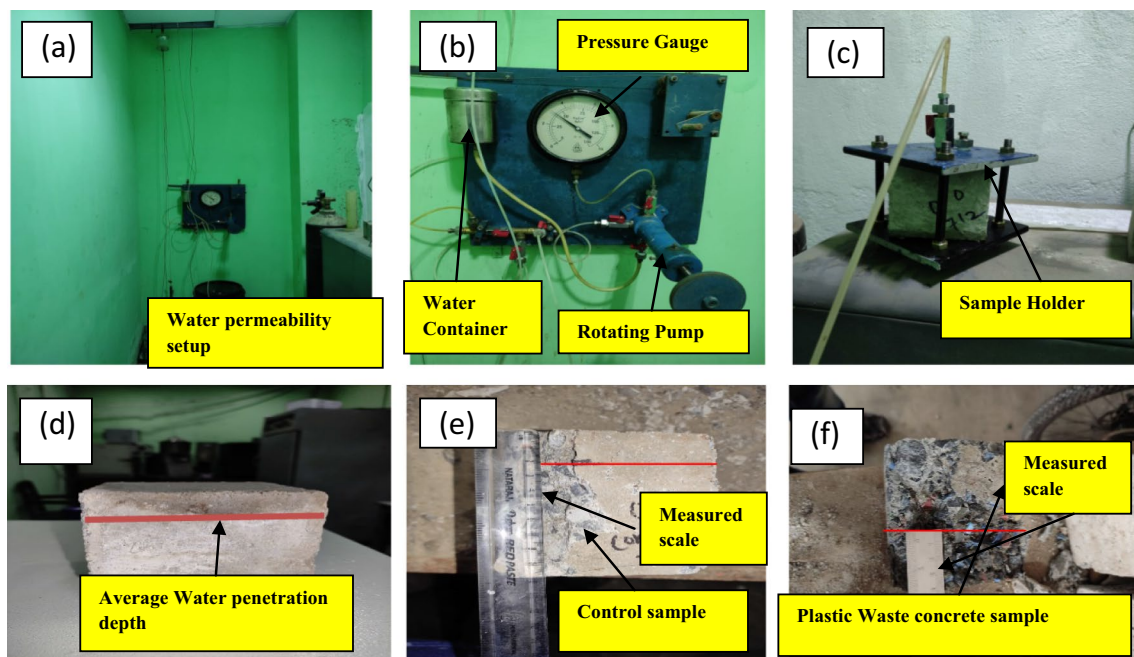
Fig. 4 **a** Water permeability set-up, **b** water permeability apparatus, c sample holding equipment, **d** pattern of water penetration, **e** water penetration depth measurement of control and **f** water penetration depth measurement of plastic waste based-concrete sample

lime solution depth 2 mm from the base of concrete during the test, the solution was continuously poured into the tray. In this experiment, the sorptivity coefficient (S) is calculated using Eq. (1).

$$I = S \times t^{1/2} \tag{1}$$

where S (g/mm^2/min$^{1/2}$) is the sorptivity coefficient, t is the time in minutes, and I (g/mm^2) is the total amount of Ca(OH)$_2$ solution absorbed per unit cross-sectional area of the concrete specimen, which is known as

Table 6 Results of water permeability tests for plastic waste-based concrete for all trials including control

Specimen	Average water penetration depth (cm)	Maximum water penetration depth (cm)	Average water permeability coefficient (cm/sec)
Control	1.76	2	1.73×10^{-11}
PE10	2	2.1	2.88×10^{-11}
PE20	2.03	2.5	
PE30	2.4	2.6	
PE40	2.6	2.8	
PET10	2.53	2.6	4.162×10^{-11}
PET20	2.6	2.68	
PET30	2.76	2.89	
PET40	3	3.2	
WPA10	2	2.2	2.19×10^{-11}
WPA20	1.8	2	
WPA30	1.9	2.3	
WPA40	2.2	2.5	

capillary suction rate. The permeability of concrete specimens (100 mm × 100 mm × 100 mm) was determined after 28 days curing adopting the forced technique using 0.3 MPa (3 bar) of hydrostatic pressure for 72 h in a permeability apparatus according to the standard procedure (DIN 1048-5:1991-06 2015) as presented in Fig. 4a–f. After testing, the depth of penetration of water through the specimens was measured after dividing it in half using a compression device and the depth of penetrations are shown in Table 6. Using observed water depth and a modified version of Darcy's law, the coefficient of water permeability (k_w) is calculated using Eq. (2) as follows:

$$\frac{dx}{dt} = \frac{h}{x} k_w \qquad (2)$$

where k_w is the permeability coefficient (m/s), x is the penetration depth (m), t is the experiment period (s), and h is the water head (m). By integrating Eq. (2), one can easily deduce the permeability coefficient using Eq. (3).

$$k_w = \frac{x_t^2}{2ht} \qquad (3)$$

Here x_t represents the penetration depth at time t. Since the water flow is irregular and related to sorptivity, it makes more sense to use the average depth of water penetration when calculating k_w rather than the maximum depth.

To study the effects of adverse environmental exposure test on concrete, three randomly selected concrete cubes were exposed to acid (5% H_2SO_4 (Fig. 5a–c) and 5% HNO_3 (Fig. 6a–c) solution to maintain pH 0.3–0.5), alkaline water (5%NaOH solution) (Fig. 7a, b), marine water (Fig. 8a, b) and municipal wastewater (Fig. 9a, b) collected from sewer line for different curing periods as mentioned in Table 5. The acid resistance test was done as per ASTM
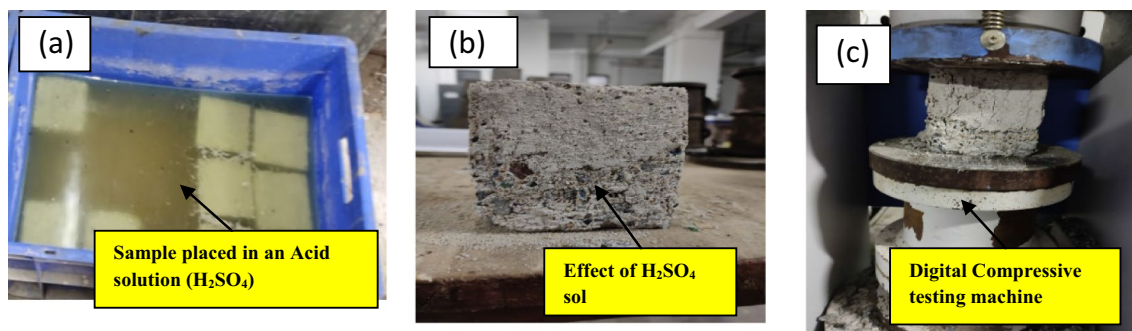

Fig. 5 **a** Cubes of 100 mm size for plastic waste-based concrete immersed in H_2SO_4 acid, **b** deterioration of specimen after storage in acid solution and **c** compressive strength test of acid-immersed sample
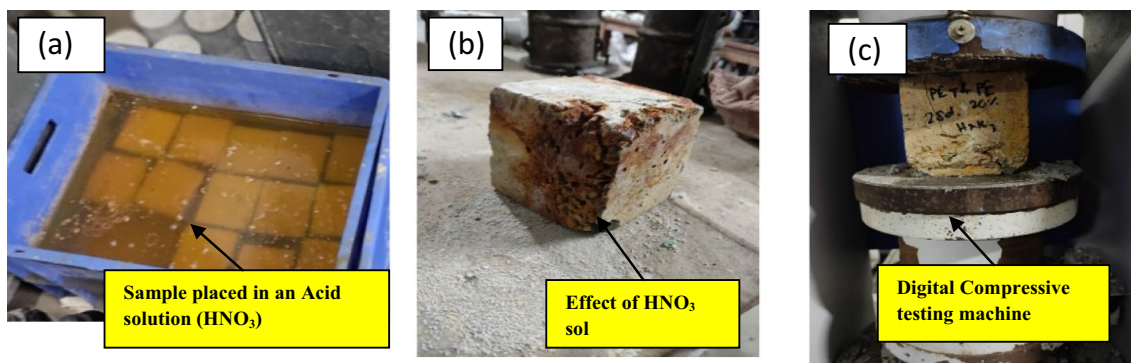
Fig. 6 **a** Cubes of 100 mm size for plastic waste-based concrete immersed in HNO$_3$ acid, **b** deterioration of specimen after storage in acid solution and **c** compressive strength test of acid-immersed sample
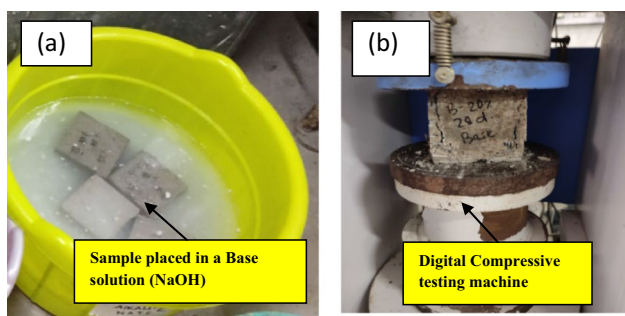

Fig. 7 **a** Cubes of 100 mm size for plastic waste-based concrete immersed in alkaline water and **b** compressive strength test of alkaline water-immersed sample
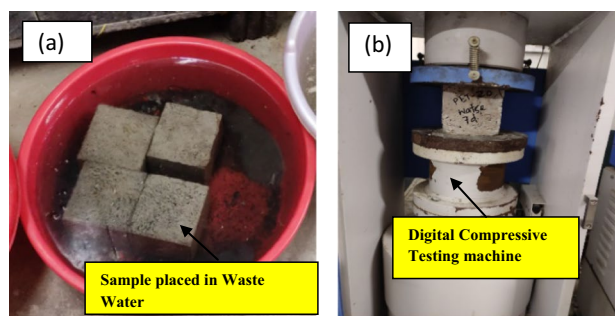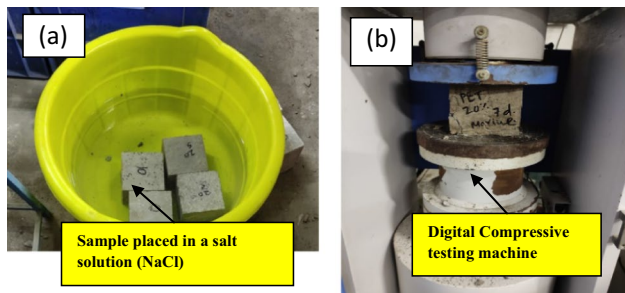

Fig. 9 **a** Cubes of 100 mm size for plastic waste-based concrete immersed in municipal waste-water and **b** compressive strength test of test specimen immersed in waste water

$$RM(\%) = \left(1 - \frac{A - B}{A}\right) \tag{4}$$

where B is the average mass of the three samples after a specific amount of time spent in an exposure solution, and A is the average mass of three samples before immersion in the exposure solution.

$$RS(\%) = \left(1 - \frac{C - D}{C}\right) \tag{5}$$

where C and D represent, respectively, the average compressive strength values of three samples before and after being stored in an exposure solution.

Fig. 8 **a** Cubes of 100 mm size for plastic waste-based concrete immersed in marine water and **b** compressive strength test of Marine water-immersed sample

C1898 (2020). The adverse effects of exposure by different solutions on concrete for different curing periods were expressed in terms of percentages of residual mass (RM) (Eq. 4) and residual strength (RS) (Eq. 5).

As a quasi-brittle substance, concrete has a very low tensile strength, a little amount of ductility, and a weak resistance to cracking when utilized as plain concrete. These characteristics severely restrict its use to high strain-rate loadings such as collisions, explosions and earthquakes. In the past, there has been a great deal of research on using polymers
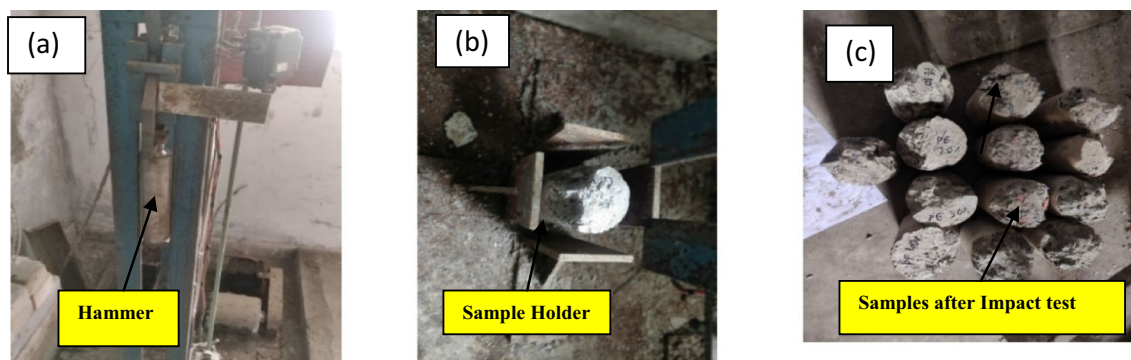
Fig. 10 **a** Drop weight impact resistance test set-up, **b** sample holder and **c** failure pattern of specimen

Table 7 Impact resistance test results for PE-, PET-, PE&PET (WPA)-based concrete specimens

Specimen	No. of blows for first crack	No. of blows for ultimate failure	Ductility index (E_2/E_1)	Average ductility index (E_2/E_1)
Control	10	18	1.8	1.8
PE 10	13	24	1.85	1.72
PE 20	16	27	1.69	
PE 30	19	32	1.68	
PE 40	20	33	1.65	
PET 10	12	30	2.5	2.185
PET 20	14	33	2.36	
PET 30	18	37	2.06	
PET 40	22	40	1.82	
WPA10	14	39	2.79	2.348
WPA20	15	40	2.667	
WPA30	21	44	2.095	
WPA40	25	45	1.84	

in the form of fibres to get around these restrictions (Islam and Shahjalal 2021). The impact resistance of plastic waste concrete was tested using drop weight test equipment, as

shown in Fig. 10a–c, which consists of a typical manually operated at 3.5-kg compaction hammer allowed to drop from 0.73 m following the work mentioned in Thiyagarajan (2014). The specimen was positioned within the impact testing apparatus, completed face up, on a base plate. The hardened steel hammer was set on top of the specimen within the bracket after the bracket with the cylindrical sleeve had been fastened in place. The drop hammer was then raised vertically, its base resting above the steel hammer. The number of blows needed to generate the first apparent fracture at the specimen's top surface and the point of eventual failure were counted after the hammer was repeatedly dropped as depicted in Table 7 including ductility index. Visual inspection allowed for the detection of the first crack. The shattered specimen butting against the base plate legs made it easy to identify the stages of final collapse.

