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Comparative Analysis of Polyethylene Terephthalate Based Blended Lean Mortar Mixes by Applying Mathematical Simulations and Regression Approach

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Abstract

Currently, construction manufacturing units need an abundant number of non-renewable resources rising in the quarrying of natural strata, producing a disparity in our precious environment. Besides this, a plentiful amount of waste material like plastic waste in several forms such as solid, filler, etc., is generated gradually. Therefore, efficient sustainable disposal seemed like a threatening mission across the world. To mitigate the issue, in the present investigation, fine aggregate (sand) was partially replaced with polyethylene terephthalate plastic waste in the manufacturing of cement mortar mixes. An experimental program evaluating the replacement of 0 to 20% (at an interval of 5%) of sand with polyethylene terephthalate in various sizes and proportions [1mm (68%), 2mm (22%), 3mm (6%), and 4mm (4%)] was developed. Slump flow, compressive and flexural strength, and fire resistance tests were performed to access fresh, mechanical, and durability parameters of blended lean mortar mixes. Mathematical simulations and regression analysis approach also substantiated enhancements and validated through polyethylene terephthalate-based mixes over control mortar mixes. Additionally, microstructural analysis using fourier transform infrared spectroscopy techniques of the internal mechanism for cement mortar mixes including polyethylene terephthalate was performed. The consequence exposed enhanced parameters at lower substitution and attributed to the masonry work.

Graphical Abstract

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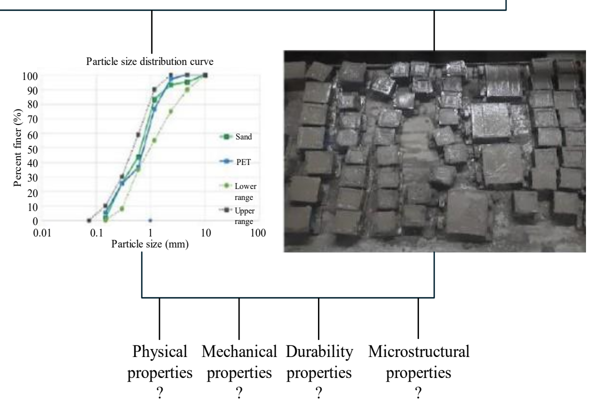

Keywords: Blended lean mortar, durability, fine aggregate, polyethylene terephthalate, regression analysis.

INTRODUCTION

The construction industry has emerged as a growing sector in the modern era and requires a continuous supply of non-renewable resources. Nevertheless, the shortage of aggregate was a major cause that needs to be considered that facades a global challenge and it's an important component for mortar production. Likewise, a momentous amount of waste particularly PET plastic is generated and consumed at its peak by the consumers. Nowadays, effective environmental and ecological disposal of polyethylene terephthalate is a severe matter. Universally, PET has multipurpose features like durability economical, packaging purposes, a wide applications in bottle manufacturing [1].

Globally, the annual production and consumption of PET plastic are designated in Figure 1, and India is the leading plastic-generated country [2]. Various solutions are implemented for sustainable treatment of PET like disposing of close to water bodies, landfills, and most are simply spread beside roadsides but still very far from a permanent solution. The probably best way to deal with the matter is only by effectively using substitute construction materials.

Various researchers worked on discovering alternative substances to substitute sand for mortar and concrete manufacturing. Azhdahpour et al. 2016 analyzed the implementation of split plastic in concrete mixes to evaluate physical and mechanical parameters [3]. Additionally, Boucedra et al., 2020 found improving fresh and hardened properties through plastic in place of fine aggregate specifically in lightweight concrete [4]. Besides this, an investigation by Akcaozoglu et al., 2010 evaluated effective use of PET in pellet forms of sizes 0–4 mm over sand substitution in mortar [5]. Peiris et al., 2024 cast samples containing fly ash and polyethylene terephthalate in cement mortar at various proportions. Subsequently, samples comprising 60% fly ash and 40% PET give the highest strength over control mixes [6]. Another study suggests the improved compressive strength of PET-based cellular mortars [7]. Likewise, PET as recycled polymerized microparticles was included in mixes to reduce fire resistance and thermal insulation properties over control mixes [8]. Moreover, another study assessed the occurrence of PET in cement mortar mixes to attain improved thermal conductivity [9]. Nevertheless, Akkouri et al., 2022 measured the thermophysical limits of an energy-efficient and

