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Feasibility Assessment of Polyethylene Terephthalate on Fresh and Hardened Traits of Blended Mortar Mixes

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Abstract: Nowadays, the construction industry requires an ample quantity of non-renewable materials resulting in the excavation of natural beds and thus creating an imbalance in our environment. Besides this, plenty of waste material such as plastic waste in the forms of powder, fiber, etc. is produced daily. Sustainable disposal of this waste has appeared as a tough task across the world. The current work was undertaken to reduce the issue of plastic waste mainly polyethylene terephthalate, disposal by its effective utilization in cement mortar mixes without affecting their physical, chemical, mechanical, durability, and microstructural properties. For this, a total of ten cement mortar mixes with 1:3 and 1:6 mix proportions were prepared by using polyethylene terephthalate plastic waste [1mm (68%), 2mm (22%), 3mm (6%), and 4mm (4%)] in place of fine aggregate upto 20% replacement at an interval of 5%. These mortar mixes were evaluated for their workability, water absorption, compressive strength, flexural strength, acid attack, and shrinkage properties. Effects on internal structure were monitored by microstructural analysis such as X-ray diffraction, scanning electron microscopy, and Fourier transform infrared spectroscopy techniques. With 5% polyethylene terephthalate instead of river sand, the mixes displayed improved strength with the highest recorded 8.03 MPa and 2.36 MPa for 1:3 and 1:6 mixes respectively, and also obtained workability with increased density and homogeneity of structure. Benefits from polyethylene terephthalate were confirmed through microstructural analysis techniques except that there was a reduction in drying shrinkage. The results recommend that polyethylene terephthalate can be a reliable material in advanced construction applications offering enhanced structural parameters to save natural resources.

Keywords: Durability, Fine aggregate, Mortar, Polyethylene Terephthalate, Shrinkage

1. Introduction

Globally, construction activities are increasing continuously and it demands a huge quantity of good quality construction materials. To fulfill this demand, quarrying and excavating natural fine aggregate through hills and river beds has increased exponentially. Resulting of these kinds of construction activities, an imbalance in our precious environment due to dissimilarities in natural channel hydraulics, impurities in water sources, environmental pollution, and destroy local ecology. However, recently, these activities have been prohibited in many countries of the world but still, it seems a temporary solution in the absence of strict government rules and regulations over it [1]. Hence effective utilization of fine aggregate in concrete and mortar-related work is a need in today's world.

Nowadays, plastic is a versatile and universally adopted material available in various forms and colors in the market. Plastic is a part of daily life due to its unique properties like lightweight, ease of molding, durability, and economical [2]. Some of the important sorts of plastic around the globe are PET, HDPE, PVC, etc. Out of these, PET plastic is widely adopted especially in various applications like bottle manufacturing, which started in Turkey in the year 1980 and was later adopted in many forms for various purposes [3]. Parallel to this, the demand for plastic, increases plastic waste at an exponential rate. A study stated that approximately 400 million tons of plastic waste will be produced annually and maybe twice in the upcoming decade [4]. A detailed report by the National Association for PET Container Resources (NAPCOR) mentioned recycling rate of PET plastic is nearly 30.8% which requires another alternative to reuse such waste sustainably. The construction industry has a large capacity to consume this waste and it would be a boon for society if any waste material like PET is sustainably replaced in place of aggregate as it saves our ecosystem as well as natural resources.

In previous studies, many researchers have adopted recycling plastic in place of aggregate in mortar and concrete mixes [5]. A researcher used high-density polyethylene (HDPE) as an aggregate in place of sand in cement mortar at various replacement levels from 0% to 100% by volume. Its result represented that the strength declined by the enhancement of recycled plastic causing a lack of bonding between the mixes and waste [6]. Another study showed that the PET particles helped develop lightweight concrete due to its lower density and lightweight as compared to natural aggregate [7]. However, other studies observed that the unwashed PET bottle waste reduces the strength parameter by weight of concrete at 5% replacement while the durability of the concrete improved by increment polyethylene terephthalate waste over control concrete mixes. Its outcome is attributed to higher ductility, less workability, and split tensile than reference mixes [3]. Additionally, substituting fine and coarse aggregate of concrete specimens through shredded PET bottles by weight at various proportions such as 5%, 10%, 15%, and 20% to check the impact resistance and energy absorption capacity of concrete mixes. Its result represented a lower value of compressive strength but provided better resistance against loading impact as an enhancement of plastic waste in concrete [8]. On similar ground, river sand replacement with an inclusion of waste plastic fragments to evaluate physical and mechanical parameters. The results indicated that density and ultrasound velocity declined in contrast, the strength of the specimen was enhanced by incorporating 5 to 10% of river sand which was replaced through the equal proportion containing polyethylene terephthalate (PET). Hence the author concluded that replacing fine particles through polyethylene terephthalate fragments may positively influence the strength-related parameters if the substation amount is below 10% [9]. Moreover, the sustainable implementations of PET waste as construction materials were observed. Here, the fine aggregate was substituted through untreated plastics waste in various percentage levels like 2.5, 5, 10, and 20% by weight, for the preparation of mortar and concrete samples. These mixes were tested for water absorption, carbonation, thermal conductivity, and mechanical properties concerning conventional mixes. The result indicates an improvement in thermal insulation whereas decrement in mechanical properties [2].

On the other hand, a study used PET in the form of shredded granule waste having sizes between 0 to 4 mm as a lightweight aggregate over fine aggregate in mortar specimens. Test results suggested that using shredded waste polyethylene terephthalate granules in mortar substantiates reduction of the dead weight of mortar which also decreases the seismic factor in structure and, consequently, would be helpful in the construction of earthquake-resistant structures and environmentally friendly [10]. A similar trend examined the behavior of recycled polyethylene terephthalate fiber on the toughness, strength, and drying shrinkage parameters of cement mortar specimens. The experimental work concluded that improving the performance of samples increased toughness and decreased drying shrinkage [11]. Another study suggests the inclusion of 40% PET and 60% filler material (20% fly ash + 80% bottom ash) in cement mortar mixes impart the highest compressive strength [12]. In contrast, compressive strength declined by 12.8 MPa from 42.7 MPa and 22.5 MPa from 49.5 MPa by an increase of PET amount from 40% and 20% replacement respectively in geopolymer mortar [13]. Another study reveals good thermal conductivity upto 60% replacement of fine aggregate by polyethylene terephthalate plastic concerning the conventional mortar [14]. The microstructure pattern of recycled PET mortar through SEM images and evaluated fire resistance parameters over conventional control mortar. Experimental results represent a decrement in the strength and heat conduction capacity due to the inclusion of PET nanoparticles in mortar [15]. Furthermore, the thermophysical parameters of an eco-friendly mortar. In this, partial substitution of sand was done with recycled PET at 5, 10, 15, and 20%. Test results stated that the workability improved and found a fair correlation ($R^2 = 0.9847$) between compressive strength and ultrasonic pulse velocity, both were reduced by improved dosage of polyethylene terephthalate. The implementation also imparts the thermophysical parameters of the cement mortar mixes [16].

The previous literature reveals that there are few studies on PET plastic waste as a valuable material in the construction field. Previous studies made on fine aggregate with polyethylene terephthalate plastic showed mechanical properties whereas durability and microstructure studies are still missing. In line with this, the present study was focused on fresh and hardened parameters of cement mortar mixes with PET waste. Also, microstructural studies were performed on selected mortar mixes to know the in-depth behavior of PET waste in mortar properties.

2. Materials and Methods

2.1 Raw materials

To conduct the current investigation, Portland pozzolana cement, fine aggregate (River sand), and polyethylene terephthalate (PET) plastic waste were used to make cement mortar mixes. The Portland pozzolana cement attributed to IS 1489-1991 [17] was used as construction binding material and the fine aggregate of zone III confirming to IS 2116-1980 [18] was used. Procurement of polyethylene terephthalate waste was from a manufacturing unit situated at Jaipur, Rajasthan, India. Figure 1 shows the image of cement, river sand, and PET plastic waste.