Abrasion resistance test is an important parameter to determine the resistance of concrete against the abrasion loads due to traffic. The abrasion resistance of concrete may be calculated by adopting Cantabro abrasion test as per C1747/C1747M (2013) and surface abrasion test as per ASTM C944/C944M (2012). The Los Angeles abrasion testing machine without steel ball (Fig. 11a–c) was used for
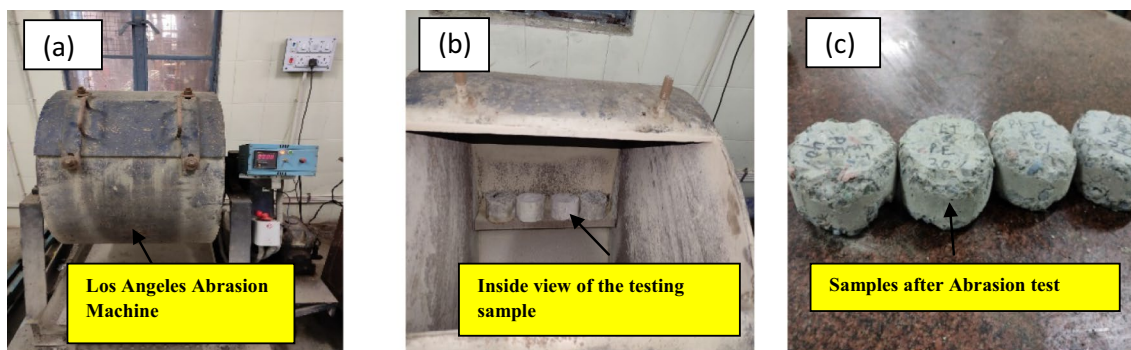

Fig. 11 **a** Los Angeles abrasion testing machine, **b** inside view of specimens and **c** shape of various specimens used in Cantabro abrasion loss test

Cantabro abrasion test, and the location of each set of three cylindrical specimens, each measuring 100 mm in diameter and 50 mm in height, inside the machine is depicted in Fig. 11b. Initial weight (W_1) of each specimen were noted before insertion into the apparatus. Then, this machine was permitted to rotate at rotation rates of 50, 100, 150, 200, 250, and 300 per minute. The abraded specimens were cleared of any loose material and precisely weighed to determine W_2 at each level of revolution. Finally, Eq. (6) is used to compute the percentage weight loss:

$$\text{Cantabro weight loss, } \% = \left(\frac{w_1 - w_2}{W_1}\right) \times 100 \qquad (6)$$

where W_1 denotes the test specimen's initial weight in grams and W_2 denotes its final weight in grams. All the experiments were performed for the concrete mix of 28-day curing time for a cylindrical shape (100 ϕ mm × 50 mm thickness).

The surface abrasion test was run for a total of 6 min for each type of concrete mix at 50 revolutions per minute for 300 revolutions using cube specimen of dimension 100 mm × 100 mm as per ASTM C944/C944M (2012) cured for 28 days using drill press with a rotating cutter (IS 1237:2012). Each of the concrete specimens was placed in the drill press and the rotating cutter was mounted slowly until the surface of the specimen was touched (Fig. 12a–c). Then the device was set to rotate for 2 min at a speed of 200 rpm with a vertical load of 98 N. After rotation the specimen was removed from the device and its surface was cleaned and weighed. The data were taken for each 1 min interval. Equation (7) is used to determine the weight loss due to surface abrasion:
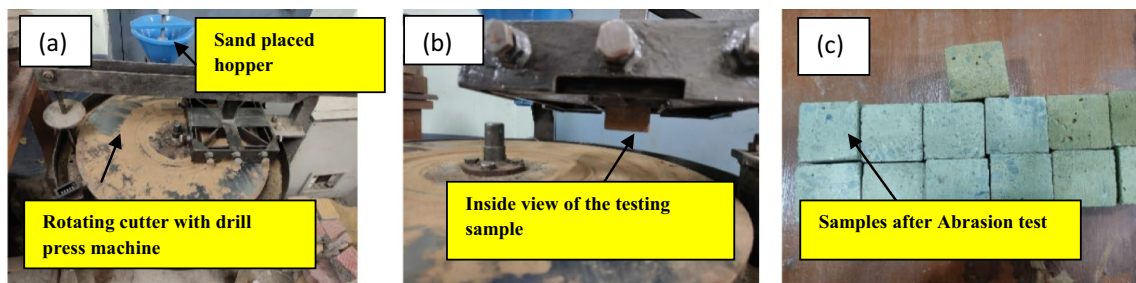

Fig. 12 **a** Rotating cutter with drill press machine, **b** sample holder and **c** surface of specimens in surface abrasion loss test
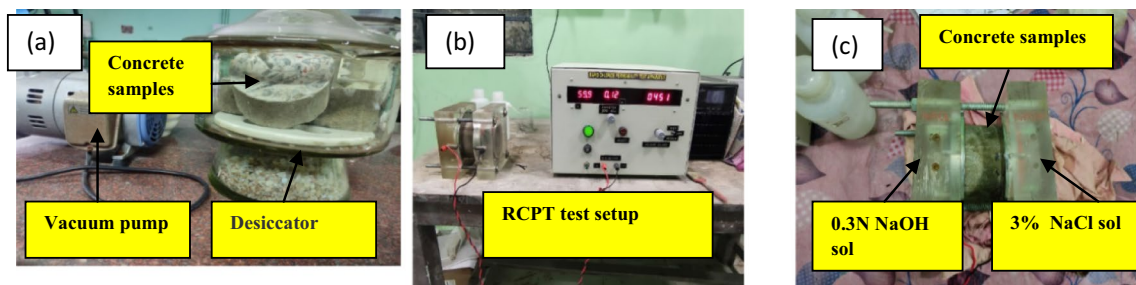

Fig. 13 **a** Saturation set-up, **b** RCPT test apparatus and **c** sample holder for RCPT test
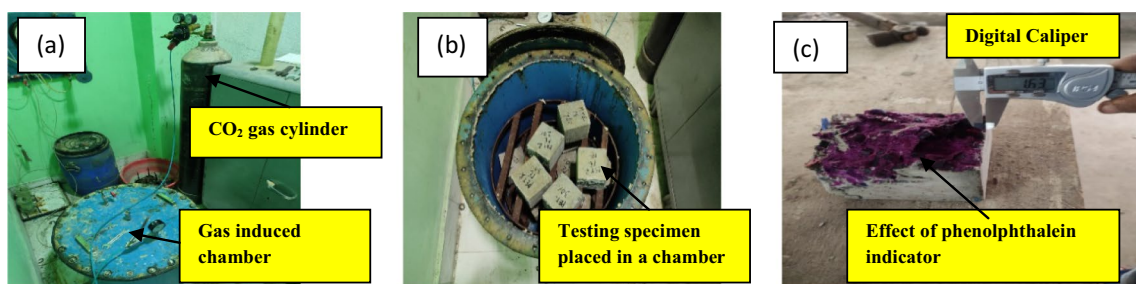

Fig. 14 **a** Gas permeability test apparatus, **b** specimens inside carbonation chamber and **c** phenolphthalein test for CO_2 cured specimen

Surface Abrasion Weight Loss, $\% = \left(\dfrac{w_1 - w_2}{W_1}\right) \times 100$

$$(7)$$

where W_1 denotes the test specimen's initial weight in grams and W_2 denotes its final weight in grams.

The rapid chloride ion penetration test was done as per ASTM C1202-12 (2012). After 28 days of curing, all concrete samples (100 mm × 100 mm) were removed from the curing tank and divided into slices of 50 mm thickness using an iron cutter. The slices were then vacuum-saturated for three hours as seen in Fig. 13a and reaerated. One face of the slice was exposed in anolyte solution (0.3N NaOH) and other face in catholyte NaCl (3%) solution while connected to the power supply. Both faces of the concrete samples were exposed in solutions for 18 and a half hours before supplying power supply (Fig. 13b, c). The voltage of power supply was set 60 V. The test was lasted for six hours, with 30-min intervals for measuring the current passed through the sample specimen during that time. According to the average value of three samples, the total charge passage was recorded in terms of coulombs, which indirectly measured the Cl^- passed through the sample.

The gas permeability test was performed following the protocol described by Kumar et al. (2019). A cylindrical metallic curing chamber with dimensions of 460 mm in height, 530 mm in diameter, and 2 kg/cm^2 retaining pressure at the outflow and intake was made for gas permeability test (Fig. 14a, b). The specimens were evaluated for compressive strength after being cured for 28 days in a CO_2 curing chamber under 20 psi of pressure. The depth of carbonation on the breakable face for each sample was determined using a phenolphthalein indicator solution (Fig. 14c). Carbonation depth was measured by digital calliper (Fig. 14c).

The elevated temperature test was performed following the protocol as suggested by Islam et al. (2022). The prepared concrete cubes after 28-day curing were heated uniformly for around 60 min at 100 °C, 200 °C and 300 °C in an enclosed muffle furnace chamber and then left in a dry environment to cool to room temperature to perform this test (Fig. 15a–c). The change in concrete's compressive strength for various combinations of mix proportions at various high temperatures was measured.

Leachability test

To assess the microplastic in concrete, the toxicity characteristic leaching procedure (TCLP) technique was modified. Concrete cube specimens of 100 mm in dimension were cast using varied amounts of plastic waste aggregate, and after air-drying for 1 day, the specimens were fully submerged in water for 28 days. The specimens were removed from the water and ground into powder after the necessary curing. For the test, crushed cube sample powder that passed through a 10-mm sieve was utilized.

In 96.5 mL of distilled water, 5 g of the crushed sample was added and agitated (Fig. 16a) for 5 min before the pH was determined for the extraction sample. All extraction samples were found to have pH values higher than 5. Then, a 3.5 mL of 1 N HCl was added with the extracted sample, mixed, heated to 50 °C for 10 min to determine P^H. The P^H was then measured once the solution had cooled to room temperature and found to have pH values lower than 5 (Fig. 16b). As seen in Fig. 16d, each of the flasks is then shaken by the shaker for 18 h at a temperature of around 25 °C and 60 rpm for different replacement along with both 100 g of crushed sample and 64.3 mL of 1 N NaOH solution and 5.7 mL of glacial acetic acid (98% pure) (Fig. 16c). After 18 h, the leachate was passed through the sieve (4.75 mm), and the fluid passed through the sieve (4.75 mm) was put into oven for 72 h at 70 °C for drying before being examined under a digital microscope (Fig. 16e–i) to detect the presence of microplastics following the NOAA Marine Debris Program (2015) guidelines.
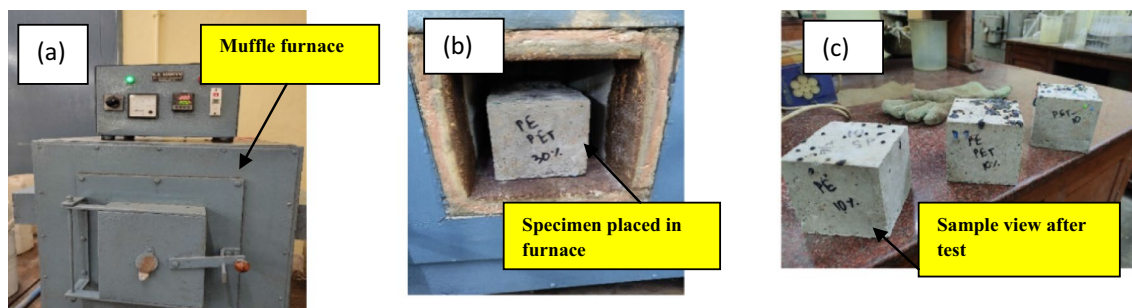

Fig. 15 **a** Muffle furnace, **b** inside view of specimen in Muffle furnace and **c** specimens after elevated temperature test cooled at room temperature
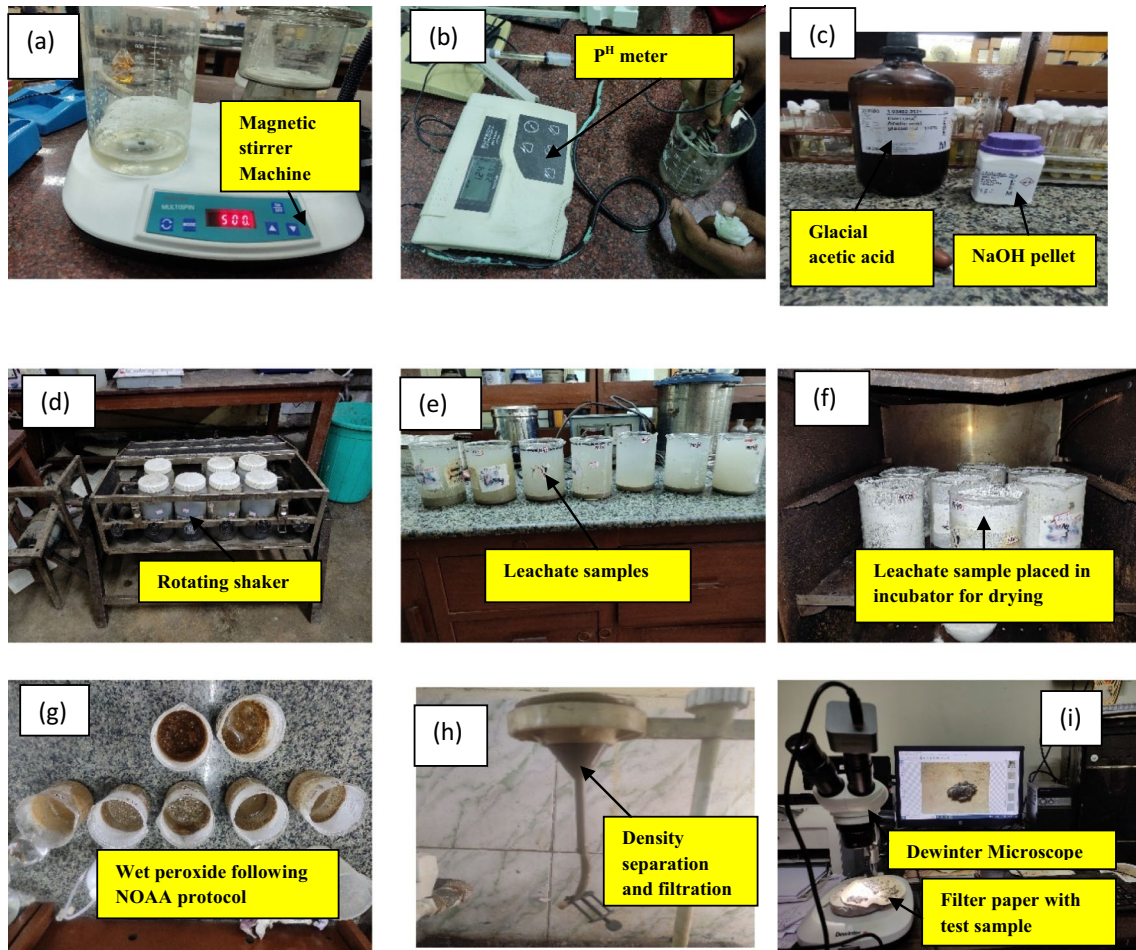
Fig. 16 **a** Mix vigorously using magnetic stirrer of crushed cube sample size less than 10 mm, **b** pH measurement of the sample, **c** NaOH pellet and glacial acetic acid, **d** Shaker, **e** extraction of leachate for test, **f** Leachate inside incubator, **g** wet peroxide, **h** density separation and filtration and **i** microplastic counting for leachability test