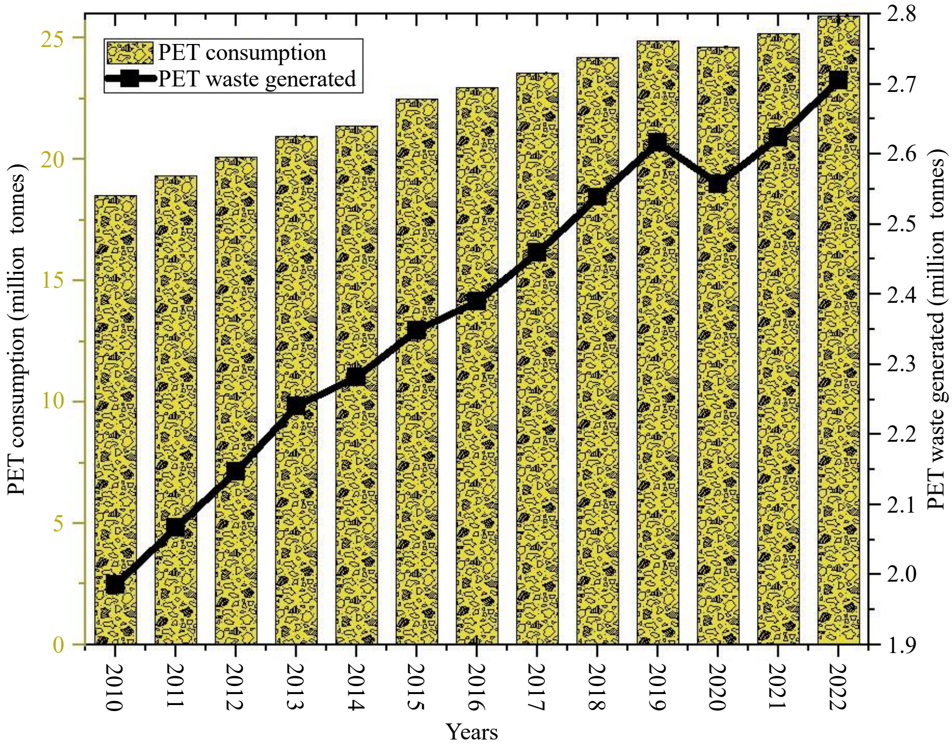

Figure 1. Produced and utilized PET annually.

environmentally friendly mortar. It observed the replacement of sand with PET at 5% to 20% at an interval of 5% comprising a 0.5 (water/cement) ratio. As a consequence, workability improved a suitable relation ($R^2 = 0.9847$) among strength [10]. Furthermore, the microstructural parameters of the mortar were assessed through Fourier Transform Infrared Spectroscopy for the outcome. Besides this, mathematical simulations were used to create relationships among the mechanical behaviors of PET-infused mortar and the included dosage of PET as shown in Equation 1.

$$\frac{f_{(\mathrm{PET\%,Days})}}{f_{cm}} = \left\{a + \left[b\left(\frac{\mathrm{PET\%}}{100}\right)\right] + \left[c\left(\frac{\mathrm{PET\%}^2}{100}\right)\right] + \left[d\left(\frac{\mathrm{PET\%}^3}{100}\right)\right] + \left[e\left(\frac{\mathrm{PET\%} * \mathrm{Days}}{100}\right)\right] + \left[f\sqrt{\left(\frac{\mathrm{PET\%} * \mathrm{Days}}{100}\right)}\right]\right\} \quad (1)$$

Where, a, b, c, d, e, and f are the regression coefficients.
The terms used are as trails:
PET = Polyethylene terephthalate
$f_{(\mathrm{PET\%,Days})}$ = Strength of PET-based mortar at several curing periods in days
f_{cm} = Strength of control mortar at 28 days of curing
PET% = Percentage of PET in mortar varying from 0 to 20%
Days = Curing period varying from 7 to 28 days
$AQ_{(\mathrm{PET\%})}$ = Quantity of ingredients required for PET mortar
AQ_{cm} = Quantity of ingredients required for control mortar
CS_{PET} = Compressive strength of PET mortar at 28 days of curing
FS_{PET} = Flexural strength of PET mortar at 28 days of curing