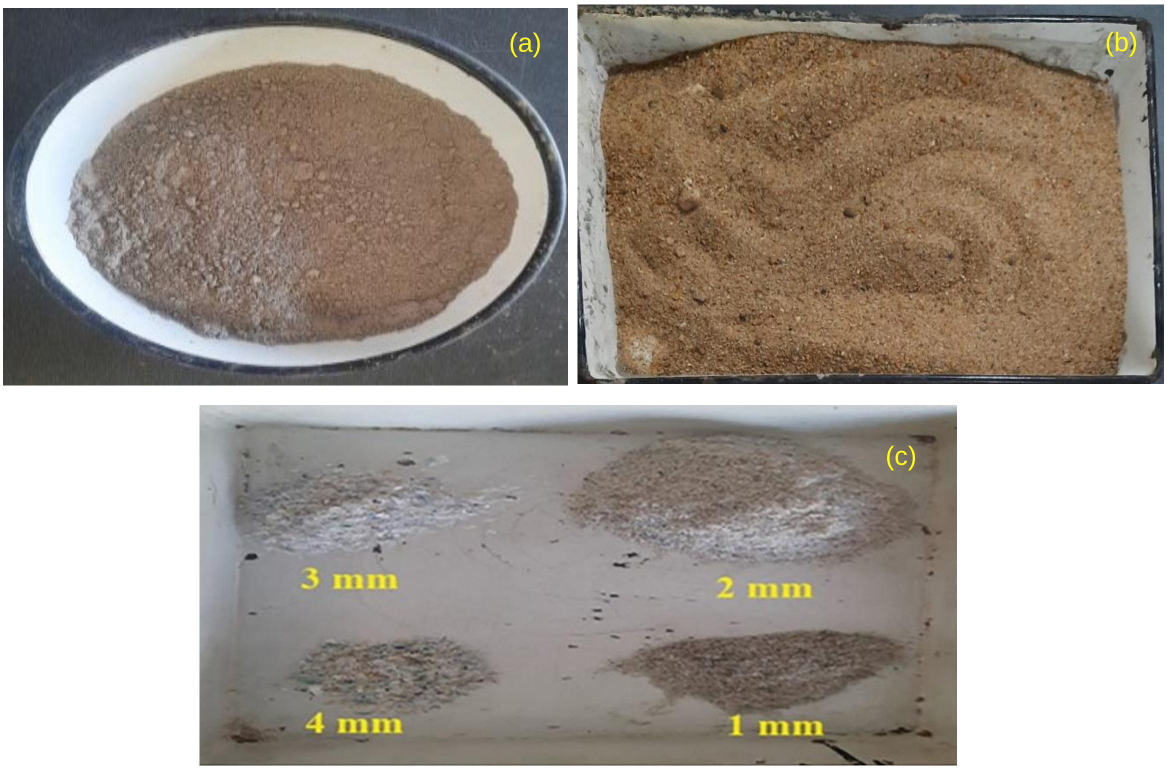


Figure 1. Images of (a) Cement, (b) River sand and (c) PET Plastic waste

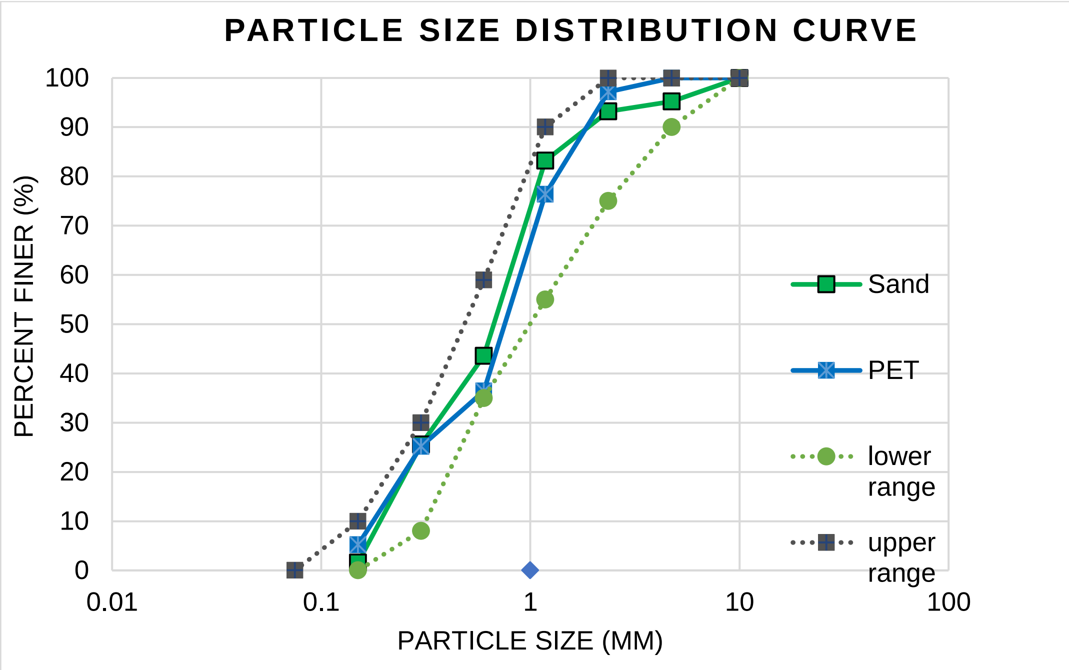


Figure 2. Gradations of sand and PET plastic

Some particle sizes of the PET plastic waste used were smaller than 1.18 mm because as per the Indian standard, IS 1542-1992 [19] and IS 2116-1980 [18], a significant portion of fine aggregate (70% for masonry mortar and 90% for plaster) would be finer than 1.18 mm.

The other sizes of PET plastic waste used were 2mm, 3mm, and 4 mm after performing an analysis of fineness modulus through IS sieves. Figure 2 summarizes the gradations of sand and PET plastic in which gradations of each material were under the specifications [18-19].

The physical and chemical compositions of sand and PET are shown in Table 1 and Table 2 respectively.

The presence of minerals of river sand and PET plastic waste was identified by X-ray Diffraction images, which are plotted in Figure 3 and Figure 4.

Table 1. Physical properties of cement, sand, and PET plastic

Property	Materials			
	Cement	**River sand**	**PET**	**Reference**
Specific gravity	2.9	2.65	0.505	IS 2386-3, 1963(Part III) [20]
Water absorption (%)	-	4.9	0.01	ASTM C 642-06, 2008 [21]
Bulk density (loose) Kg/m^3	1100	1580.6	342	ASTM C 642-06, 2008 [20]
Fineness modulus	-	2.576	2.596	IS 2116-1980 [18], IS 1542-1992 [19]
Compressive strength after 28 days (Mpa)	35.9	-	-	ASTM C348, 1988 [22]
Initial setting time (minutes)	135	-	-	IS 1489-1991 [17]
Final setting time (minutes)	255	-	-	IS 1489-1991 [17]
Consistency (%)	33	-	-	IS 1489-1991 [17]

Table 2. Chemical compositions of PET plastic waste and river sand

Material	**C**	**O**	**Si**	**Al**	**Au**	**K**	**Fe**	**Na**
PET plastic waste (%)	88.65	8.16	-	-	3.19	-	-	-
River sand (%)	1.35	20.94	41.72	13.00	2.76	14.81	2.44	2.98

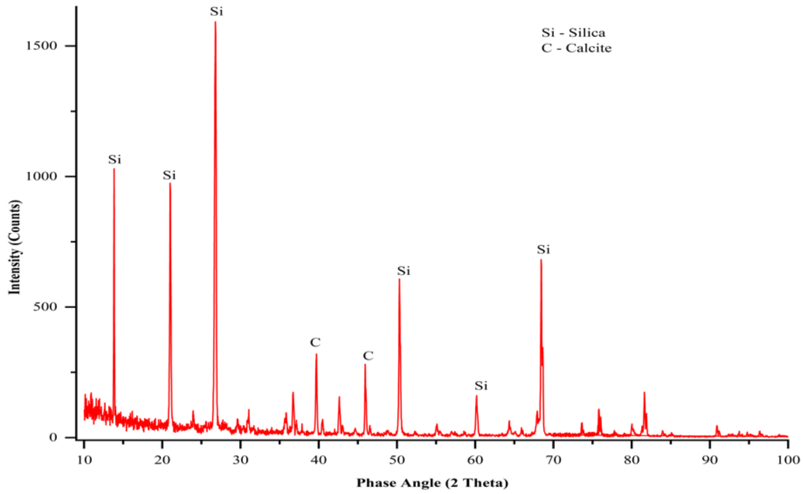


Figure 3. XRD image of River sand

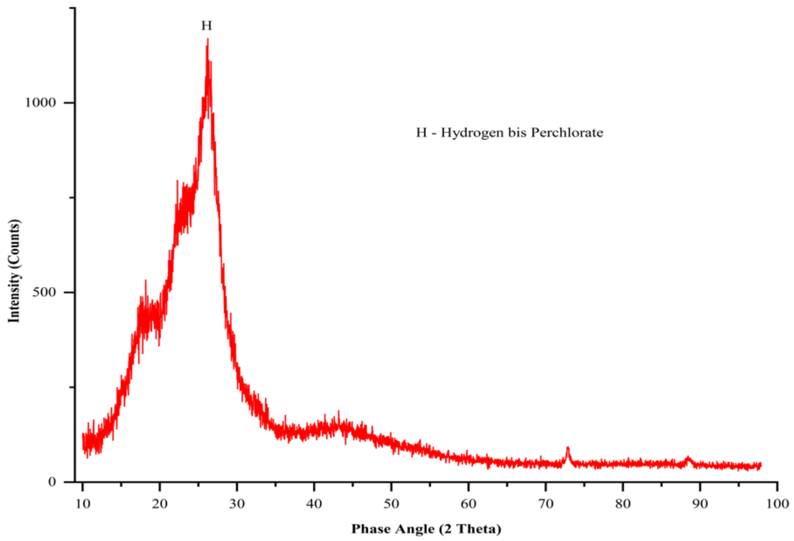
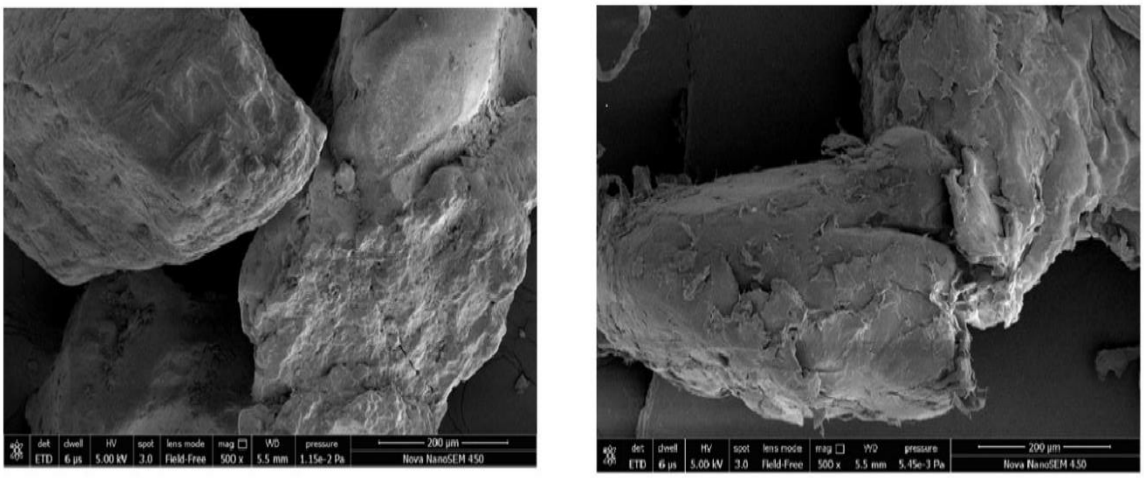


Figure 4. XRD image of PET Plastic waste



(a) (b)

Figure 5. SEM image of (a) River sand and (b) PET Plastic waste.

Table 3. Overview of Mix proportions

Series	Mix	% Replacement	Materials (g)			
			Cement	River sand	PET plastic waste	Water
1:3	Control	0.00	150.66	649.34	0.00	129.56
A	AC5	5.00	155.34	636.89	7.77	135.14
	AC10	10.00	160.96	624.55	14.49	136.82
	AC15	15.00	166.67	610.00	23.33	140.00
	AC20	20.00	172.41	594.83	32.76	155.17
1:6	Control	0.00	83.16	716.84	0.00	138.04
B	BC5	5.00	86.21	706.03	7.76	151.73
	BC10	10.00	89.39	693.63	16.98	160.00
	BC15	15.00	92.91	681.07	26.02	188.62
	BC20	20.00	96.74	667.47	35.79	209.93

Note: In the mix, the number represents the percentage of replacement of river sand by polyethylene terephthalate and the alphabet denotes the name of the series and waste type (C: Coarse sand).