Fig. 17 Variation in compressive strength of plastic waste-based concrete for different mixtures
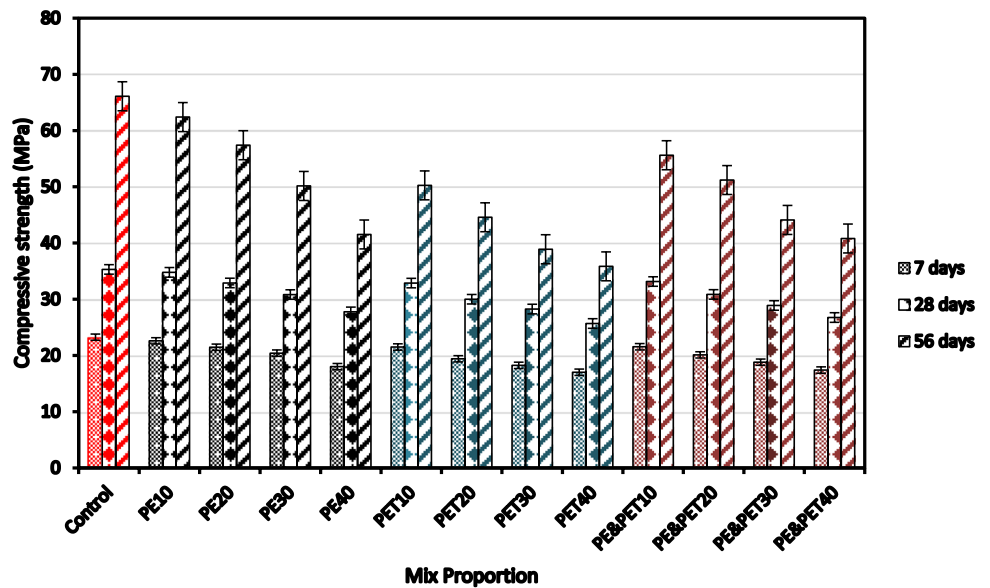
Results and discussion

Mechanical property

Compressive strength test

The compressive strengths of different concrete mixes for curing ages 7, 28, and 56 days are depicted in Fig. 17. With increase of PE content in concrete in place of NFA, the compressive strength decreased. It was observed that the compressive strength reduced by 3%, 8%, 12.21%, and 22.5%, respectively, for PE 10–40 as compared to the control mix. For the same proportional mixture, the strength increased from 7 to 56 days curing period. For replacement of NCA by PET, the compressive strength reductions were even more compared to control mixture for same curing ages. The compressive strengths improved for curing age 28 days as compared to the 7 day curing age for PET10-40. For WPA 10–40, the compressive strength reduction was in between PE concrete and PET concrete for 7-day curing period with compared to the control mix. The compressive strengths improved for 56-day curing period. The compressive strength was maximum for 56-day curing period for PE 10. Though compressive strengths reduced with incorporation of PE aggregates in place of natural fine aggregates but the concrete mixture can be utilized up to 30% replacement level as M30 grade concrete, while for PET concrete and WPA concrete the permissible replacement level was obtained up to 20% for curing period of 28 days. However, all the concrete mixtures (PE10-40; PET10-40 and WPA10-40) can be utilized for structural purpose for 28-day curing period.

The decrease in compressive strength as noted may be the result of weak interfacial transition zones (ITZ) between the plastic aggregates and cement paste. In addition, the hydrophobic properties of the plastic waste aggregate in concrete prevent cement near the ITZ from hydrating, leading to a poorer bond between the cement paste and aggregates. Similar results were also reported by others researchers (Jassim 2017; Saxena et al. 2018; Needhidasan et al. 2020; Tayeh et al. 2021; Shiuly et al. 2022; Sau et al. 2023).

Durability properties

Sorptivity test

Durability properties of concrete are mostly evaluated by its porosity and water absorption capacities. Higher sorptivity coefficient and water adsorption capacity of concrete can reduce service life of concrete by allowing penetration of contaminated water containing different chemicals. On the other hand, for the concrete pavement porous structure is advantageous to increase rain water penetration to soil. Plotting the best-fitted straight line between total amount of $Ca(OH)_2$ solution absorbed per cross-sectional area (I) against the square root of time $t^{1/2}$ yielded the sorptivity coefficient (S) from the slope as shown in Fig. 18a–c and Fig. 19a–c. Sorptivity analysis was conducted for 7, 28, 56, and 90 days of curing time, and only the test results corresponding to 56 and 90 days were described for all mixtures (Fig. 18d). For 56-day test, capillary suction rate lied between 21.42–71.424% for PET10-PET40 mixtures, while for PE10-PE40, the rate varied from 4.5 to 23.64%. But for WPA10 to WPA40 concrete, enhanced capillary suction rate was observed in the range of 12–46% (Fig. 19d). For 90 days curing time, capillary suction rate lied between 8–25.80% for PET10-PET40, for PE10-PE40, capillary suction rates lied between 4.34–26.08% but for WPA10-WPA40 enhanced capillary suction rates were observed in the range of 0–51.06%. Similar results were depicted by Jayeshkumar Pitroda (2013), Suram et al. (2021). The bulk of investigations on the sorptivity of plastic waste-based concrete as a discrete material replacing natural aggregate appear to support the conclusion that, regardless of the type of plastic, the water capillary suction rate increases with an increase in plastic waste aggregates content in the mix. The reasons behind the increased sorptivity value compared to control may be the increased porosity in concrete due to plastic aggregate, evaporation of extra water that is present around hydrophobic plastic waste aggregate; weak ITZ near plastic particles due to a poor connection between plastic waste aggregate and the binder matrix; introduction of plastic species, which disturbs the mixture's homogeneity; and effects of particle size and shape of plastic waste-based aggregate on the rheology and compaction properties of the composites.

Water permeability test

Results of the water permeability test for all trials of plastic waste concrete mix are shown in Table 6 and Fig. 20. Results show that water permeability coefficient was minimum for control concrete (1.76 cm) followed by PE10-PE40 and PET10-PET40 (Fig. 20). Similar findings were made by other researchers (Coppola et al. 2018; Saxena et al. 2018; Jain et al. 2020). When both natural aggregates were replaced by plastic aggregates, i.e., for WPA10-WPA40, water permeability coefficient increased but compared to PET and PE mixes it decreased. In other way, we can write in terms of water permeability coefficient for different concrete mix Control mix < WPA concrete < PE concrete < PET concrete (Table 6). The fundamental explanation for the rise

Fig. 18 **a** Cumulative capillary surface water absorption against time$^{1/2}$ for PE mixture series specimen after 56 days of curing. **b** Cumulative capillary surface water absorption against time$^{1/2}$ for PET mixture series specimen after 56 days of curing. **c** Cumulative capillary surface water absorption against time$^{1/2}$ for PE&PET (WPA) mixture series specimen after 56 days of curing. **d** Sorptivity coefficient of 56 days curing test for all concrete mixes
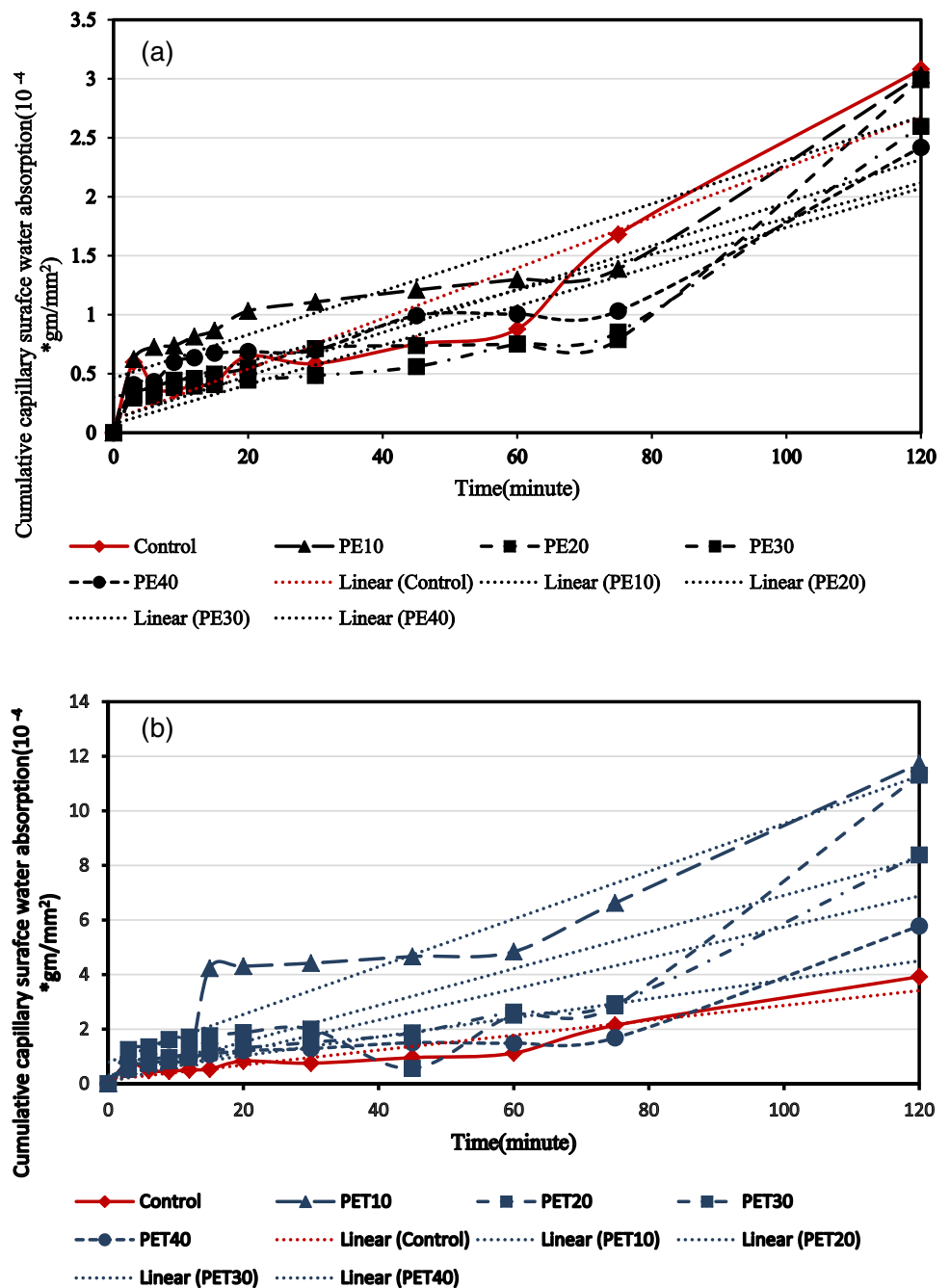

in permeability coefficient may be the increased porosity brought on by the development of fragile spots as a result of the tenuous bond between plastic waste aggregate and cement matrix in concrete and in homogeneous microstructure. The permeability of concrete can be decreased by decreasing pore density and discontinuous pore system between the cement paste and plastic waste aggregate.

Exposure test in different adverse solutions

Figure 21a, c, e presents the residual mass of different concrete specimens exposed to sulphuric acid solution for 28, 56 and 90 days. The results demonstrated that incorporation of plastic waste as aggregates increased residual mass as compared to the control mix for different curing times. The residual mass was maximum for 40% replacement of

Fig. 18 (continued)
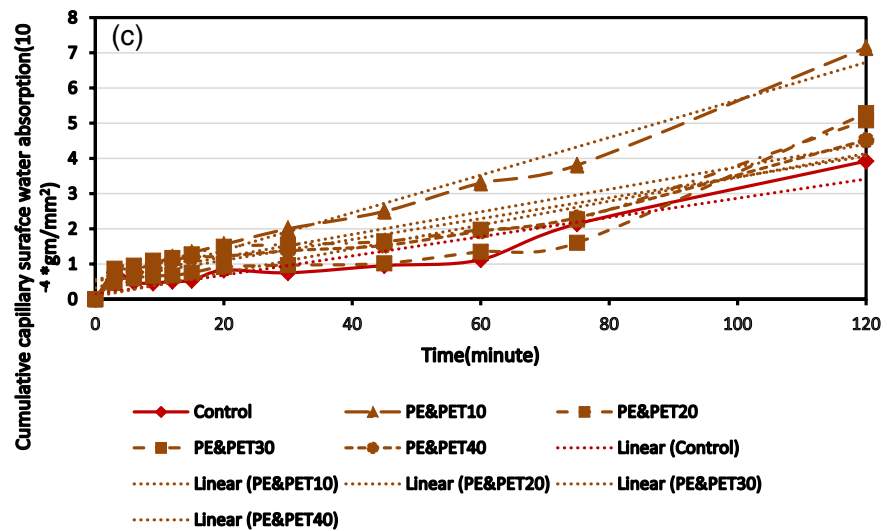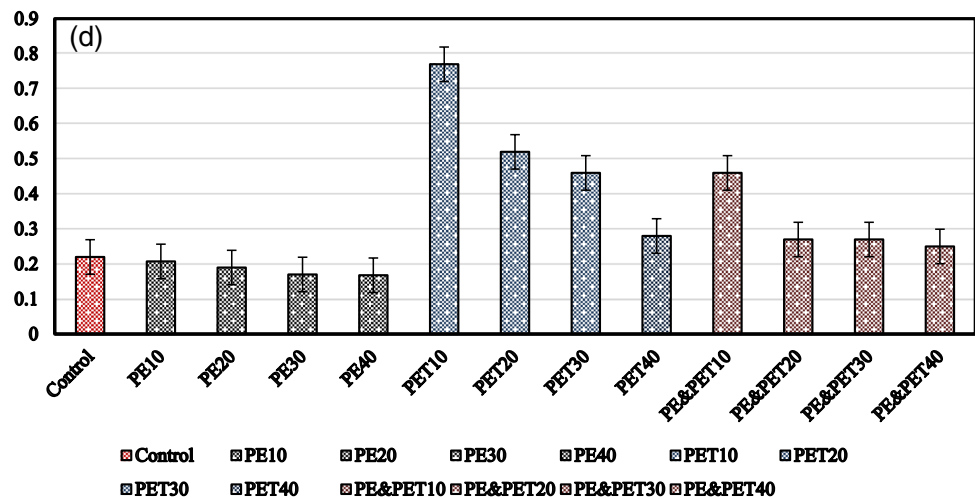
natural aggregates by PE and PET aggregates as observed. For WPA10 mix, no mass was observed to be reduced even after exposure to H_2SO_4 solution for 28 days. However, for WPA40 mix it was observed that the residual mass was maximum for 56-day curing time in H_2SO_4 acid. Control mix showed greater mass loss due to the availability of free calcium hydroxide $(Ca(OH)_2)$. The results as depicted in Fig. 21b, d, f demonstrated the strength loss for different concrete mixes for three different curing periods in H_2SO_4 acid solution. When a sample is immersed in H_2SO_4 acid solution, the strength loss was initially higher for all replacements at 7, 28 days compared to the control mix, but for 56 days of curing time, the strength loss was reduced for all replacements compared to the control mix. Sulphuric acid reacting with free $Ca(OH)_2$ produces

calcium carbonate in powder form and gypsum and eventually leading to the formation of ettringite. Ettringite causes concrete to expand, which results in internal pressure, and therefore, it deteriorates. Figure 22a, c, e presents residual mass of all samples for all trials exposed to nitric acid solution for 28, 56, and 90 days. The residual mass was maximum for 40% replacement of natural aggregates by PE and PET aggregates exposed to HNO_3 solution for 7 and 56 days and WPA with 10% replacement has maximum residual mass. Figure 22b, d, f presents residual strength of all samples for all trials exposed to HNO_3 solution. The residual strength was maximum at 56 days when exposed in HNO_3 solution for PE-based concrete as compare to control. The residual strength was maximum at 20% replacement by PET aggregates in concrete. Similar