MATERIALS AND METHODS

Materials Utilized in This Examination

The Portland pozzolana cement (PPC) after tested has 33% consistency and specific gravity was 2.9 consumed for the study following IS 1489-1991 [11]. The sand as fine aggregate (zone III) constrained water absorption, fineness modulus, and specific gravity are 4.9%, 2.576, and 2.76 individually following the specification of IS 2116-1980 [12] and shown in Figure 2(a). Similarly, PET (Figure 2(b)) comprising water absorption, fineness modulus, and specific gravity were 0.01%, 2.596, and 0.505 individually according to IS 1542-1992 [13]. The sieve analysis of PET and sand denoted in Figure 3 represents that PET was slightly bigger than the sand. The chemical elements of PET and sand are labeled in Table 1.

Blended Lean Mixes Proportion

A total of five lean mortar mixes such as 1:6 (cement: sand) were cast through volumetric fractions. Besides this, PET replaced sand at proportions of 5% to 20% at a range of 5% to manufacture blended lean mixes. The mix design is designated in Table 2. The casted mortar mix samples as depicted in Figure 4.

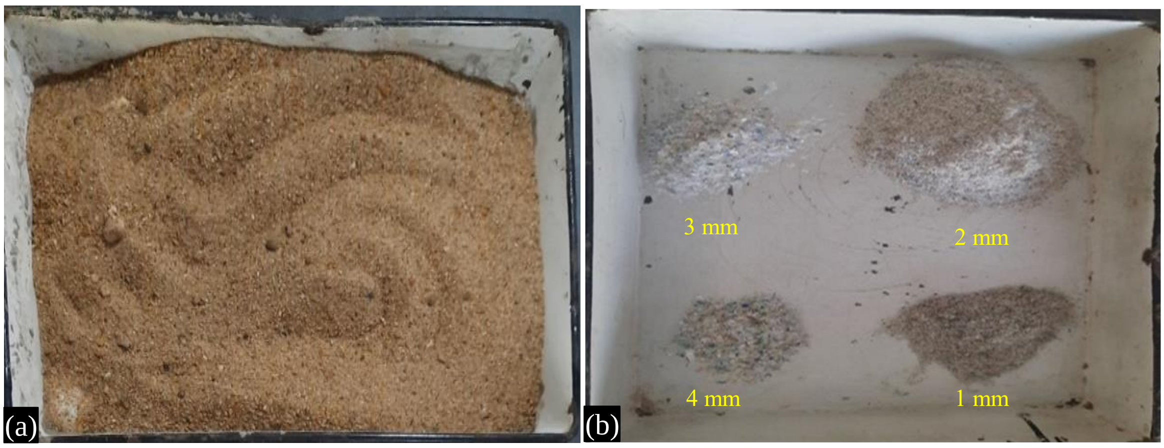

Figure 2. Materials (a) sand (b) PET.