The texture of every substance was observed by the Scanning Electron Microscope images, clearly represented in Figure 5. Through images, PET plastic waste has an irregular shape and smooth surface over the river sand which has an irregular shape and rounded texture.

2.2 Mix proportions

This study was conducted with a total of ten cement mortar mixes having two volumetric ratios of 1:3 and 1:6. PET plastic waste replaced river sand by volume from 0 to 20% at an interval of 5%. These mortar mixes were classified into two series A and B. Series A and Series B consist of mortar mix generated with rich mortar (1:3) mixes and lean mortar (1:6) mixes respectively. The detailed mix proportions are mentioned in Table 3.

2.3 Methodology

2.3.1 Mechanical Tests

Water absorption and percentage air voids of mortar mixes were evaluated through specifications of ASTM C 642-06, 2008 [21]. Water absorption and percentage air voids tests were performed on a 70.6 mm cube specimen (three for each mix), which was cast and then after being immersed in a curing tank for 28 days and further oven-dried for 24 hours at 100° C temperature. Repeat the same procedure until it attains 100% dry condition. Furthermore, specimens were immersed in a curing tank for 24 hours to calculate the weight in water-submerged and saturated surface dry conditions.

The compressive strength and flexural strength of each mix were analyzed and confirmed by ASTM C348, 1988 [22]. For the compressive strength of mortar mixes, the mortar samples of size 50mm x 50mm x 50mm were cast with varying proportions of polyethylene terephthalate plastic waste with respective water-cement ratios. After demolding, the mortar samples were immersed in a curing tank for 7 and 28 days before testing till they gained sufficient strength. The flexural strength of beam samples of size 40mm x 40mm x 160mm were tested using the center point load technique.

The workability of mortar mixes was accessed through the amount of water used to attain the required flow range. IS 2250-1981 [23] recommended a range of 205 mm to 215 mm for rich mortar (1:3) and lean mortar (1:6) mixes. It was adopted and confirmed by ASTM C230, 2010 [24].

The ultrasonic pulse velocity (UPV) test is a non-destructive technique by this time taken by an ultrasonic pulse to cover the distance into the mortar was measured. A test was used to investigate the compactness of mixes by the incorporation of PET. Ultrasonic-pulse velocity test was performed on mortar beams having dimensions 40mm x 40mm x 160 mm to investigate the mortar homogeneity, presence of pores or voids, and also for the determination of its physical parameters. Crack detection, homogeneity, and hardening properties of mortar beam samples were measured by ultrasonic pulse velocity test attributed to the specifications of ASTM C597, 2016 [25].

2.3.2 Durability Tests

Resistance of mortar mixes to withstand acid attack was as per the guidelines of ASTM C 267-01[26]. Through this test, plastic-based mortar samples and cement mortar samples were kept in a container consisting of a 5% solution of sulfuric acid mixed with distilled water for experimental testing at 1, 7, 14, 28, and 90 days. After 28 days of curing, samples were wiped off with a dry cloth. The drying shrinkage test is primarily correlated to available cement content, relative humidity, and water content. In this test, mortar shrinkage bars having a mold of dimensions 25 mm x 25 mm x 285 mm were prepared. For each mix, three specimens were cast and immersed and the procedure was confirmed by ASTM 1148-92 [27].

2.3.3 Microstructural Tests

To understand the in-depth internal mechanism regarding the structural geometry of mortar mixes having polyethylene terephthalate plastic waste, a scanning electron microscope (SEM) technique was performed on raw and mortar mix specimens. For this study, the first prepared polished mortar specimen of size (10 mm× 10 mm × 10 mm) was examined after 28 days of curing to observe the surface texture and shape using a Nova Nano SEM 450 device. In addition, the identification of minerals of river sand and polyethylene terephthalate plastic waste was monitored through the X-ray diffraction (XRD) technique. To access change in bond strength and their characteristics by the incorporation of polyethylene terephthalate waste in mortar mixes were analyzed by Fourier transform infrared spectroscopy (FTIR). A test sample of mortar powder consisting thin pellet film was prepared with potassium bromide(K-Br) for spectrum analysis. The presence of crystal form substance was identified using a PANalytical Xpert PRO diffractometer between 10 degrees to 100 degrees range and its pattern was monitored by Origin Pro-9 and Xpert high score plus software.

3. Results and Discussions

3.1 Workability of fresh mortar by flow table test

To understand the behavior of workability on all fresh mortar mixes, a flow table test was performed to achieve the desired target consistency. It was determined through the sufficient quantity of water required for mortar mix. The amount of water continuously changed until the flow value limit of 205 to 215 mm was obtained; these were processed by continuous hit and trial process and the outcomes were correlated to the water-cement ratio. Figure 6 represents the water-cement ratio of cement mix which was affected by the implementation of polyethylene terephthalate waste over river sand. It was shown that the water-cement ratio enhanced as the amount of PET plastic waste increased in series B. Moreover, for series A, the water-cement ratio increased at 5% replacement whereas its value decreased upto 15% and reached a maximum at 20% replacement over the control mortar mix. The maximum water-cement ratio was found at 20% replacement of river sand by PET plastic waste for series A and B. It was 1.31% and 1.05% more than the control mortar mix. However, the minimum water-cement ratio was obtained at 15% replacement of river sand by PET plastic waste for series B, it was 1.03% less than that of the control mortar mix. The decrease in water quantity was due to the filler effect of the incorporation of PET plastic. The gaps in fine aggregates in mixes that were previously filled by the amount of water were now filled by PET plastic waste. It implies that present water may be effectively used to liquefy particles and hydrate cement. This outcome is correlated with the study mentioned a reduction in the mortar flow by the presence of flaky particles of plastic with more angularity and sharp edges [28]. Additionally, the thixotropic behavior of PET plastic could be the reason for this nature which causes less energy content to obtain the desired mortar mix flow [1].

In series B, the water-cement ratio observed continuously increased over the control mortar. This outcome could also be accredited to a more surface-specific area causing an excess water requirement to obtain sufficient mix flow. Additionally, this may also be because the plastic has a smooth texture which results in more water requirement that is beneficial to maintain the consistency of the mix [18]. Another researcher stated effective use of a pellet-shaped PET aggregate with a smooth and spherical surface minimizes slump as compared to flaky-shaped PET aggregates consisting of angular shapes and sharp edges [29].

3.2 Water absorption and percentage air voids

Figure 7 and Figure 8 illustrate the variation in water absorption and percentage air voids for rich and lean mortar mixes. In Figure 7, a continuous increase in water absorption for both series was obtained by the increased substitution of PET content. The maximum water absorption value was obtained at 20% substitution for series A and series B, which was 129.8% and 128.37% respectively higher over the control mix. The reason behind water absorption enhancement was due to non-homogeneity in mortar mixes by more specific surface area and also creating voids by the presence of various sizes of PET in the mortar mixes over sand. Due to this behavior, a maximum number of voids were produced in higher substitution with PET as shown in Figure 8 Similarly, the maximum percentage of air voids was obtained at 20% substitution for series A and series B, which was 124.71% and 123.57% respectively higher than the control mix. These results may be attributed to improved hydration by PET resulting in more ultrasonic pulse velocity than that of the control mix. This outcome is correlated to previous research stated that water absorption and permeability of mortar consisting of 100% PET aggregate as a substitute for river sand were more than mortar consisting of an equal ratio by volume of PET and sand together [10]. Furthermore, it was mentioned that the water absorption and permeability enhancement obtained for mortar mixes having PET-based fine aggregate in place of the control cement mortar matrix [30]. A similar pattern was found in an improvement in water absorption by increasing the dimension of PET aggregate and water-cement ratio[7].

3.3 Compressive and flexural strength of hardened mortar mix

The effect of PET waste on compressive and flexural strength was measured at 7 days and 28 days as plotted in Figure 9-12. For series A and B, the maximum compressive strength was found at 5% replacement of river sand by PET plastic waste. The increment in compressive strength for series A and B at 7 days was observed as 105.1% higher and approximately the same respectively than that of their control mortar, whereas for the same series A and B, the improvement in compressive strength at 28 days was observed 102.96% and 103.5% higher over respective control mix. Similarly, for series A and B, the highest flexural strength was obtained at a 5% replacement level of river sand by PET plastic waste. The enhancement of flexural strength for series A and B at 7 days was found approximately the same and 119.04% higher respectively than that of their control mortar, whereas for the same series A and B, the improvement in flexural strength at 28 days was found approximately same and 110.9% higher respectively over control mix. Enhancement in strength property by the filling of pores through PET and its plasticity nature accredited improvement in the bulk density of construction. Scanning electron microscope images Figure 20-23 also confirmed the filler tendency in the cement mortar matrix.

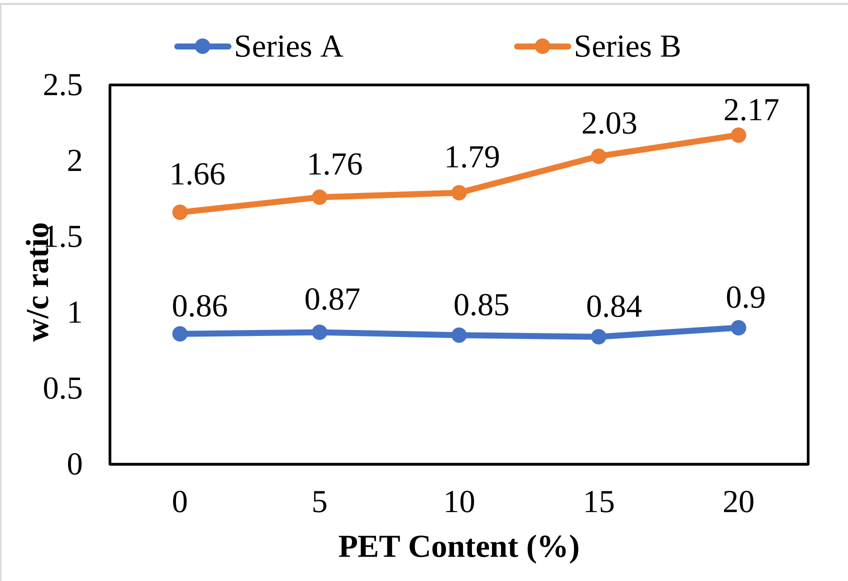


Figure 6. Variations in w/c ratio vs PET Content (%)