Fig. 19 **a** Cumulative capillary surface water absorption against time$^{1/2}$ for PE mixture series specimen after 90 days of curing. **b** Cumulative capillary surface water absorption against time$^{1/2}$ for PET mixture series specimen after 90 days of curing. **c** Cumulative capillary surface water absorption against time$^{1/2}$ for PE&PET (WPA) mixture series specimen after 90 days of curing. **d** Sorptivity coefficient of an after 90 days curing test for all mix proportion-based concrete
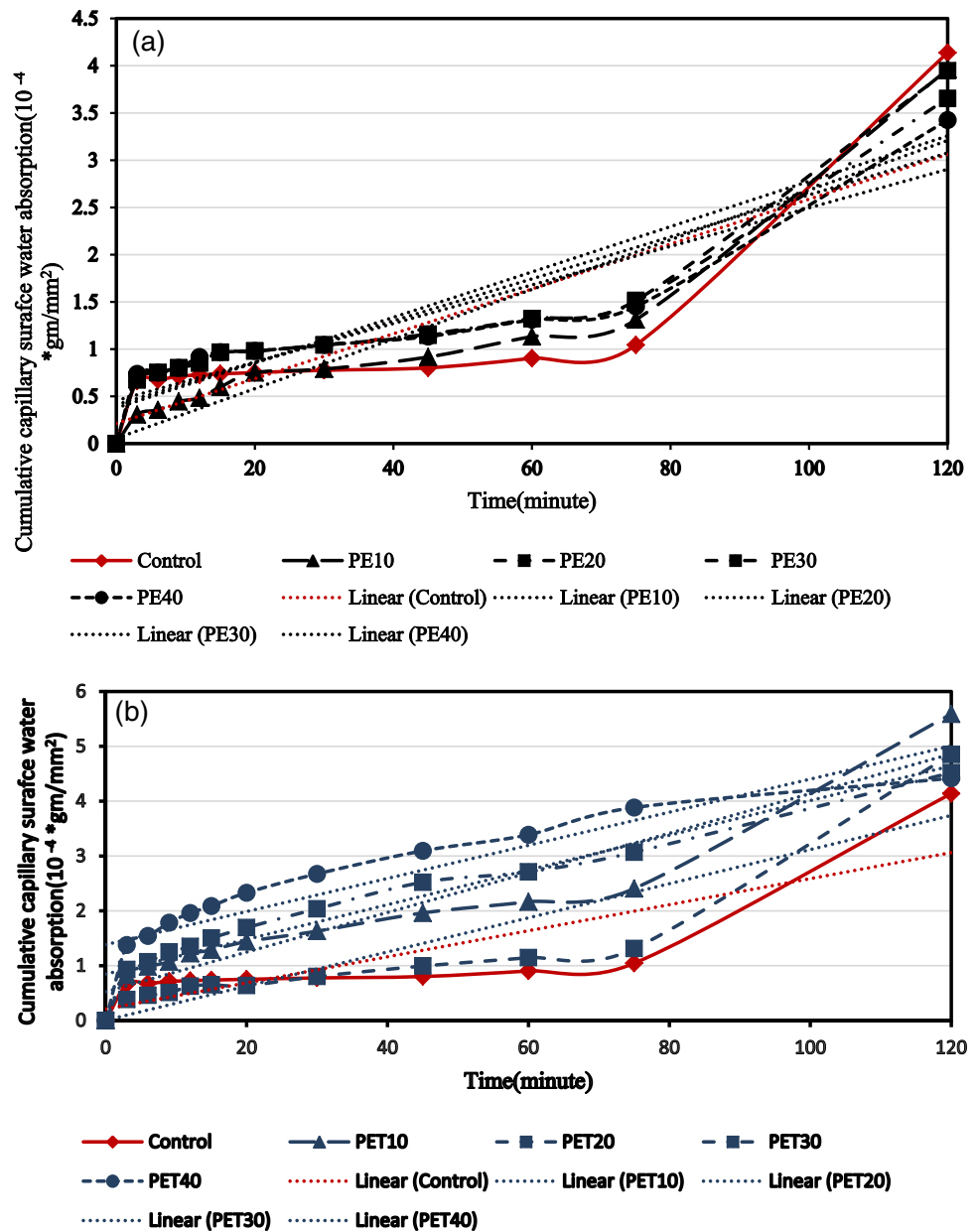
outcomes for RM(%) and RS(%) were shown in different studies (Pather et al. 2021).

The results of exposure test in 5% NaOH solution are depicted in Fig. 23. All concrete specimens exhibit fairly similar residual strength values at 28 days when compared to the control mix meaning alkaline solution has no adverse effect on plastic waste-based concrete.

After 56 days of curing in marine water, the strength of the cubes is shown in Fig. 24. It was observed that residual strengths were maximum for concrete specimens having plastic aggregates as replacement of natural aggregates for different replacement levels as compared to the control mix. The

residual strength was maximum for PE10 followed by PET10 and WPA 10 for 7-day curing time. Similar results were pointed out by several previous studies such as Bryant Mather (1964), Tijani et al. (2013). For marine water exposure test, it was observed that the degree of interaction between $Ca(OH)_2$ and sulphate is often limited by the reduction in the amount of free $Ca(OH)_2$ caused by the pozzolanic reaction (Massazza 1993). Additionally, it was claimed that chlorides, as found in marine water, prevent concrete from swelling and expanding as a result of sulphate attack. The increased solubility of hydrated $CaSO_4$ in chloride solution may also inhibit swelling in damaged concrete.

Fig. 19 (continued)
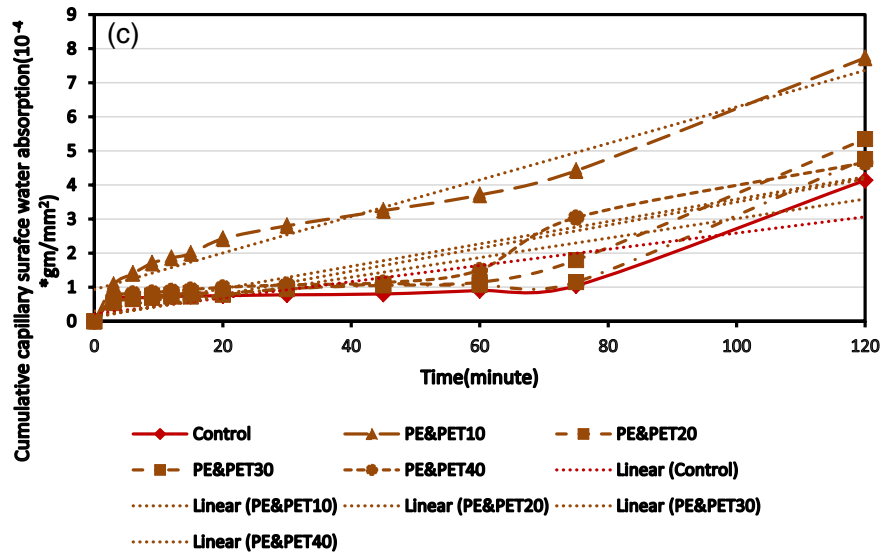
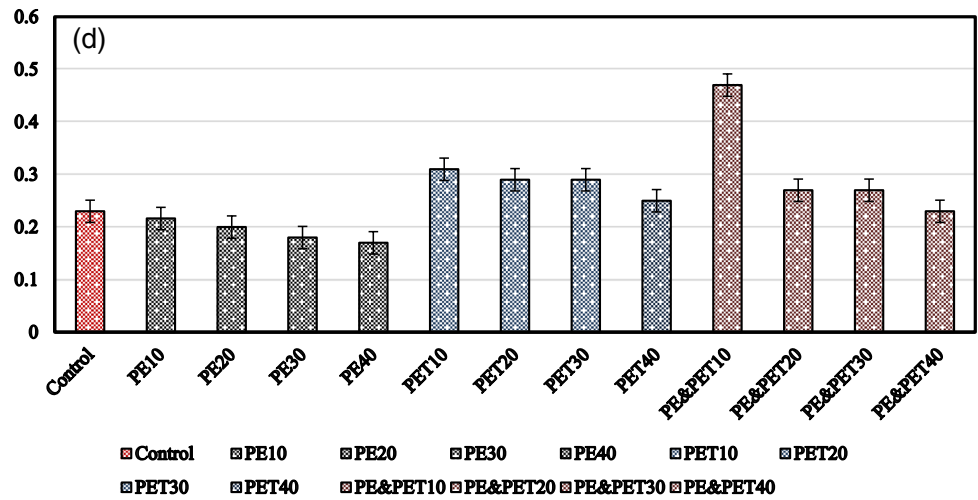**Sorptivity Coefficient (10^{-4} *gm/mm²/min$^{1/2}$)**

Fig. 20 Water permeability coefficient for all mix proportion including control of plastic waste-based concrete
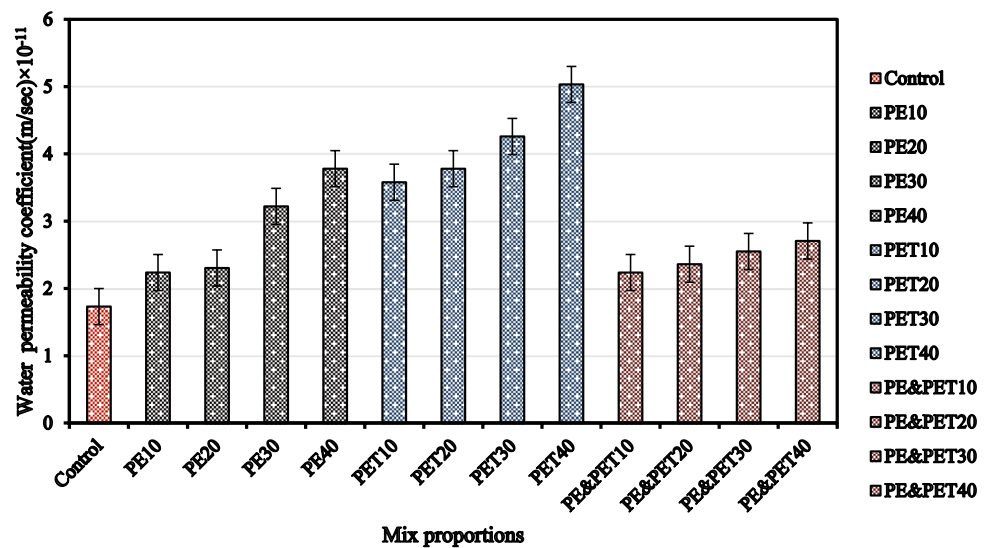
Fig. 21 **a** Residual mass values for PE-based concretes stored in H_2SO_4 acid solutions. **b** Residual compressive streng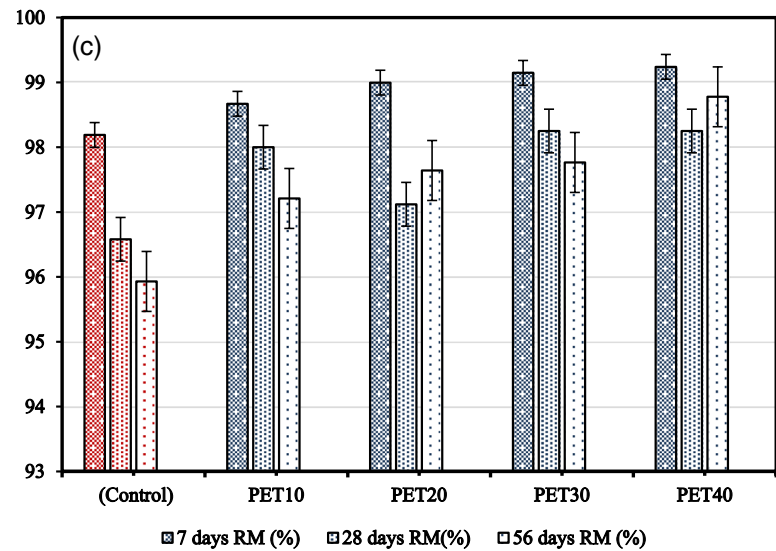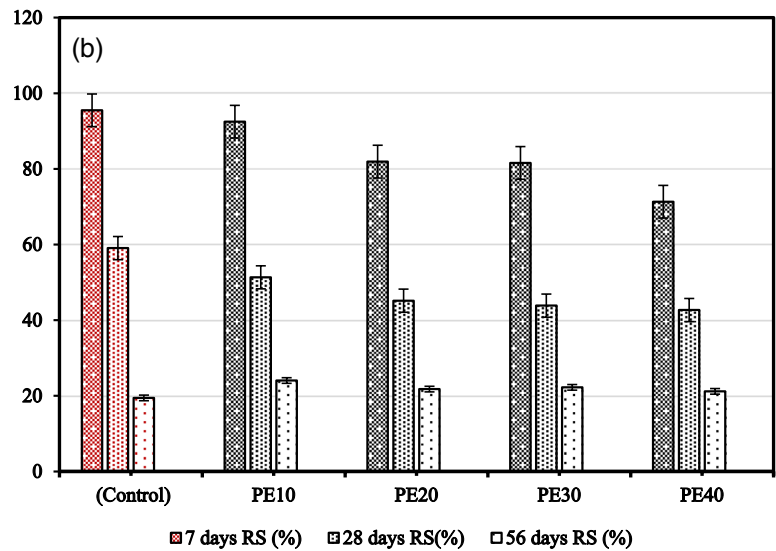ths of PE-based concretes stored in H_2SO_4 acid solutions. **c** Residual mass values for PET-based concretes stored in H_2SO_4 acid solutions. **d** Residual compressive strengt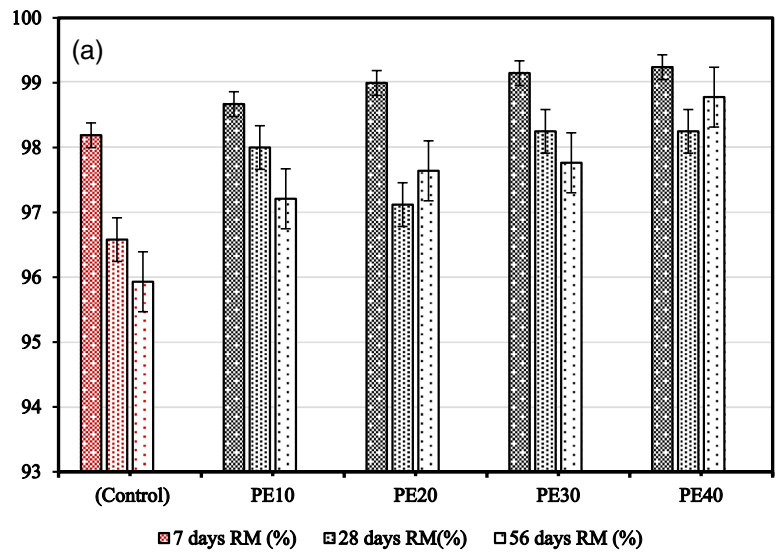hs of PET-based concretes stored in H_2SO_4 acid solutions. **e** Residual mass values for PE&PET (WPA)-based concretes stored in H_2SO_4 acid solutions. **f** Residual compressive strengths of PE&PET (WPA)-based concretes stored in H_2SO_4 acid solutions

Fig. 21 (continued)

(d)

7 days RS (%)   28 days RS(%)   56 days RS (%)

(e)

7 days RM (%)   28 days RM(%)   56 days RM (%)

(f)