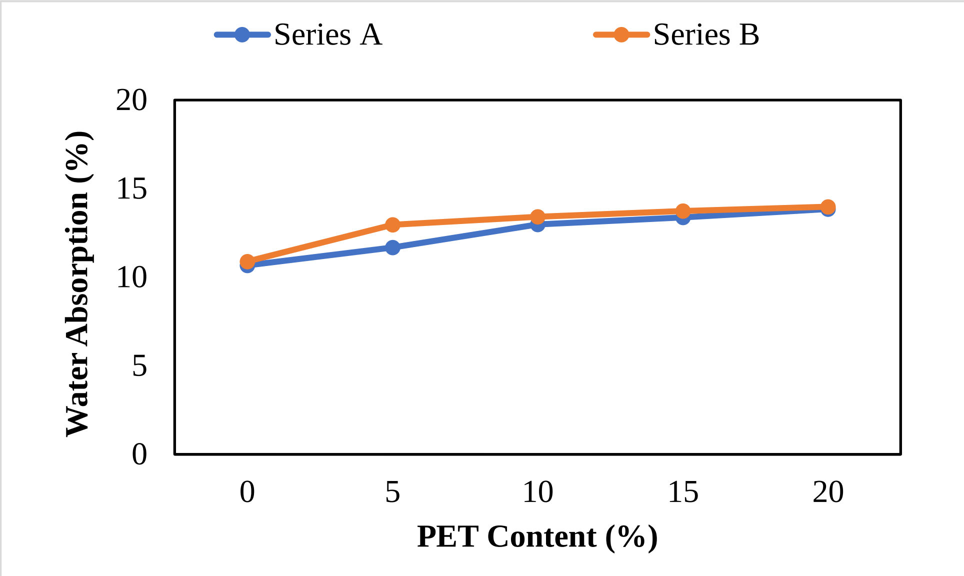


Figure 7. Variations in water absorption of mortar with PET Content (%)

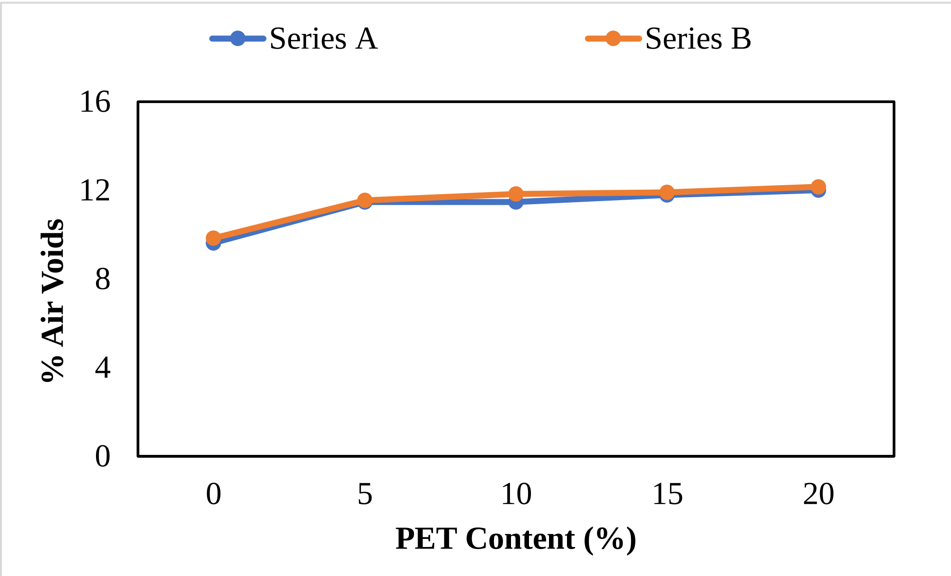


Figure 8. Variations in % air voids of mortar with PET Content (%)

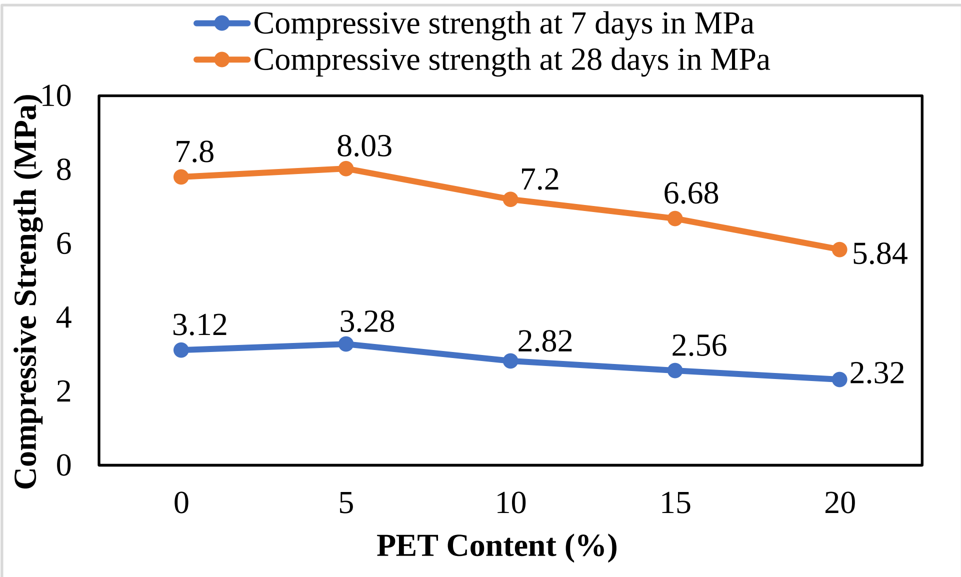


Figure 9. Variations in compressive strength of rich mortar mixes

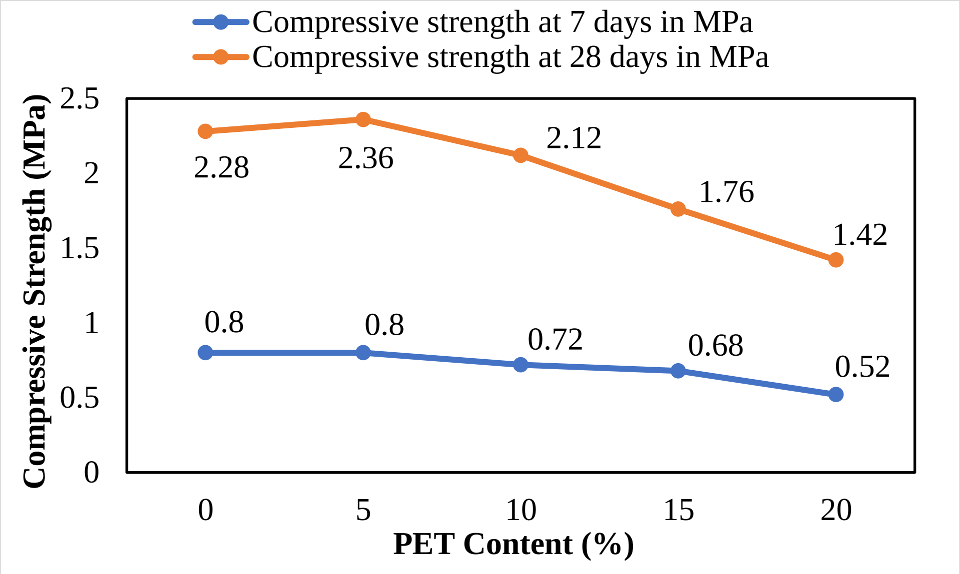


Figure 10. Variations in compressive strength of lean mortar mixes

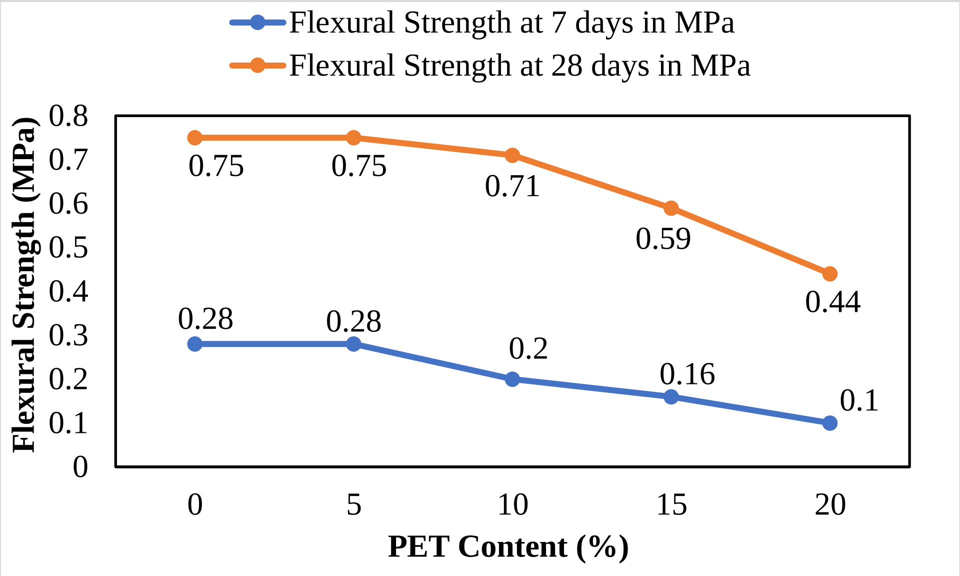


Figure 11. Variations in flexural strength of rich mortar mixes

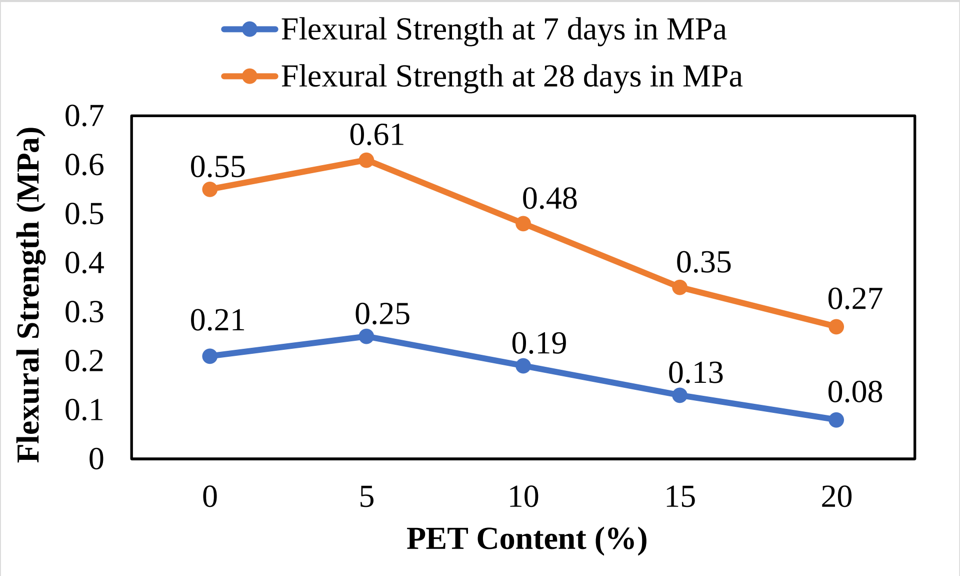


Figure 12. Variations in flexural strength of lean mortar mixes

However, beyond 5% substitution value of strength was reduced in both series A and B, which was mainly because of the smooth texture and sharp edges of PET attributed to weak interaction among particles and mix. A similar trend was mentioned in a study where the compressive and flexural strength of specimen consisting of less quantity of cement and more water-cement ratios decreased by a high amount attributed to the weak bonding of aggregate resulting in a weak mix[30]. Additionally, this trend was also observed by the incorporation of various forms (like course, fine, and pellet) of PET plastic aggregate in the mix [31]. This result is consistent with the previous research stated that the bonding strength between the mortar and the texture of the plastic waste decreases [32]. Also, the implementation of PET aggregate particles as a cementitious material replacement of upto 5% compensated for a greater quantity of bleeding water present across the PET particles that creates a weak interaction of mortar and PET [3].

3.4 Ultrasonic Pulse Velocity (UPV)

The change in UPV for series A and series B is shown in Figure 13. It was analyzed that the UPV value continuously declined at all replacement levels for both the rich and lean mortar mixes. For both series A and series B, ultrasonic pulse velocity is highest for the control mortar mix, indicating a dense and well-compacted structure and it was reduced up to a maximum replacement level of 20% of sand by PET. This is because the mortar with PET formed a porous nature through which ultrasonic waves travel slower over the control mix. Decrement in compactness was stated due to the hydrophobic behavior of PET waste in mixes. Further enhancement in PET replacement results non-uniform mix by obtaining a permeable sample leads to poor compaction that reduces pulse velocity. A similar result was mentioned in a study that a decline in the value of velocity of self-compacting mortar mixes prepared with plastic waste in place of river sand [33]. Furthermore, another observation reveals that implementing PET alters the permeability through the mix; these created cavities attenuate waves as they pass through mortar, PET, and voids so their velocity decreases [34]. This trend is related to previous research investigating the ITZ and voids formed by the incorporation of PET. This may also attributed to the velocity of the ultrasonic wave as the incident wave travels via voids, ITZ, PET, and cement matrix, a portion is reflected, and the remaining portion is transmitted, resulting in a decrease in the velocity of the wave [14].

3.5 Acid Attack

The acid attack test was used to measure the capability of mortar mixes to withstand acid. Mortar is highly alkaline when the range of pH values is between 12 to 13.8. The chemical reaction of sulfuric acid with cement mortar paste creates a highly soluble calcium sulfate salt. Due to the presence of this salt, it attacks mortar paste resulting change in strength. The change in compressive strength was calculated using the formula:

Change in compressive strength (%) = [Fc-Fab]/ Fc x 100

Where,

Fc = Compressive strength of mortar specimen in distilled water after 28 days of curing

Fab = Compressive strength of mortar specimen in sulfuric acid on a particular day of testing

The results presented in Figure 14-15 show that the placing of polyethylene terephthalate plastic specimens for less than 28 days did not much affect the resistance against sulfuric acid. Consequently, the resistance against the attack of sulfuric acid was increased by the incorporation of polyethylene terephthalate waste. The increment in weight of AC0 was 6.73%, which further improved to 7.47% with the incorporation of 10% polyethylene terephthalate waste. Similarly, the increment in weight of BC0 was 9.49%, which further increased to 11.05% with the incorporation of 10% PET waste. This was mainly because of less interaction between the polyethylene terephthalate waste and mortar. Additionally, the incorporation of polyethylene terephthalate waste enhanced the permeability of the mortar and subsequently more prone to acid attack [13].

Additionally, the residual compressive strength for rich and lean mortar mixes at various proportions for 1, 7, 14, 28, and 90 days are shown in Figure 16-17. Results represented that with the substitution of sand by PET, the value of residual compressive strength was improved over the control mix for 28 days. Change in residual compressive strength at 90 days, for control, AC5, AC10, AC15, and AC20 were observed as 16.32%, 31.73%, 33.61%, 31.07%, and 30.30% respectively. Similarly, changes in residual compressive strength at 90 days, for control, BC5, BC10, BC15, and BC20 were observed as 2%, 25.42%, 47.17%, 43.19%, and 39.44% respectively. The reason behind this may be due to fewer pores and dense packing of PET in a mortar [35-36]. When the cement mortar mixes came in contact with sulfuric acid, C–S-H and C-H chemically reacted with acid to form calcium sulfate (gypsum) and calcium sulfoaluminate (ettringite) to contribute to the weight and compressive strength change of the sample.

3.6 Drying Shrinkage

The drying shrinkage is a property to understand the capability of mortar in the plastering application. From the initial reading, the mortar specimen's shrinkage was evaluated every 7 days till 28 days. Figure 18-19 shows the percentage change in shrinkage with PET. It was noticed that the drying shrinkage decreases with an enhancement in PET amount in cement mortar mixes. The main reason for the positive impact was the enhancement in fineness by the incorporation of PET; whereas, at a higher replacement level, the trend is significant and would obtain a minimum drying shrinkage over the control mortar mix. The shrinkage of mortar samples containing polyethylene terephthalate and river sand combined was lower than the control mortar [10]. However, shrinkage parameters of mortar mixes improved by the enhancement of recycled plastic aggregate which is due to the low value of elastic modulus of the plastic, resulting in the weak resistance of cement mix[3]. Moreover, an increased value for drying shrinkage was suggested by the incorporation of fly ash in place of river sand [37].

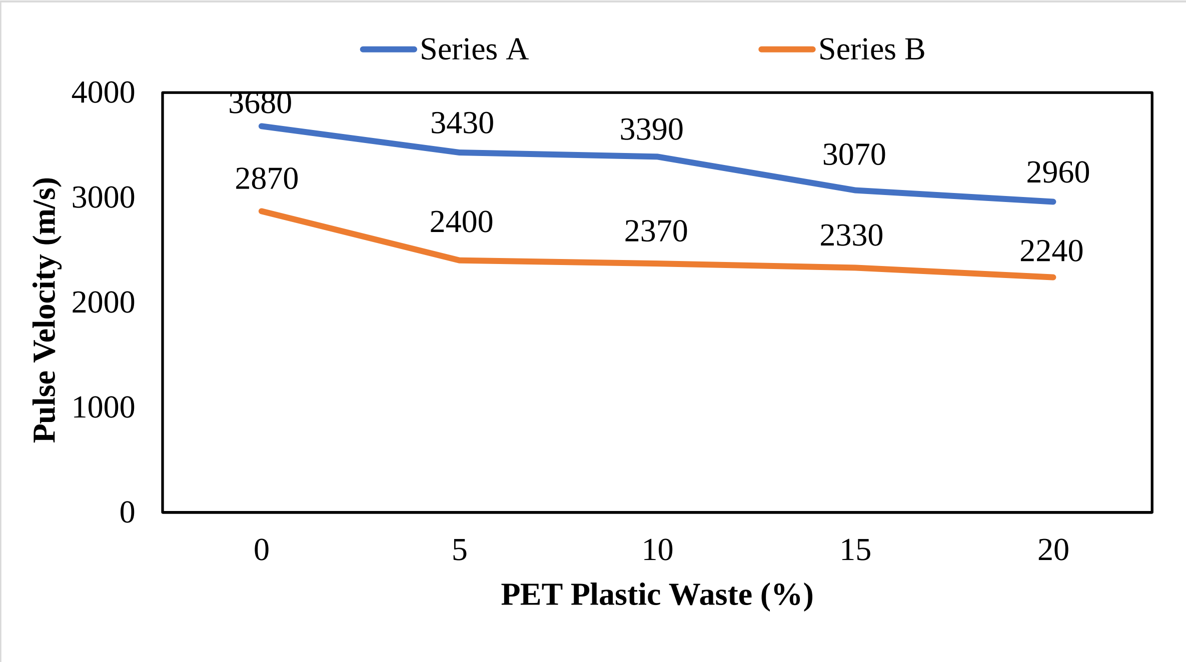


Figure 13. Ultrasonic pulse velocity of mortar mixes

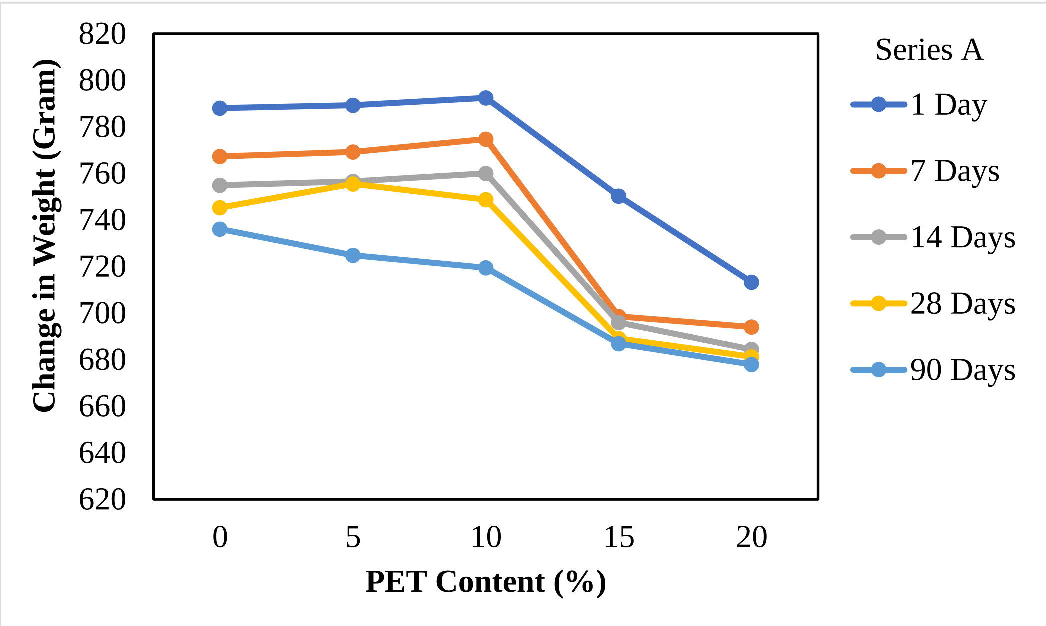


Figure 14. Change in weight of rich mortar mixes with PET Content (%)