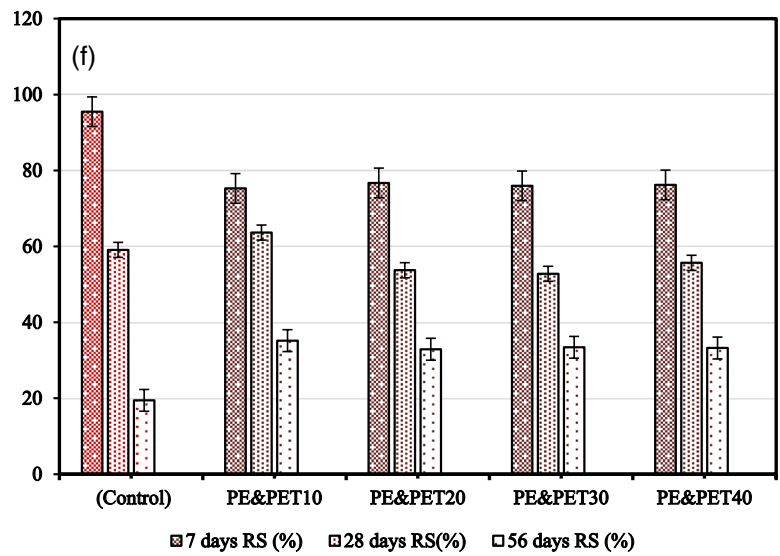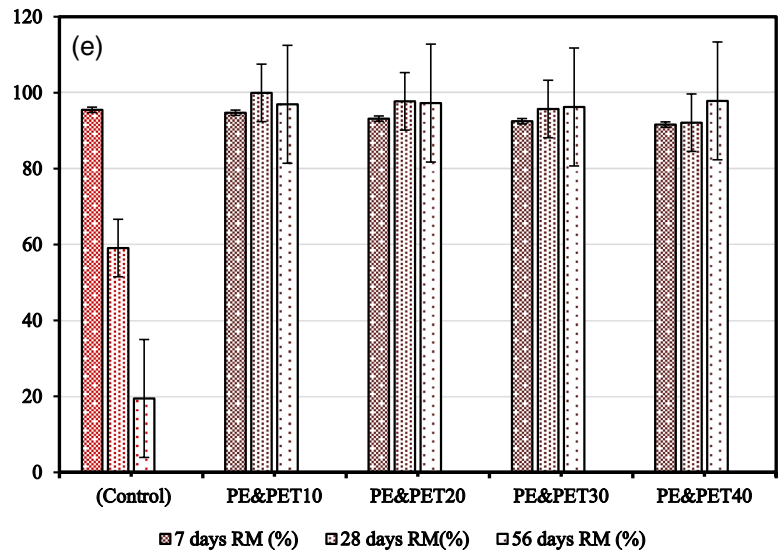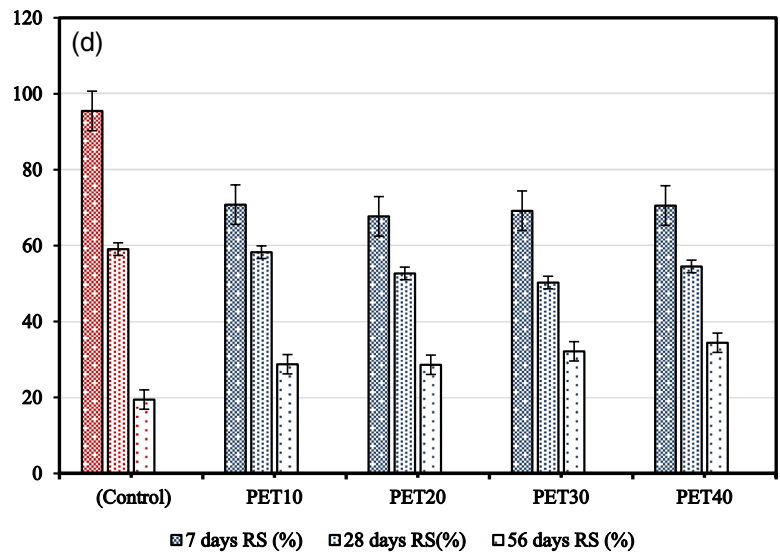7 days RS (%)   28 days RS(%)   56 days RS (%)

Fig. 22 **a** Residual mass values for PE-based concretes stored in HNO₃ acid solutions. **b** Residual compressive strengths of PE-based concretes stored in HNO₃ acid solutions. **c** Residual mass values for PET-based concretes stored in HNO₃ acid solutions. **d** Residual compressive strengths of PET-based concretes stored in HNO₃ acid solutions. **e** Residual mass values for PE&PET(WPA)-based concretes stored in HNO₃ acid solutions. **f** Residual compressive strengths of PE&PET (WPA)-based concretes stored in HNO₃ acid solutions
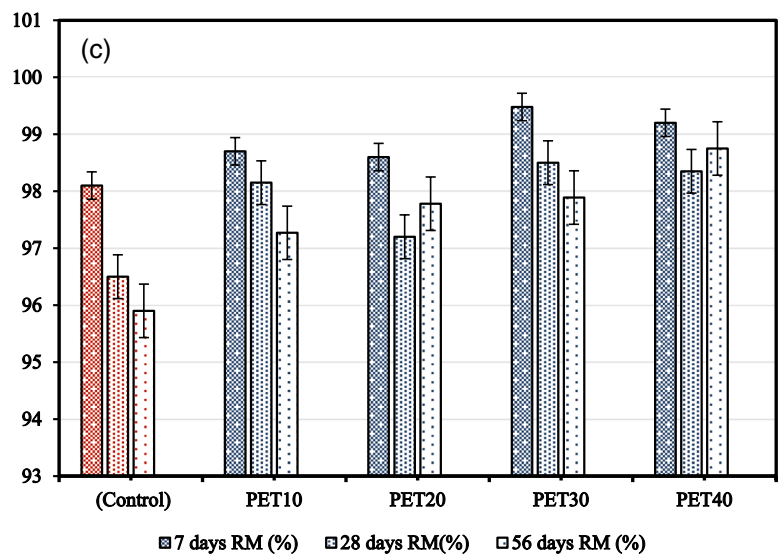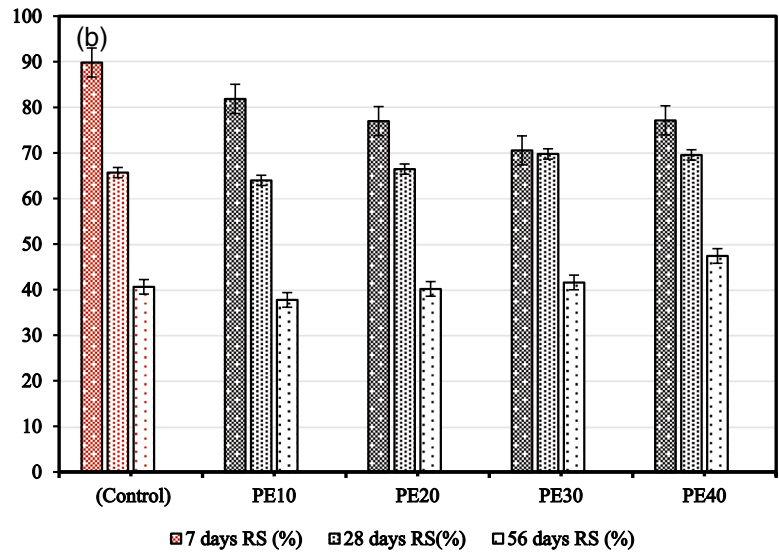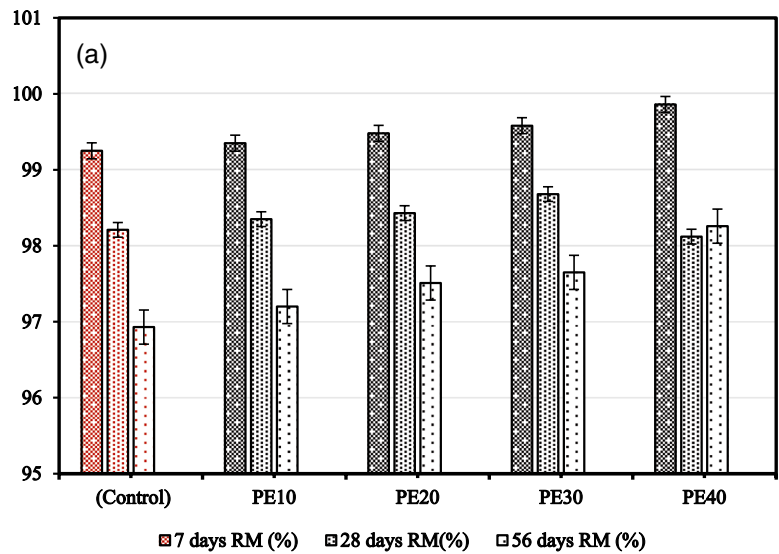
Fig. 22 (continued)

(d)

7 days RS (%)　　28 days RS(%)　　56 days RS (%)

(e)

7 days RM (%)　　28 days RM(%)　　56 days RM (%)

(f)

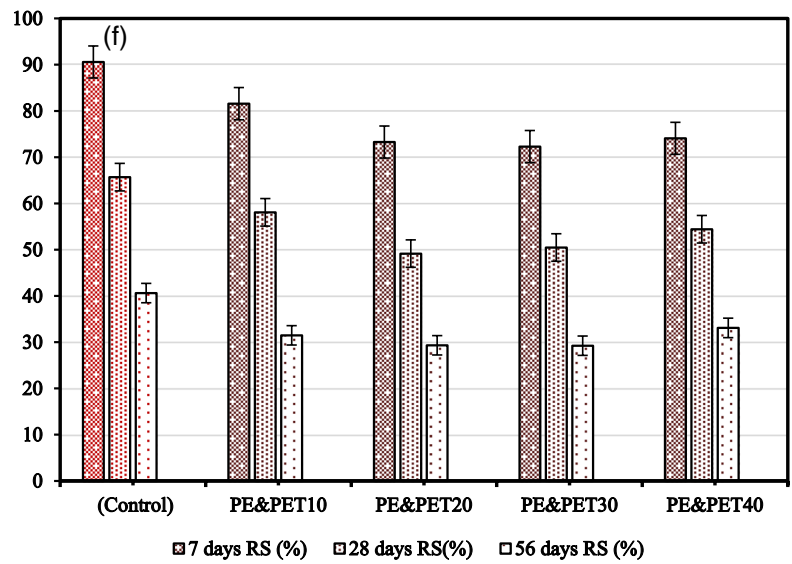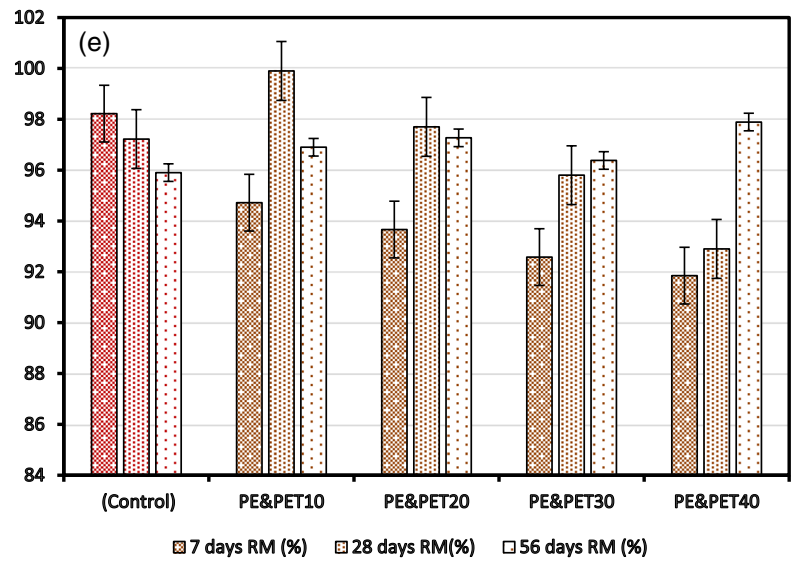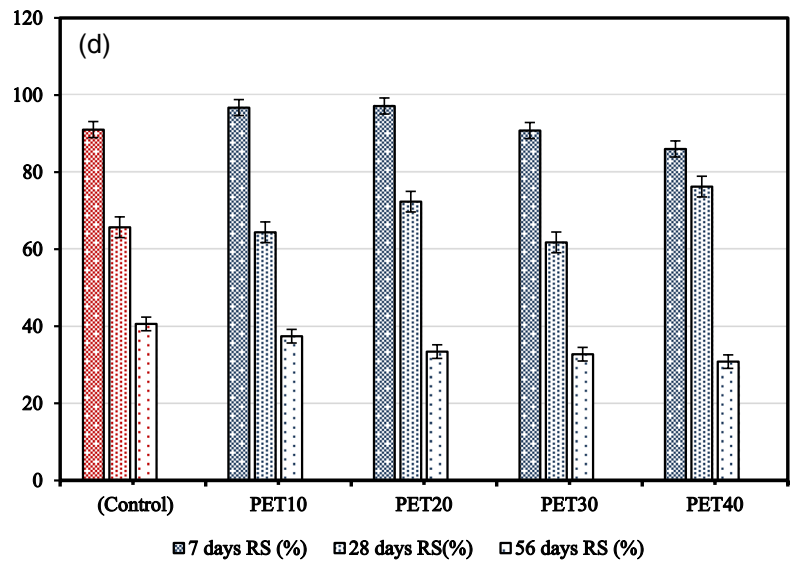7 days RS (%)　　28 days RS(%)　　56 days RS (%)

Fig. 23 Residual compressive strengths for different mixture-based specimens stored in alkaline water solutions
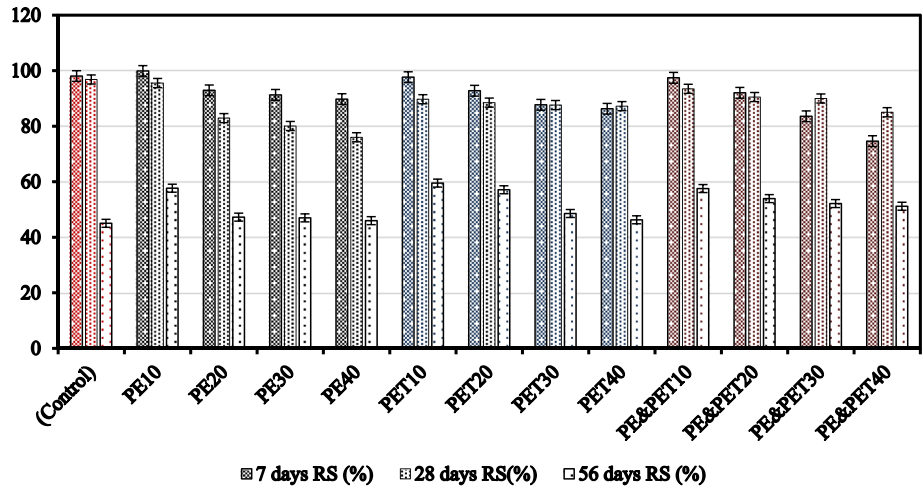