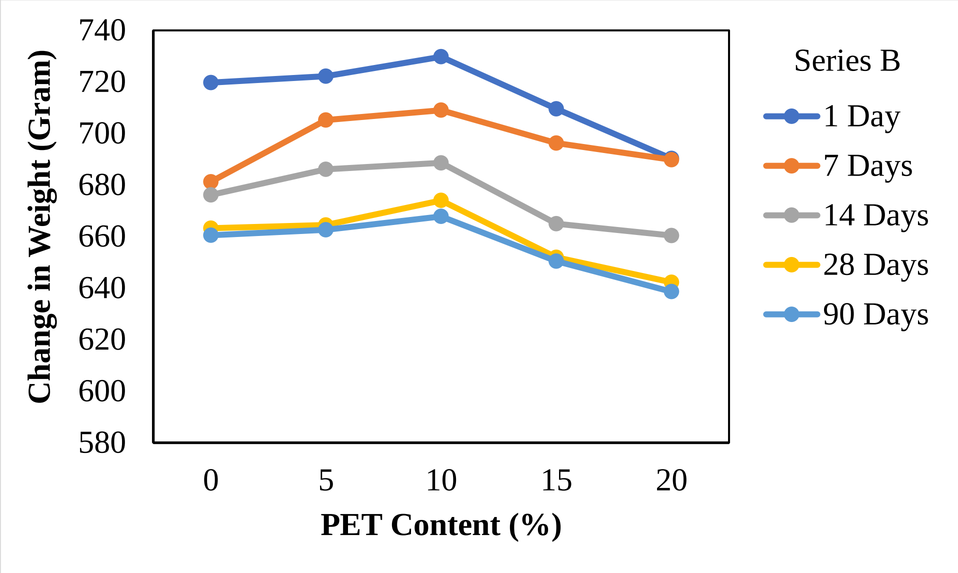


Figure 15. Change in weight of lean mortar mixes with PET Content (%)

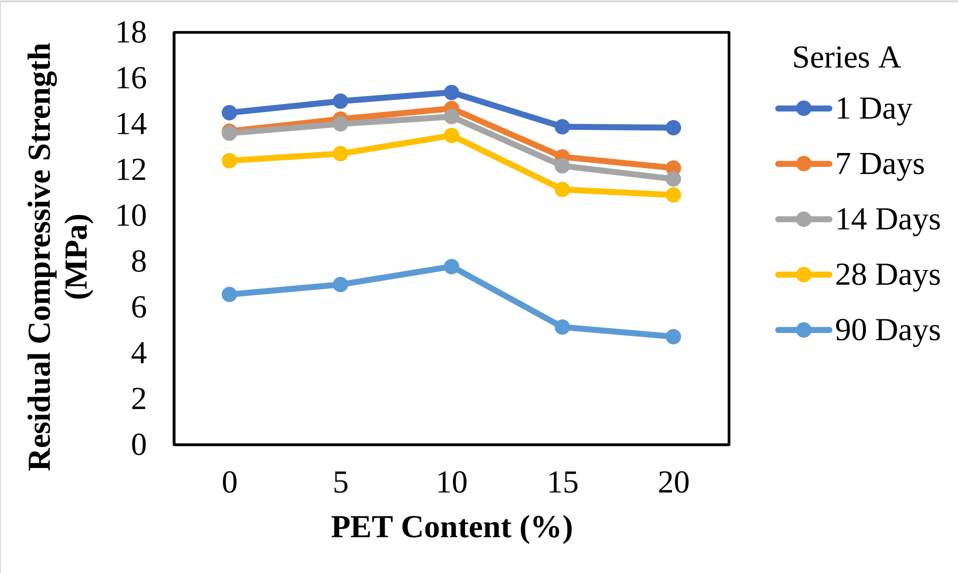


Figure 16. Residual compressive strength of rich mortar mixes with PET Content (%)

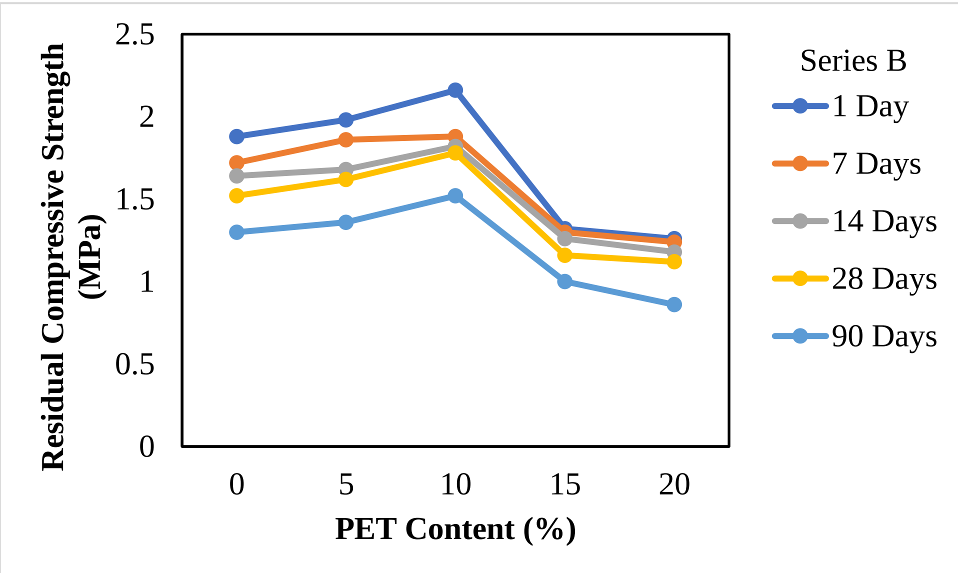


Figure 17. Residual compressive strength of lean mortar mixes with PET Content (%)

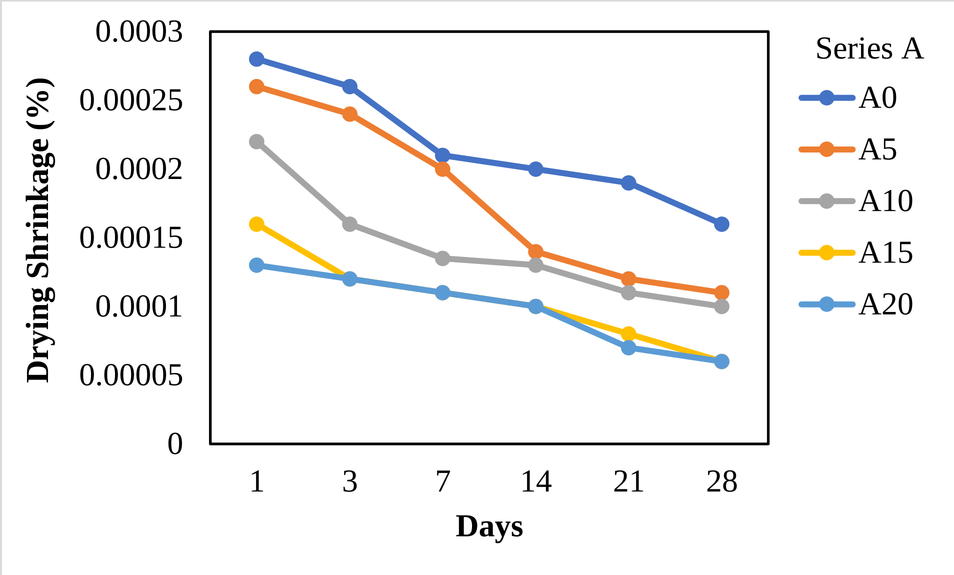


Figure 18. Variation in drying shrinkage of rich mortar mixes with PET

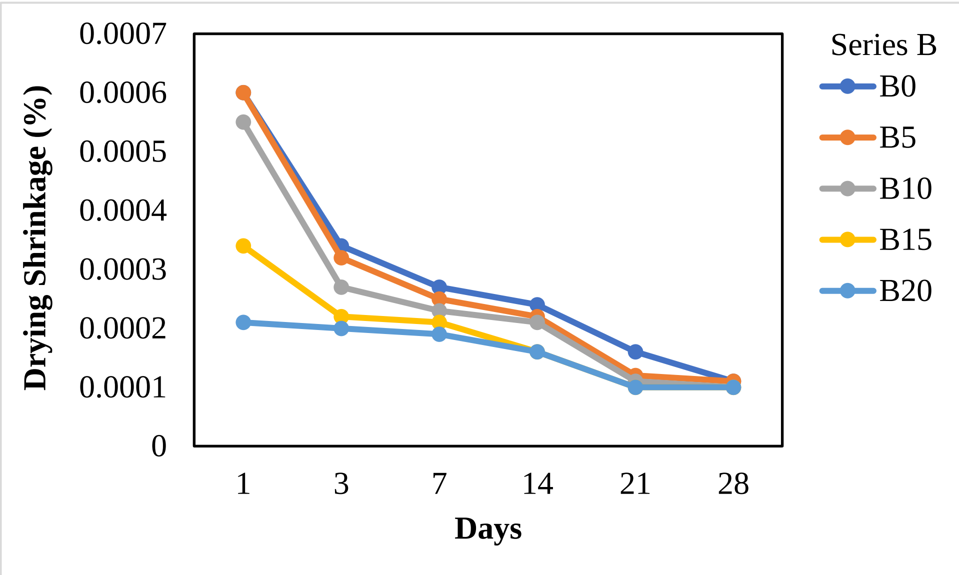


Figure 19. Variation in drying shrinkage of lean mortar mixes with PET

3.7 Scanning electron microscopy (SEM)

A scanning electron microscope technique was utilized to understand the microstructural behavior of mortar mixes, especially bonding between paste and aggregate. These samples surface was smoothed with abrasive papers through P400, P600, P800, and P1200. The gold coating was done so that the samples became electrically conductive. Images obtained by the SEM technique are shown in Figure 20-23. Low-density portions like holes, weak portions like interfacial transition zone, and hydrated products like calcium silicate hydrate (C-S-H), calcium hydroxide (C-H), and ettringite were found in SEM images. Holes were visible through voids or dark black holes, Interfacial Transition Zone (ITZ) through the long dark line, CH appears by long hexagonal crystals and C-S-H represents thin form rubbery crystals [38, 39]. In Figure 20-23, pores were visible in bigger sizes and presented weak compacted portions whereas mortar with PET plastic waste indicates a smaller number of pores. The area of the interfacial transition zone was comparatively stronger for mortar by PET Plastic waste, indicating that PET plastic waste-based mortar obtained of denser and solid structure over the control mortar mix.