Fig. 24 Residual compressive strengths for different mixture-based specimens stored in marine water
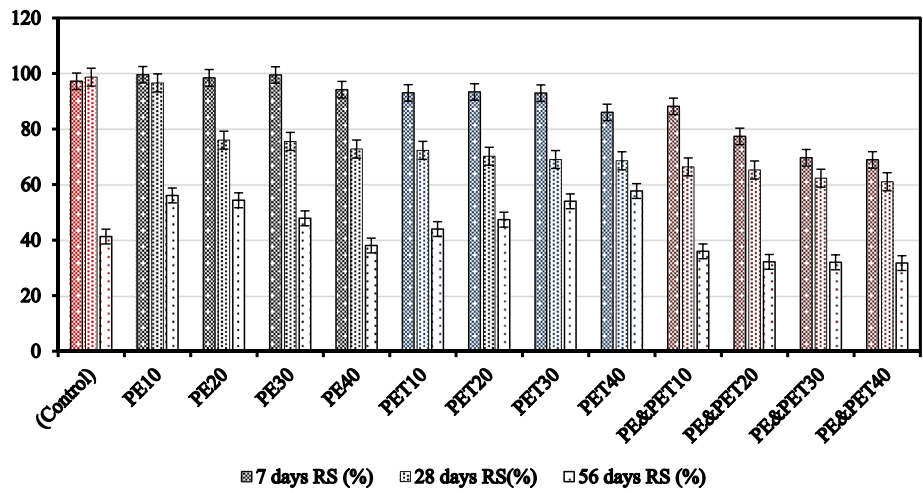

Fig. 25 Residual compressive strengths for different mixture-based specimens stored in municipal wastewater
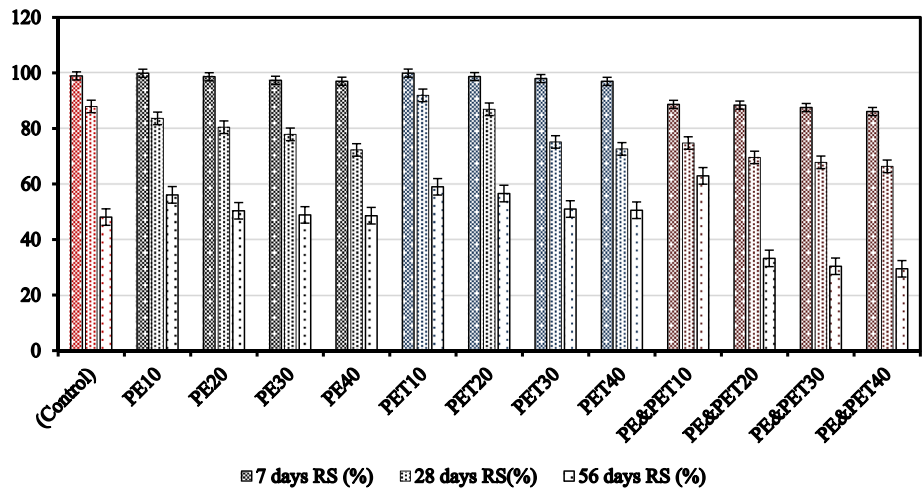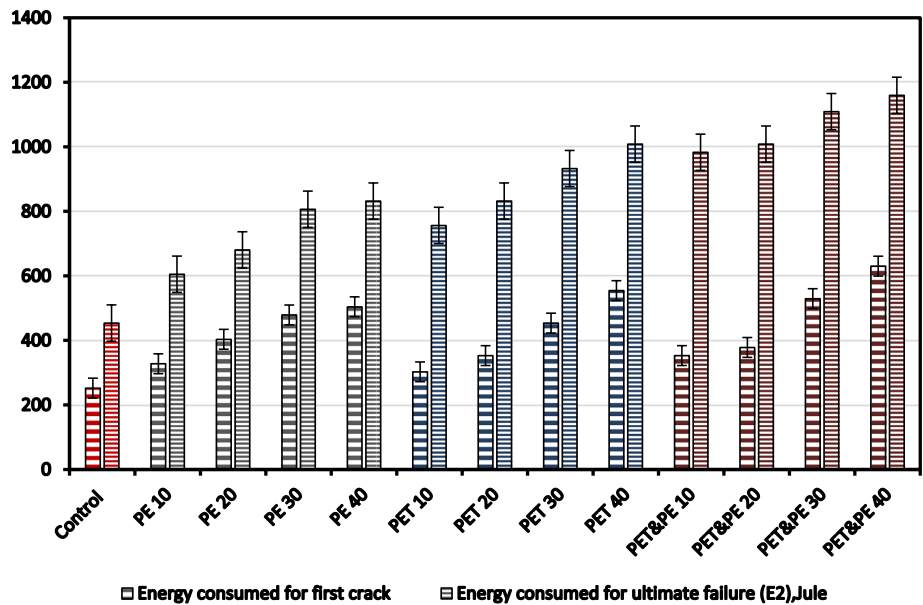
Fig. 26 Energy consumed against cracks for different mixtures of specimen-based concretes

□ Energy consumed for first crack   □ Energy consumed for ultimate failure (E2),Jule

The residual strengths of different concrete mixes cured in municipal wastewater are depicted in Fig. 25. It is observed from Fig. 25 that residual strength decreased for all concrete mixes for 56-day curing time. However, compared to the control mix, PE10, PET10 and WPA10 showed more residual strength for 56-day curing time.

Impact resistance test

The specimen's energy consumption until failure was taken into account as a gauge of its impact resistance. Equation (8) is used to calculate the energy consumption:

$$\text{Energy (E)} = \text{Hammer Weight} \times \text{Height (m)} \qquad (8)$$

where the height is equal to the total failure heights.

Weight $=$ Mass (kg) $\times g$ (m/sec^2), where "g" stands for the gravitational acceleration.

Figure 10c displays the failure patterns of each group of specimens. Energy consumed by the specimen for first and last cracks is shown in Fig. 26.

According to the test results, the PE10-PE40 concrete specimens consumed 83.33% more energy than control mix for the detection of the first crack. Around 122.22% more energy was absorbed by PET10-PET40 concrete as compared to control mix, as indicated in Fig. 26. Around 155.55% more energy was absorbed for WPA40 mix as compared to control mix. In these three trials, the third experiment has the highest energy consumption and the highest ductility index, which agrees with past literature (Saxena et al. 2018; Al-Tayeb et al. 2017, 2021). The impact resistance of concrete is improved with the use of waste plastic aggregate (WPA). All of the researchers

emphasized that WPA has a significant capacity for absorbing energy and is more flexible than control mix in addition to having a lower modulus of elasticity. These elements enable the effective transmission of impact stresses to the components of concrete, increasing concrete's resistance to impact failure. Although a plastic waste-based concrete mixture typically has a lower characteristics compressive strength of concrete (f_{ck}), which may restrict its use in some structural applications, it has several advantageous properties over conventional concrete, including lower density, greater toughness, increased impact resistance, increased ductility, and better sound and heat insulation. For a variety of building applications, these engineering characteristics are helpful.

Abrasion loss test

Cantabro abrasion loss test In Cantabro abrasion loss test, during the first 50 and 100 rotations, no significant weight loss was observed. However, as stipulated in the normal test process, as the number of revolutions increased, the cylindrical shape (100 ϕ mm $\times$ 50 mm thickness) gradually rounded off at the edges towards the end of 300 revolutions per minute. The Cantabro weight loss changes in percentages for different concrete mixes are shown in Fig. 27a–c with different revolutions. For PE10-PE40, PET10-PET40, and WPA10-WPA40, Cantabro weight losses were less as compared to the control mix. However, for the same concrete mix, this loss increased with increase in revolutions per minute. Further, the Cantabro weight loss decreased with increase in % of plastic aggregate. Similar outcomes were demonstrated by other researchers (Ferreira et al. 2012; Saikia and de Brito 2014; Jain et al. 2020). The type

Fig. 27 **a** Variation of Cantabro abrasion weight loss with no. of revolutions for PE-based concretes. **b** Variation of Cantabro abrasion weight loss with no. of revolutions for PET-based concretes. **c** Variation of Cantabro abrasion weight loss with no. of revolutions for PE&PET (WPA)-based concretes
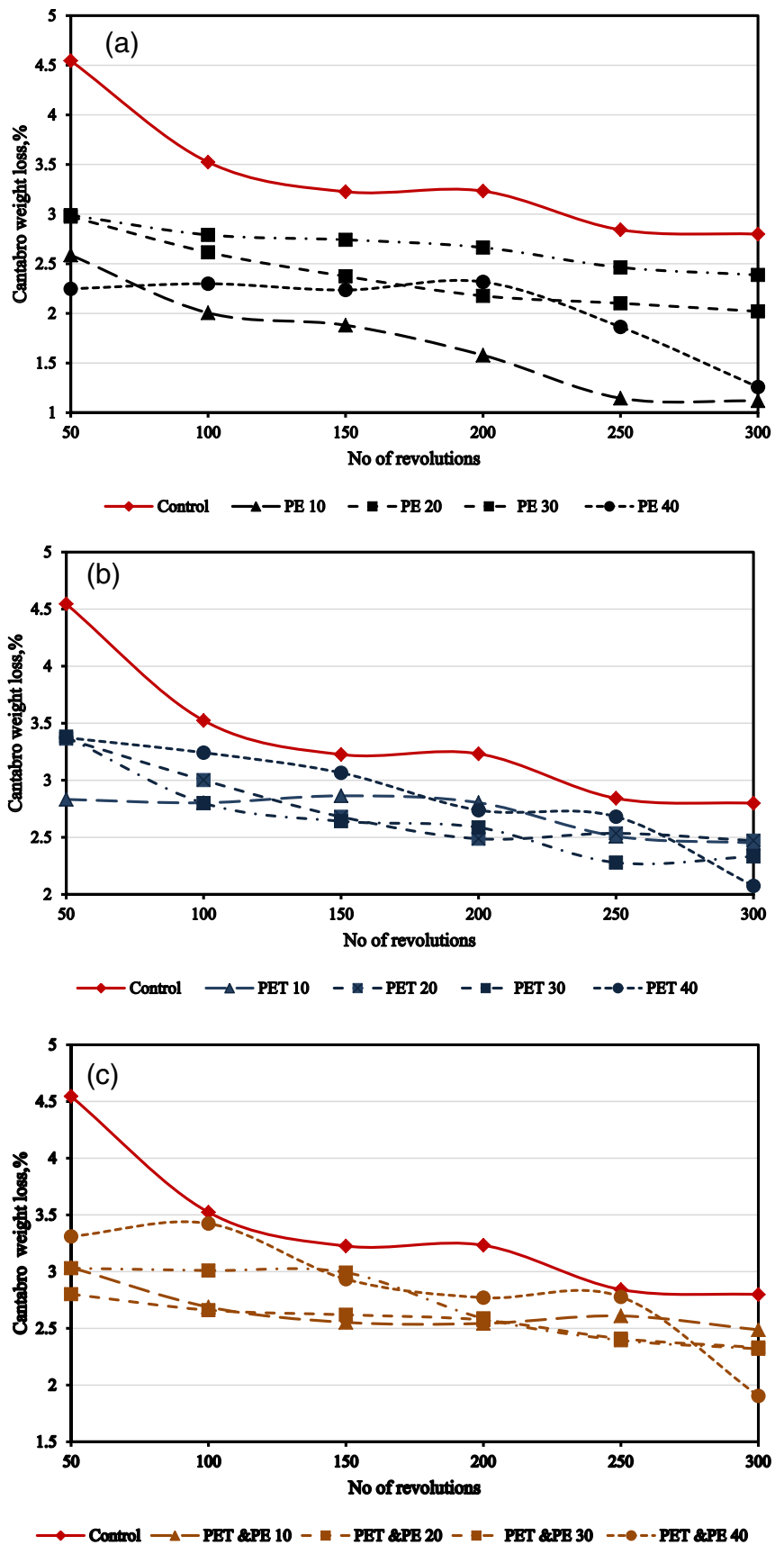
Fig. 28 **a** Variation of surface abrasion weight loss with no. of revolutions for PE-based concretes. **b** Variation of surface abrasion weight loss with no. of revolutions for PET-based concretes. **c** Variation of surface abrasion weight loss with no. of revolutions for PE&PET (WPA)-based concretes
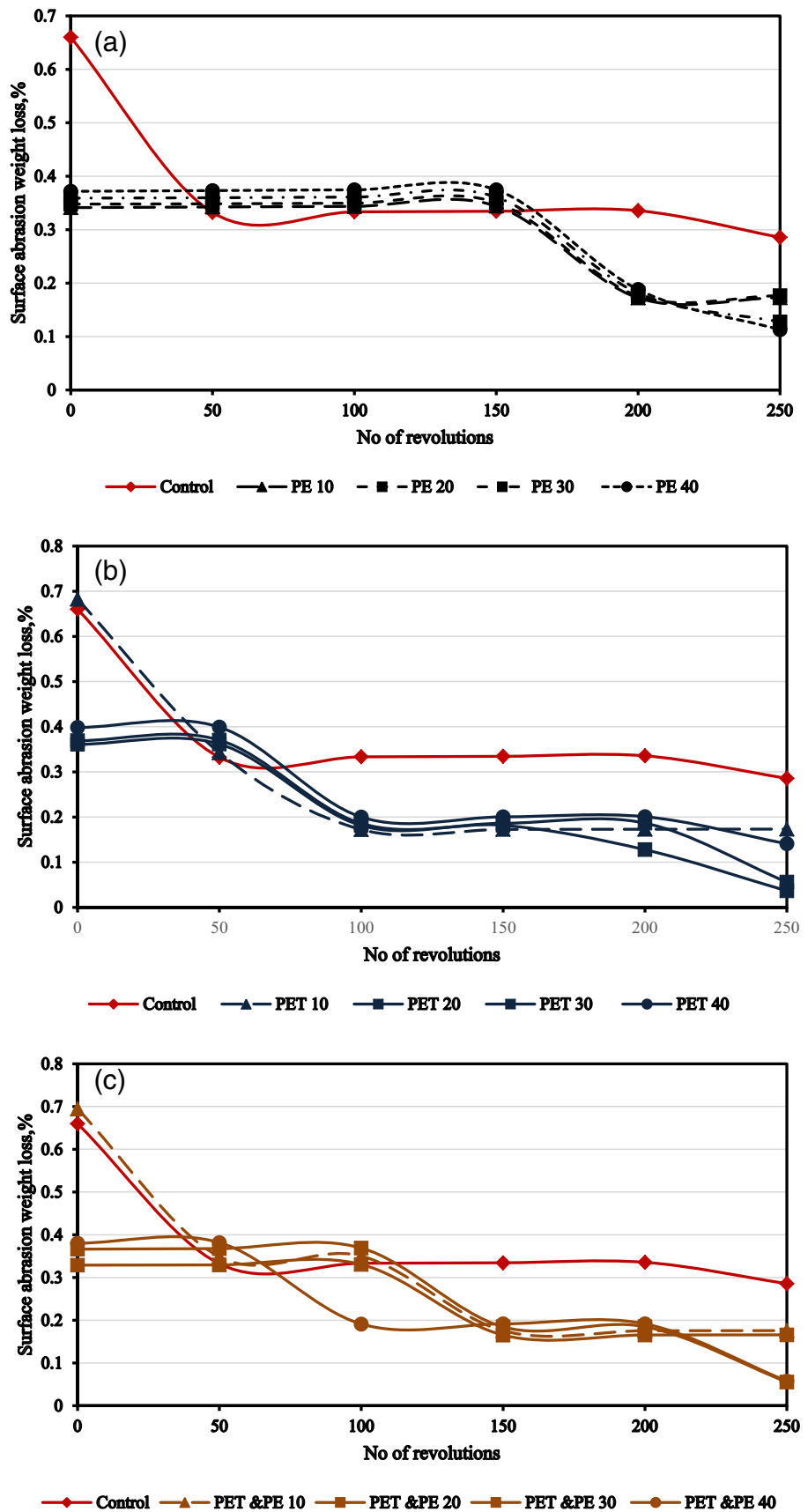
Fig. 29 Variation of compressive strength for both normal and CO_2 cured plastic waste-based concrete specimens
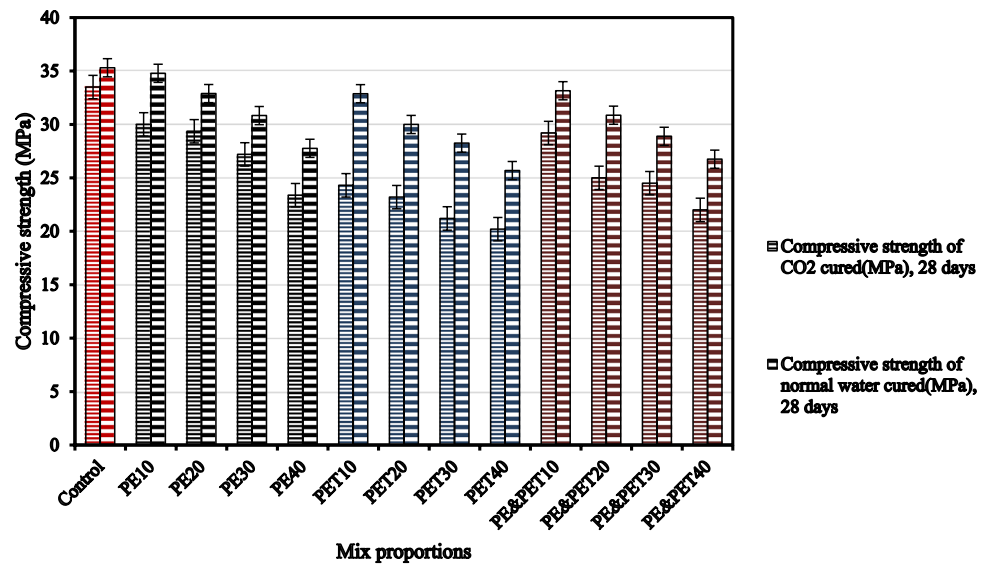

Table 8 Results of average and maximum gas penetration depth for plastic waste-based concrete for all trials including control

Specimen	Average gas penetration depth (m)	Maximum gas penetration depth (m)
Control	1.1175	1.78
PE10	2.04	2.56
PE20	1.56	2.03
PE30	1.55	1.94
PE40	1.18	1.84
PET10	1.60	2.61
PET20	2.045	2.65
PET30	1.565	2.15
PET40	1.195	2.33
WPA10	2.83	4.27
WPA20	2.64	3.39
WPA30	1.68	2.57
WPA40	1.57	2.39

and quality of the aggregates used to form the concrete have a significant impact on its surface qualities. Here plastic waste-made aggregates adsorb more impact, which results in increase abrasion resistance. As a result, the parameters of the link between the plastic aggregates and the cement paste have a big impact on the abrasion resistance.

Surface abrasion loss test The variance of surface abrasion weight loss (%) with respect to number of revolutions is shown in Fig. 28a–c for different replacement levels of natural aggregates. As can be observed from Fig. 28a–c, surface abrasion weight loss is less for 28-day curing time for plastic

aggregate-based concrete as compared to the control mix. However, for PET10-PET40 and WPA10-WPA40 the surface abrasion weight losses were minimum. Other researchers likewise reported similar outcomes like (Alqahtani et al. 2018; Galvão et al. 2011). All forms of plastic waste aggregate might give greater wear resistance because of their intrinsic hardness, plasticity nature and improved abrasion behaviour, despite the weak binding properties with the cement paste. Wear resistance is aided by the fibrous surface texture of plastic and the ability to manage cracks. Plastic waste aggregate coarser particles (PET) perform better at controlling abrasion than plastic waste aggregate smaller particles (PE). When the concrete is exposed to abrasion, the coarser particles stay attached to the paste, while the smaller particles are forced out of the matrix. The findings of several studies also showed that PET aggregates are more resistant to abrasion than PE aggregates since PET aggregates have a stronger interfacial connection between concrete and plastic aggregate and comparatively higher strength.

Gas permeability test

As indicated in Fig. 29, the outcomes in terms of compressive strength of concrete mixes for both CO_2 and water curing are compared. Carbonation depth of test specimens is depicted in Table 8. For all experiments, the carbonation depth increased when there was more plastic waste aggregate in the concrete mix than when only NA was used (control mix), as indicated in Table 8. Another author likewise produced a similar outcome like (Lee et al. 2019). A rapid curing method known as carbonation involves injecting CO_2 gas into the curing chamber, where it solidifies as calcium
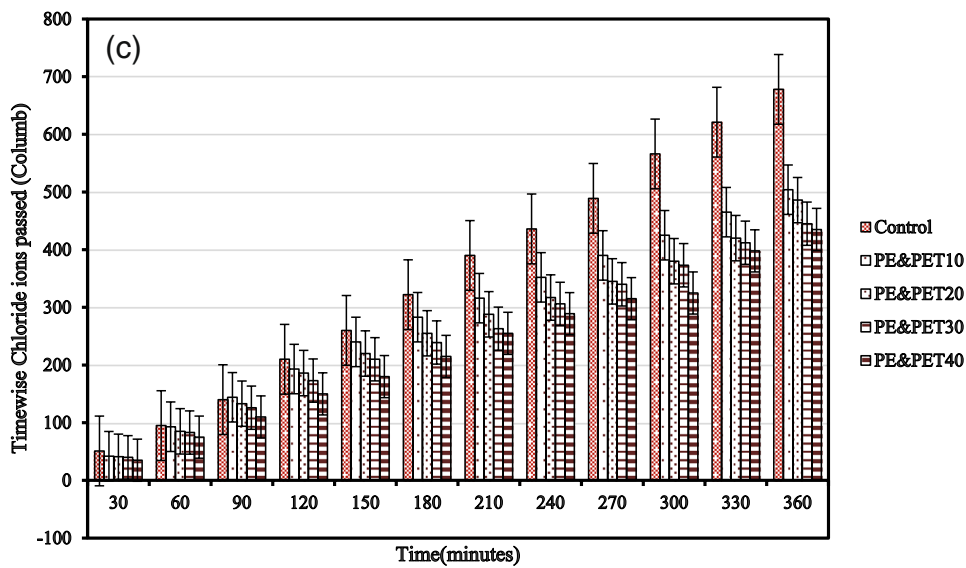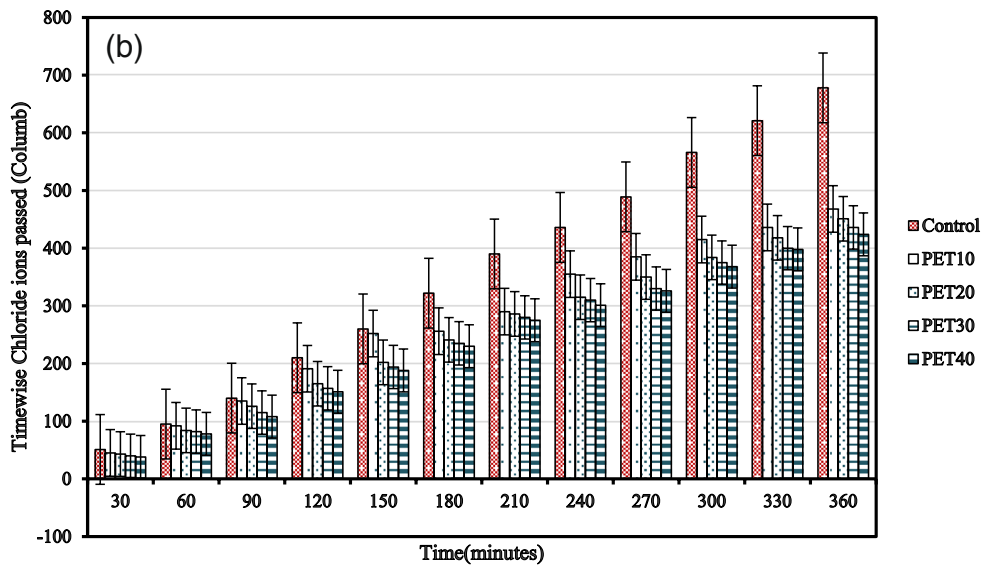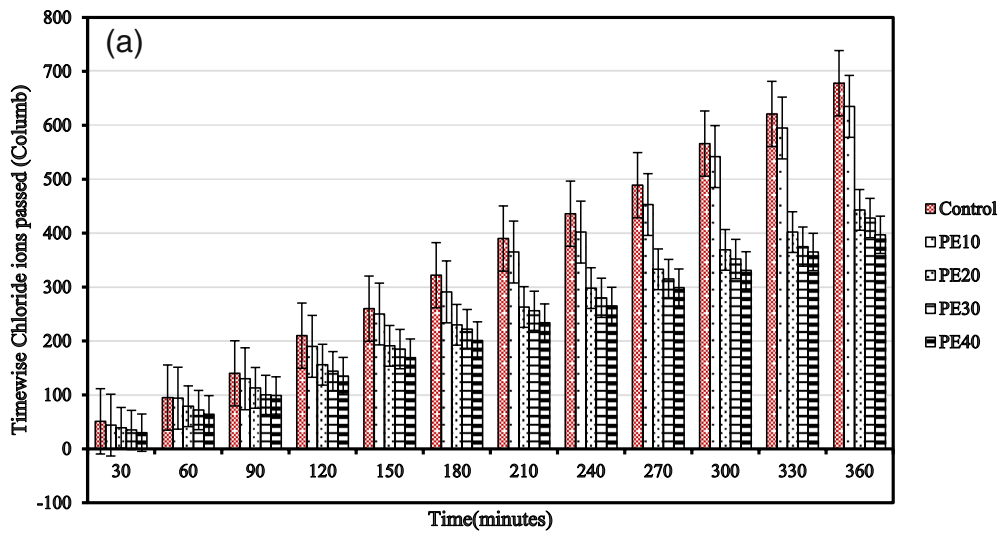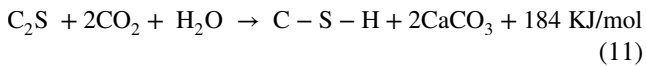
carbonates ($CaCO_3$) at room temperature and diffuses into freshly mixed concrete under low pressure.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (9)$$

$$C_3S + 3CO_2 + H_2O \rightarrow C-S-H + 3CaCO_3 + 347 \text{ KJ/mol} \qquad (10)$$

$$C_2S + 2CO_2 + H_2O \rightarrow C-S-H + 2CaCO_3 + 184 \text{ KJ/mol} \qquad (11)$$
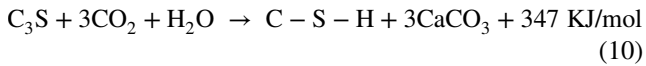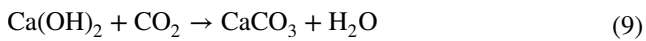
Early-age CO_2 curing strengthens concrete products and increases their strength, surface hardness, and water resistance while decreasing efflorescence (Santhosh Kumar Balaji and KVGD Thrilok Nath Reddy 2019). Concrete naturally contains carbonates as a result of the interaction between its calcium-containing components and atmospheric carbon dioxide in the presence of water, which results in the formation of calcium carbonate. In non-reinforced concretes, it is a helpful reaction since it results in less porosity and a stronger carbonated paste. In contrast to the normal concrete, the plastic aggregate-based concrete showed opposite results that means strength reduced with increase in CO_2 exposure and with increase in replacement the compressive strength decreased as shown in Fig. 29. The contrast results may be due to the increase in porosity in concrete mix due to poor bonding in ITZ.

Rapid chloride penetration test (RCPT)

Chloride migration inside concrete is a bad phenomenon that reduces its tensile strength and long-term useful life. Concrete's permeability, porosity, and absorption all have an impact on how easily chloride migrates through concrete. The RCPT tests at 28 days were used to determine the Cl^- ion passing terms of coulombs for all of the concrete specimens, which were measured for 6 h (every 30 min interval) and are depicted in Fig. 30a–c. The average Cl^- ion passing control mix after 28-day curing is 678 Coulombs, which is categorized as "low" chloride ion penetrability. In a similar vein, the Cl^- ion passing by the plastic waste cement composite mixtures was found to be between 435 and 635 Coulombs as seen in Fig. 30a–c. In comparison with control samples, concrete samples containing plastic debris showed a generally reduced electrical current, indicating lesser

chloride ion penetration. Similar findings were obtained in other researches (Alqahtani et al. 2018; Silva et al. 2013).

Elevated temperature effect test

Mechanical qualities of concrete deteriorate as a result of several physical and chemical processes brought on by exposure to high temperatures. The use of plastics as aggregate in concrete raises serious concerns about the durability of concrete at high temperatures simply because the melting temperature of plastics is substantially lower than natural aggregates. The change in concrete's compressive strength for various combinations of concrete mixtures against different high temperatures is shown in Fig. 31. Overall, it is evident that exposure to high temperatures causes a reduction in compressive strength and that reduction is linear with temperature. After being exposed to temperatures of 100 °C, 200 °C, and 300 °C for the control specimen with a w/c ratio of 0.37, the compressive strength declined by 9.88%, 15.01%, and 19.26%, respectively. When exposed to temperatures of 100 °C, 200 °C, and 300 °C, respectively, compressive strength is reduced by 20.87%, 28.43%, 20.33%, and 31.34%; 24.59%, 26.04%, 27.95%, and 26.13%; and 28.24%, 30.19%, and 25.072%, respectively, for PE10-PE40. For PET 10, the compressive strength was reduced by 30.24%, 27.07%, and 23.75% after exposure to temperatures of 100 °C, 200 °C, and 300 °C, respectively. For WPA 10 to 40, after exposure to temperatures of 100 °C, 200 °C, and 300 °C, respectively, the compressive strength was reduced by 36.65%, 39.987%, 44.85%, and 46.429%; by 39.66%, 44.19%, 48.28%, and 54.20%; and by 40.63%, 45.39%, 51.88%, and 56.44%, respectively. In short, it can be concluded that considerable decrease in strength of plastic waste aggregate concrete was observed when exposure temperature exceeds melting temperature of plastic (100–180 °C). Comparable outcomes are reported by (Saxena et al. 2018; Correia et al. 2014; Sojobi and Owamah 2014). A sizable amount of water vapour is produced inside the concrete when it is exposed to a temperature exceeding 100 °C. This water vapour in the concrete matrix causes pore pressure, which makes it easier for microcracks to spread and results in a decreased compressive strength and deterioration of durability properties. Reduced thermal stability of plastic waste aggregate; induced porosity in concrete as a result of the formation of volatile products when plastic waste aggregate is heated above their melting point; development of an unbalanced thermal gradient within the concrete; and build-up of pore pressure as a result of the confinement of water vapours in distinct pockets

Fig. 31 Variation of compressive strength of different temperature in elevated temperature test for different specimens
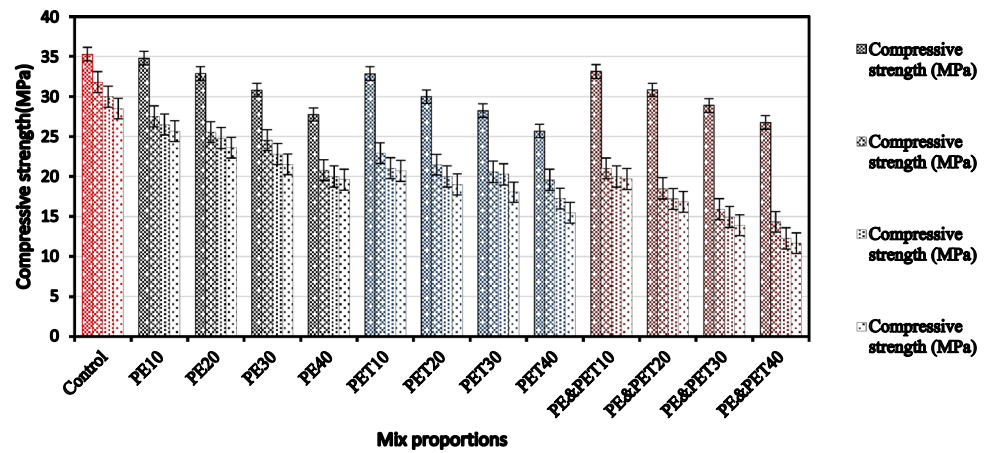

Table 9 Leachability test results for plastic waste-based concrete for different mix proportion specimens

Specimen	Microplastic
Control	Nil
PE10	Present
PE20	Present
PE30	Present
PE40	Present
PET10	Nil
PET20	Nil
PET30	Nil
PET40	Nil
WPA10	Present
WPA20	Present
WPA30	Present
WPA40	Present

created after plastics breakdown may be the possible reasons for reduced strength and durability of concrete. It should be noted that exposure temperatures below 100 °C have no impact on strength values regardless of the kind of plastic waste aggregate used in concrete. The creation of new hydrate brought on by an increase in temperature is responsible for this unexpectedly favourable impact at moderate temperatures.