This was found by the presence of dense C-S-H Gel indicated in Figure 21 resulted in an enhanced strength parameter of PET-based mortar. Whereas, at a higher substitution level, a greater number of voids obtained results in a maximum permeable structure with enhanced water absorption as shown in Figure 7. Similar results indicated that more amount of water, attributed to the hydrophobic behavior of PET, engenders an increment in the number of pores [14].

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3.8 Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) analysis was performed on rich and lean mortar of series A and series B respectively. The instrument used was 'Spectrum Two' with a K-Br splitter of resolution 4 cm^{-1} with 8 scans. A fine powder mortar was required to perform the test and the pattern was shown in Figure 24-27.

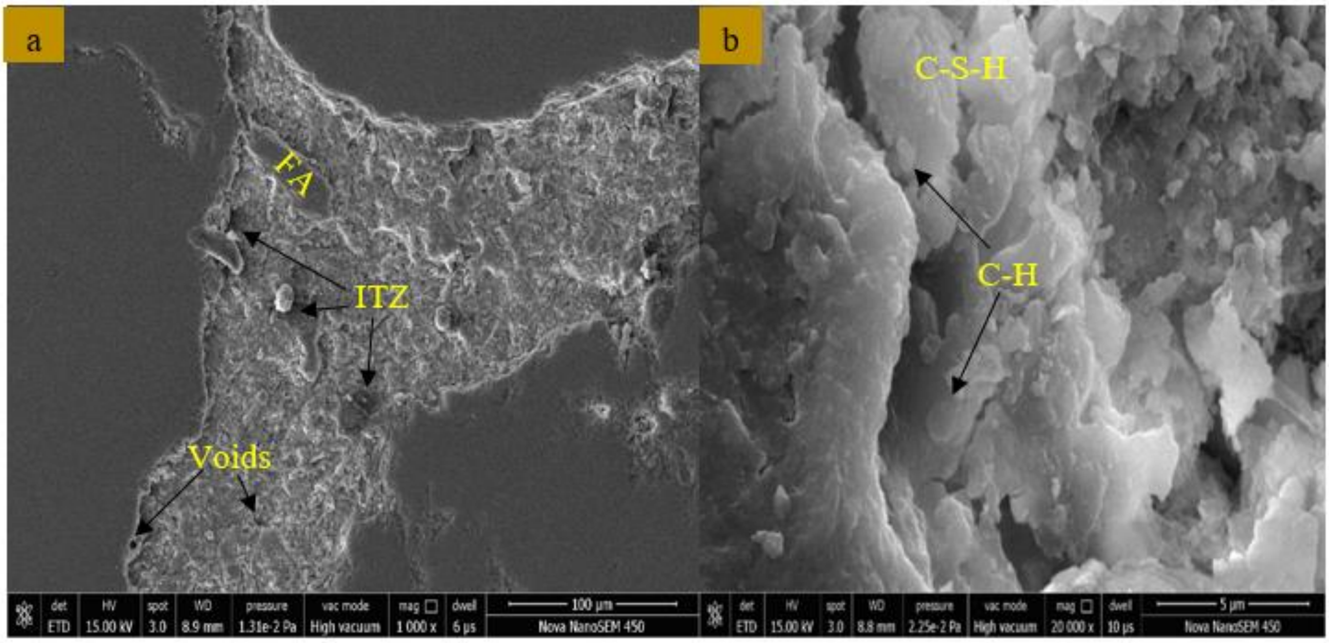

Figure 20. SEM images of control rich mortar mix

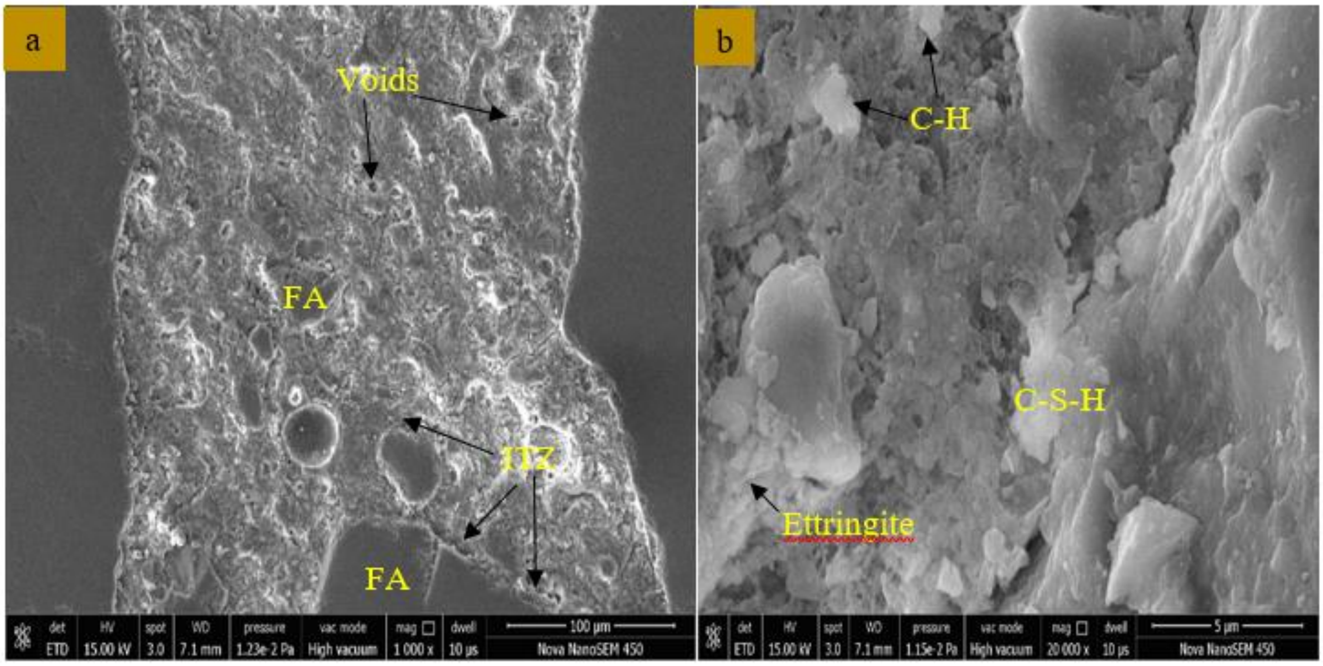

Figure 21. SEM images of AC5 mortar mix

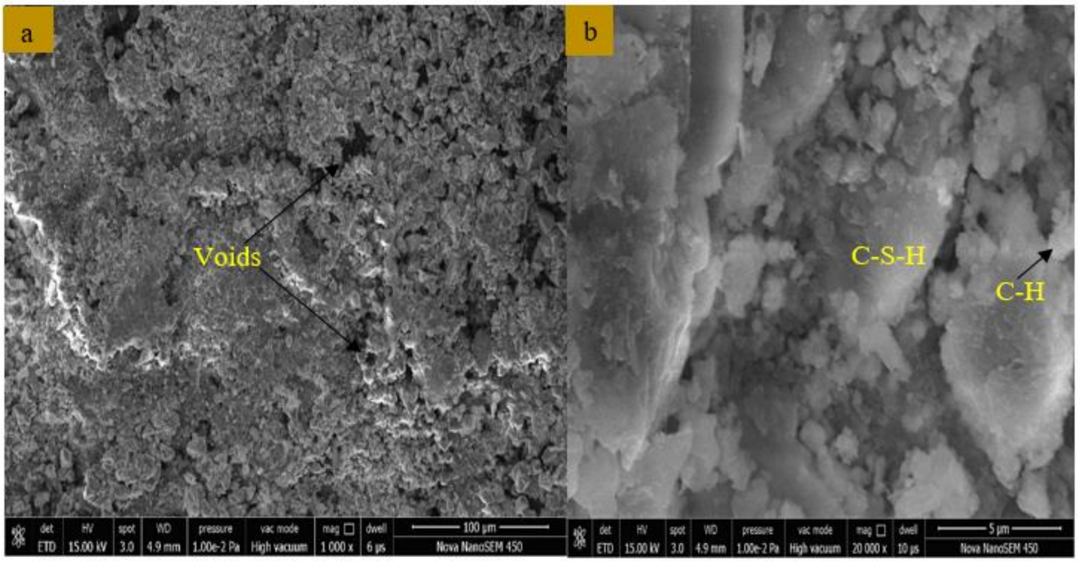

Figure 22. SEM images of control lean mortar mix

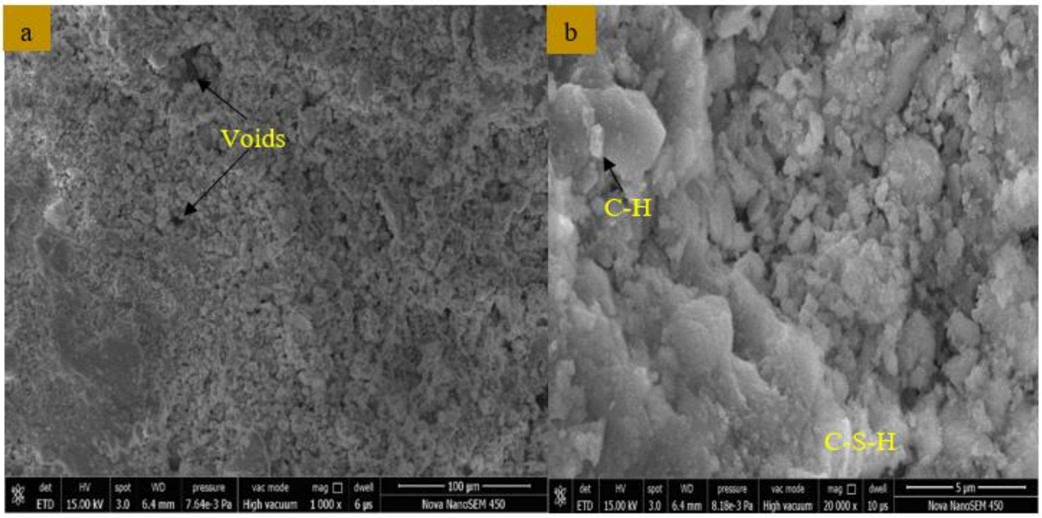

Figure 23. SEM images of BC5 mortar mix

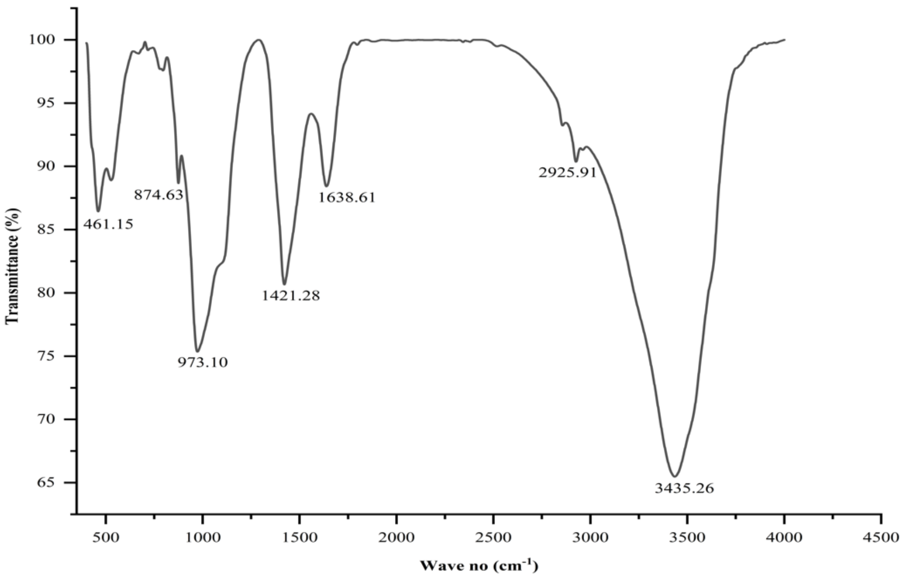

Figure 24. FTIR spectra for control rich mix

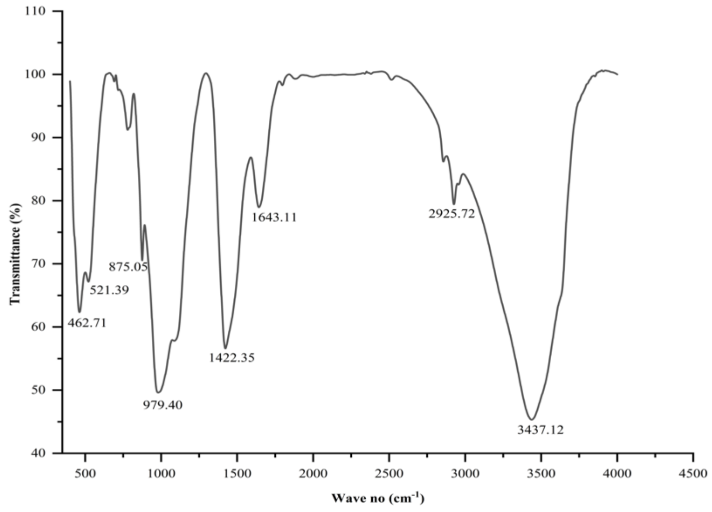

Figure 25. FTIR spectra for AC5 mix

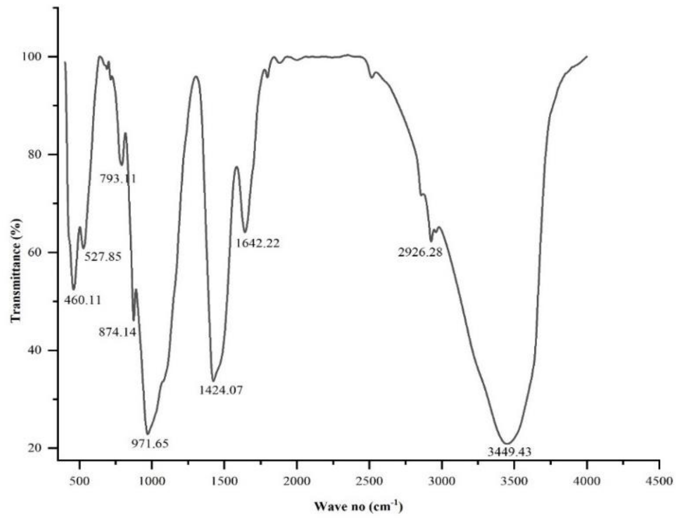

Figure 26. FTIR spectra for control lean mix

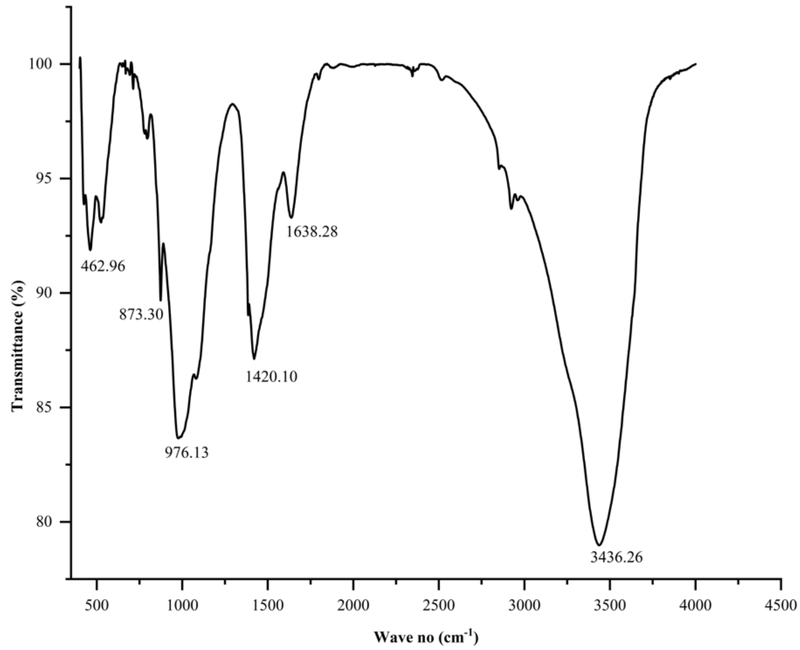

Figure 27. FTIR spectra for BC5 mix

Strong narrow absorptions at strips 1421.28 cm^{-1}, 1422.35 cm^{-1}, 1424.07 cm^{-1}, 1420.10 cm^{-1} and sharp deep strips at 873–875 cm^{-1} were due to CaCO3[40]. Moreover, with less amount of calcite peaks were obtained at 2925–2926 cm^{-1} (C–H)[41]. It was understood that peaks were attributed to the mortar with PET Plastic waste, while in the control cement mortar mix, these were observed through very low intensity. Peaks visible approx. 460 cm^{-1} (Al-O), 1000 cm^{-1} (Si-O-Si), and 779– 795 cm^{-1} were mainly for silicates and due to quartz in cement mortar mixes [38-42]. The peaks found approx. 1000 cm^{-1} were moved through approx. 979 cm^{-1} from 973 cm^{-1} by the implementation of PET plastic waste in cement mortar mixes. These changes concluded that the variation in microstructure through excellent interlinking among Al-O and Si-O bonds resulted in the enhancement of calcium alumina silicate hydrate (C-A-S-H) in mortar mixes by PET plastic waste [42]. This outcome satisfies the overall increment in compressive and flexural strength properties as indicated in Figure 9-12. A long strip appears around 3440 cm^{-1} because of the water molecules found in the mortar specimen.

4. Conclusions

The current work focuses on learning about the feasibility of polyethylene terephthalate plastic waste over river sand in cement mortar mixes. For this, a total of ten (rich (1:3) and lean (1:6)) mortar mixes were prepared with the inclusion of polyethylene terephthalate. These mortar mixes were analyzed and examined based on fresh, hardened properties and also through microstructural studies (XRD, SEM, and FTIR).

As per the results, the conclusions are as follows:

1. Thixotropic behavior and fineness of polyethylene terephthalate plastic waste are beneficial in the enhancement of the workability of mortar mixes. The water-cement ratio improved by enhancement in polyethylene terephthalate amount to 5% replacement for both mortar mixes series.
2. Satisfactory outcomes were found by water absorption and percentage air voids in all mortar mix series by the presence of polyethylene terephthalate plastic waste. The reason is that a more specific surface area and varying sizes of polyethylene terephthalate create non-homogeneity in the blended mortar mixes over control mortar.
3. Enhancement and highest strength were found at 5% replacement of river sand through polyethylene terephthalate plastic waste for both series i.e. 8.03 MPa and 2.36 MPa at 28 days respectively. This improvement is substantiated by the high plasticity of polyethylene terephthalate plastic waste and also through the filling of pores with fine material resulting in a dense mortar mix.
4. Ultrasonic pulse velocity was obtained superior at the control mix as compared to all replacement levels for both mortar mix series. The inclusion of polyethylene terephthalate plastic waste, in its result was accredited due to high porosity and thus causes a lack of interaction between cement and polyethylene terephthalate plastic waste in mortar mixes.
5. The acid attack resistance becomes maximum at 10% replacement whereas, the drying shrinkage was consequently decreased and represented a minimum value at 20% replacement. Shrinkage mainly decreased by the hydrophobic nature of polyethylene terephthalate but at higher incorporation, it enhanced the permeability of the mortar and subsequently more prone to acid attack.
6. The microstructural analysis of mortar mixes through scanning electron microscopy and fourier transform infrared spectroscopy techniques substantiated enhancement in properties from control to 5% substitution of river sand by polyethylene terephthalate plastic waste. Its result is attributed to the filler effect by the presence of polyethylene terephthalate waste forming dense and compact mortar mixes.

Therefore, it was concluded that polyethylene terephthalate (PET) plastic waste may be used in cement mortar mixes to reduce non-renewable materials by providing an alternative to natural resources. Additionally, recommendations for further research such as optimization and simulations of the sustainable composition of the mortar mixes performed using various AI models and techniques to achieve economic and environmentally friendly construction.

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Yes

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Authors Contribution Statement

Rituraj Singh Rathore: Conceptualization, Methodology Development, Data Curation, Investigation, Writing-Original Draft, Visualization. Divya Prakash: Formal Analysis, Writing - Review and Editing. Harshwardhan Singh Chouhan: Methodology Development, Validation, Formal Analysis, Writing - Review and Editing. All the authors have read and approved the final version of the manuscript.

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Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.