Leachability test

Microplastic (MP) in particular is released through leaching (Van Praagh and Modin 2016), which happens when plastic wastes in the environment come into contact with water and adverse environmental conditions. As per the results of the microplastic analysis, PE-based concrete showed more microplastic in leachate than in other trials. PET-based concrete showed less microplastic concentration during leaching as compared to other mix proportions. Table 9 shows the

microplastic present or absent over various mix proportions of plastic waste-based concrete as confirmed with Fig. 16i. WPA-based concrete also showed the same results as PE-based concrete as shown in Table 9. Through the leaching test, it was observed that concrete made up of PE-based aggregate resulted in the presence of microplastic in leachate but for PET-based concrete no such MP was found.

Optical microscopy test

All trial specimens after curing for 28 days were subjected to microstructure studies using high-resolution optical microscope (Dewinter), and the outcomes are depicted in Fig. 32. The objective of the microstructure investigation was to define the morphology of the plastic waste-based hardened concrete, observe the ITZ between the plastic aggregates and cement matrix, identify the presence and intensity of air voids, and investigate the surface topography. From Fig. 32c, it is clear that the PE-based aggregates were surrounded by small NFA particles and cement paste, which made it homogeneous and compact, thus leading to improved mechanical and durable properties. In contrast, the PET-based mixture (Fig. 32b) showed a less dense microstructure, more ITZ voids, and more porosity because there was less adhesive bond between the cement matrix and the PET aggregates than there were between the cement matrix and coarse aggregates. This may have an impact on the strength loss of concrete samples. The uniform and plain surface of PET can also lead to a weaker bond between the cement matrix and PET, resulting in porous microstructures and less mechanical and durable properties. Additionally, WPA-based mixture (Fig. 32a) showed a more porous microstructure with more ITZ voids and high porosity compared to control mix due to the weaker adhesion between the cement matrix and both

Fig. 32 Microscopic image of plastic waste-based concrete
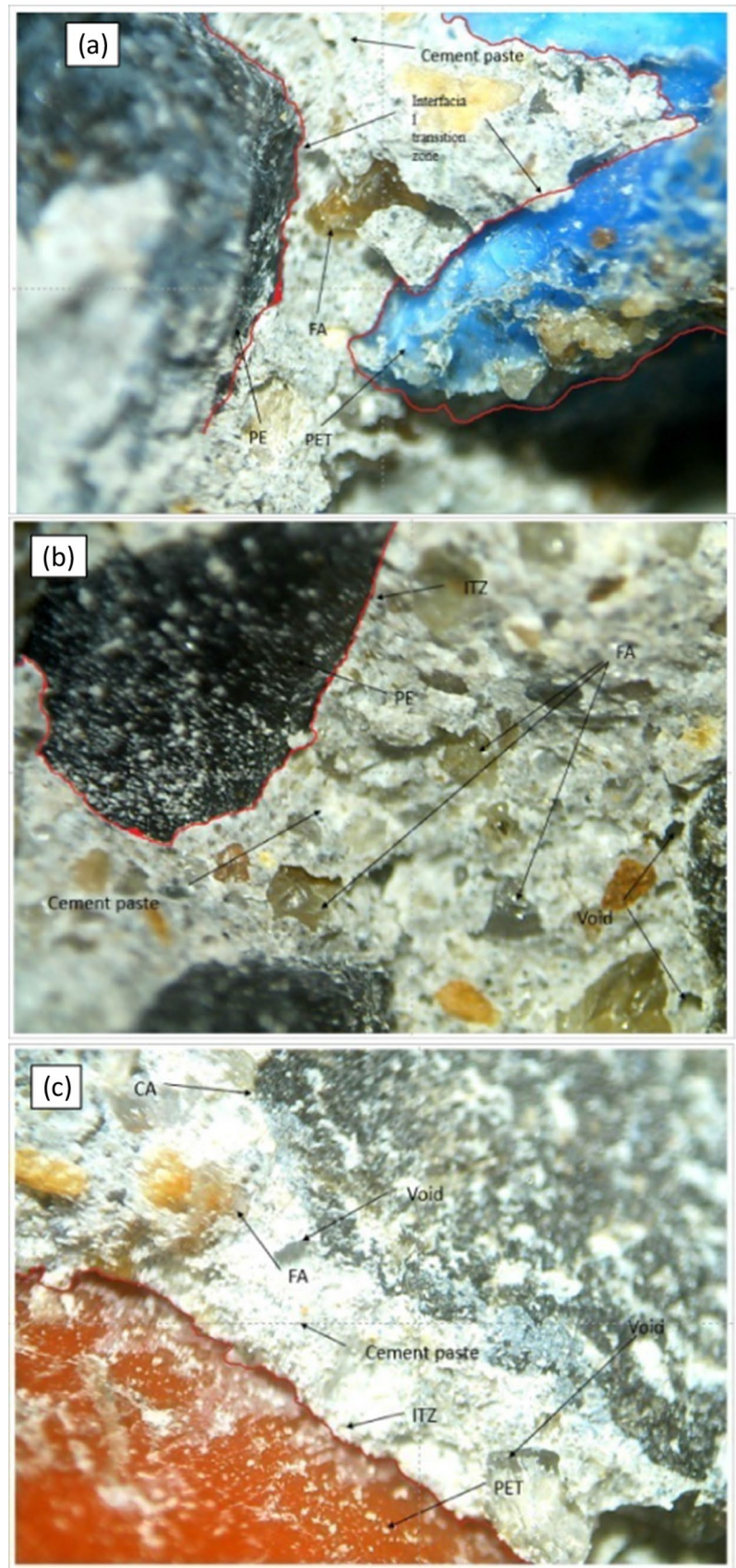
PE- and PET-based aggregates. This may have an impact on the strength loss of concrete samples. The compressive strength and unit weight of composite concretes may both decrease as a result of the existence of these pores or voids. Alqahtani et al. 2017; Şimşek et al. 2013; Gu and Ozbakkaloglu 2016; Belmokaddem et al. 2020; Vo et al. 2022 reported that the poor adhesion between the plastic waste-based aggregates and the cement matrix is the cause of the decreased mechanical and durability characteristics of the composites that were developed.

Disadvantages or shortcomings of using PET- and PE-based aggregates in concrete and the scope for future study:

There are still several restrictions that prevent their widespread application in concrete matrix irrespective of obvious environmental and financial advantages of using PE- and PET-based aggregates in favour of natural aggregates. The following are briefly mentioned some of the main drawbacks related to the usage of plastic waste in concrete matrix:

1) The separation and preparation of PET and PE before recycling is one of the main restrictions on their use. PE and PET collected from the various waste streams where they are produced, they are frequently polluted with different kinds of organic and pathogenic contaminants.
2) When used in concrete matrix for construction, PET and PE, which differ from natural aggregates, may not function isotropically.
3) As PE and PET have low specific weights, therefore, they minimize the self-weight of concrete structures. Consequently, they are inappropriate for applications requiring high strength.
4) Low water adsorption capacity may improve workability, but because PE and PET are hydrophobic, lots of free water accumulate on the surface and weaken the transition zone, lowering the strength of the concrete with greater percentages of PET and PE aggregates.
5) As a result of the aggregate particles' smooth surfaces and flaky shapes, there is a greater space between the cement paste and the plastic aggregates, which weakens the bonding strength. Moreover, it raises the permeability of concrete and lowers the final composite's overall mechanical performance. In order to raise the surface roughness of the manufactured plastic aggregate particles and increase the bonding in the interstitial zones (ITZs), mechanical or chemical treatment is advised.
6) Since the replacement ratio of aggregate made from PET and PE has a negative relationship with acid and fire resistance, it should be enclosed when utilized in building construction.

So, the main elements influencing the mechanical performance are the lower elastic modulus of the plastic waste in comparison to NA and the porosity that developed in the microstructure of the composites after its addition. Due to their poor bonding properties with the cement paste and the increase in porosity of typical cementitious materials in concrete mix, these two factors also negatively affect the durability characteristics of the concrete, particularly those related to the transfer behaviour and straining capacity of concrete. By employing some corrective procedures, these impacts that cause poor durability performance can be reduced. These include using a finer fraction of plastic waste aggregate in pellet or powder form rather than a coarser fraction or an elongated and flaky form, treating the plastic's surface to increase cement paste adhesion, using pozzolanic admixtures as an additional binder to improve the matrix's microstructure, and converting plastic particles into novel light waste aggregate through thermal treatment and agglomeration with NA or mineral admixtures. All of these corrective actions provide instruction for upcoming work.

Conclusion

The purpose of the current study was to determine the impact of recycled PE and PET aggregates on the mechanical and durability characteristics of concrete by replacing naturally obtained FA and CA, respectively, for 4 different volumetric replacement levels keeping same W/C ratio for M30 grade concrete. The following conclusions can be formed in light of the results:

1) Compressive strength was reduced by the presence of plastic aggregates. The maximum reduction was observed when natural coarse aggregates were replaced by PET aggregates. Though compressive strength reduced with increase of plastic aggregates, it can be permissible up to 30% of replacement in case of PE-based concrete. However, the mixed concrete can be used for lightweight structural purpose as the minimum compressive strength was obtained greater than 17 N/mm^2.
2) The inclusion of PET as a replacement of NCA and both PET and PE aggregates as replacement of NCA and NFA, respectively, in concrete significantly increased the sorptivity for 10–40% replacement ratios. This performance was attributed to the increase in porosity caused by the evaporation of surplus water around the hydrophobic PET particles as well as heterogeneity in shape and superficial textures of PET at ages 7, 28, 56, and 90 days of curing. When PE was added to a concrete specimen replacing NFA, the sorptivity was reduced for a 10–40% replacement ratio at 7, 28, 56, and 90 days after curing as compared to others mix proportions.

3) For water permeability test, PET-based concrete showed higher permeability coefficient value over the other mix proportions including control. The rise in permeability may be due to the increased porosity brought on by the development of fragile spots as a result of the tenuous bond between WPA and cement matrix.

4) Alkaline, marine, and municipal wastewater did not show any adverse effect on the plastic-based concrete mix. Plastic waste-based concrete showed greater resistance to SO_4 attack from H_2SO_4 exposure tests.

5) For impact resistance test, it was observed that PE40 consumed 83.33% more energy for the detection of the first crack as compared to control mix. For PET40, the energy consumption was 122.22% higher as compared to control concrete. Further, for WPA40 energy consumption was 155.55% higher as compared to control mix.

6) For Cantabro abrasion loss test, the incorporation of PE and PET as replacement of NFA, NCA, in concrete caused less loss of weight for all mix proportions as compared to the control mix for 28 days of curing. For WPA concrete, when both the natural aggregates were replaced by plastic aggregates the loss was even minimum as compared to control and PE and PET mix.

7) For surface abrasion loss test, the incorporation of plastic aggregate reduced the surface weight loss as compared to the control mix. Surface weight loss is maximum for PE aggregates when used as replacement of FA compared to all plastic aggregate-based concrete.

8) For the gas permeability test, the incorporation of WPA in concrete showed decrease compressive strength trend for CO_2 curing as compared to control. Average penetration depth of CO_2 increased with increase in WPA. Concrete that is supposed to have a greater capacity to evacuate gas, as in the case of pervious concrete, benefits from increased permeability caused by the use of plastic particles. Average gas penetration depths of PE- and PET-based concrete were almost same but higher when both the aggregates were replaced by PE and PET (WPA concrete).

9) During elevation temperature test, the compressive strength of WPA-based concrete decreased when compare to the control mix and the decrease is increasing with increase in temperature and % replacement of aggregates. The decrease in compressive strength is minimum for PE mix followed by PET mix and WPA mix. Due to its high degree of porosity, concrete develops a temperature gradient that causes cracks to first appear.

10) For rapid chloride penetration test, chloride ions penetration rate of control mix was highest as compared to other mix proportions of PWA. Chloride ion penetration rates of WPA concrete were lower as compared to PE and PET concrete mix. Chloride ions penetrability of all trials can be classified as "Low" as per (ASTM C1202-12 2012).

11) For leachability test of microplastic of concrete, maximum MP concentration was observed for PE-based concrete. PET mix did not show any microplastic concentration in TCLP test.

12) The microstructure analysis depicted that the uniform and plain structure of plastic-based aggregates leads to a weaker bond between plastic aggregates and cementitious materials, resulting in porous structure and reduced mechanical properties.

The findings of this experimental study support the usefulness of using WPA as a partial replacement of NCA and NFA in the production of green concrete up to 40% volumetrically. The application of PWA may not improve the mechanical properties of concrete but enhance its durability properties in terms of resistance to abrasion and impact and resistance to chloride ions. The results of this study confirm and validate the applicability of PWA in production of light weight green concrete for sustainable development. Plastic waste aggregate has a higher ratio of density reduction to loss of concrete strength than other lightweight material. Therefore, the design of earthquake-resistant structures can be benefitted from the usage of plastic waste aggregate concrete. It is desirable to employ plastic-incorporated concrete to produce pervious concrete for ground water recharge through pavement area. Because it resists chloride migration, concrete made with PET and PE can be utilized to shield the reinforcement in reinforced structures from corrosion. Last but not least, concrete for road pavements, crash barriers, etc., may be made using plastic waste cement composites because of its resilience to impact loading and abrasive pressures. Plastic may therefore become a viable replacement for traditional NA in some cases adding environmental sustainability by reducing issues related to disposal or open burning of plastic waste. It will also reduce the environmental impacts brought on by the excessive natural resource depletion to satisfy the skyrocketing demand for aggregates. The long-discussed argument for sustainability through plastic waste consumption in the construction sector may be strengthened by the measurement of the environmental benefit of employing plastic waste inside concrete in terms of carbon footprint and other consequences through life cycle assessment studies. Reusing plastic waste in construction industries and a comprehensive and efficient plan of plastic waste management may minimize microplastic pollution.

Declarations

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