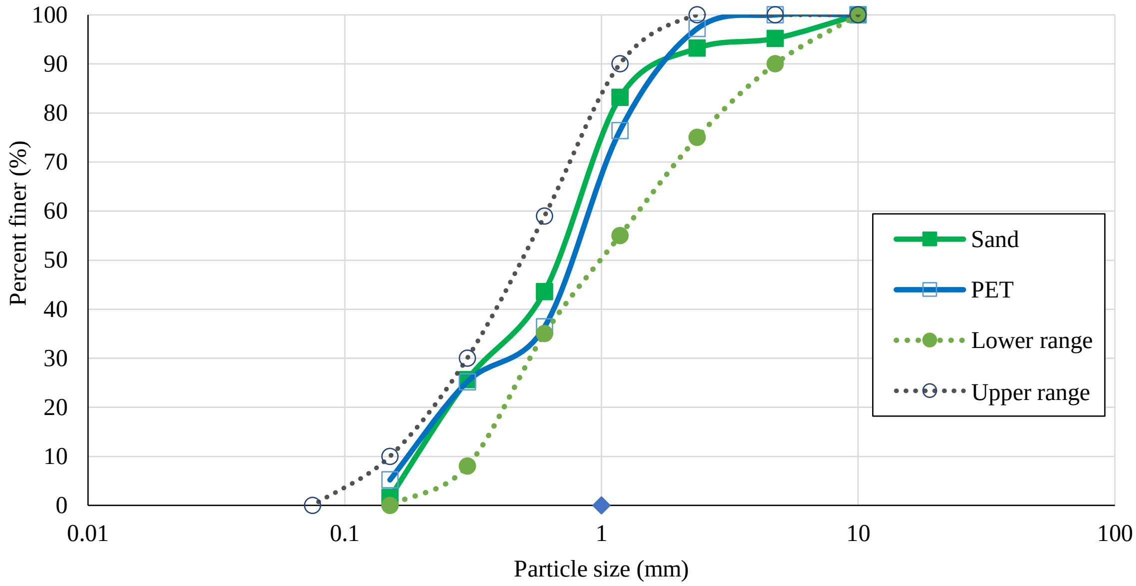

Figure 3. Particle size distribution curve of PET and sand.

Table 1. Chemical elements of PET and sand.

Element	PET (%)	Sand (%)
Carbon (C)	88.65	1.35
Oxygen (O)	8.16	20.94
Silicon (Si)	-	41.72
Aluminium (Al)	-	13.00
Gold (Au)	3.19	2.76
Potassium (K)	-	14.81
Iron (Fe)	-	2.44
Sodium (Na)	-	2.98

Table 2. Mix design of blended lean mortar.

Mixes	% Replacement	Raw Materials (Kg)			
		Cement	***Sand***	***PET***	***Water***
1:6	0.00	200	1724.00	0.00	332.00
	5.00	200	1637.80	18.61	352.00
	10.00	200	1551.60	37.22	358.00
	15.00	200	1465.40	56.04	406.00
	20.00	200	1379.20	74.65	434.00

Figure 4. Casted samples of mortar.

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Experimental Analysis

Workability

Fresh parameters were measured through a flow table apparatus confirmed through ASTM C230, 2009 [14] comprising a cone having dimensions of a top 70 mm, bottom 100 mm, and height 60 mm. To attain required flow value, an essential amount of water is necessary consisting flow range of 205-215 mm as recommended through IS 2250-1981 [15]. This test contains several volumetric proportions by varying the water-cement ratio for lean mortar mixes as depicted in Figure 5.

Compressive and Flexural Strength

The compression testing machine as presented in Figure 6(a) and (b) was required for mortar samples to be tested. A 50 mm cube and 40 mm * 40 mm * 160 mm beam samples were cast for compressive and flexural strength simultaneously as per IS: 2250-1981 [15] and ASTM C 348, 1988 [16].

Figure 5. Flow table lean mortar mix.

Figure 6. Compression machine (a) cube specimen and with flexural assembly (b) beam specimen.

Fire Resistance

The resistance of mortar specimens to withstand against fire attack during exposure to fire was checked as per ISO 834-1999 [17]. In this test, three specimens of 50 mm and 70 mm (for each mix) were placed in a high-heating furnace at a temperature of 200, 400, 600, and 800°C. The variation in compressive strength and weight by the formula:

$$\text{Change in compressive strength (\%)} = [Fc - Ft] / Fc \times 100 \quad (2)$$

$$\text{Change in weight (\%)} = [Wa - Wt] / Wa \times 100 \quad (3)$$

Where, Fc = Compressive strength of mortar specimen after 28 days of curing in water
Ft = Compressive strength of mortar specimen under fire exposure conditions at a particular temperature
Wa = Oven-dry weight of the mortar specimen after 28 days of curing
Wt = Weight of fire-exposed mortar specimen on a specific temperature

Fourier Transform Infrared Spectroscopy (FTIR)

A Fourier transform infrared spectroscopy (FTIR) technique access the functional groups with variation in bond strength through the inclusion of polyethylene terephthalate in cement mortar mixes. The specimen was prepared for spectrum analysis through potassium bromide (K-Br) in powdered form as a thin film pellet as depicted in Figure 7. Furthermore, several functional groups with relevant wave numbers were observed through peaks conforming to Al (Alumina), C (Calcium), Si (Silica), and OH (Water molecules) bond.

RESULT AND DISCUSSIONS

Workability for Fresh Traits

Workability is defined as efficiently handling any substance how easily or difficulty at the construction. It is assessed through the amount of water sufficient to accomplish an appropriate flow value for the mixes. The result obtained correlates to w/c ratio consequences of excess water availability to produce plastic-based mixes [18]. Additionally, the fineness of various fractions of plastic has enhanced specific surface area resulting in increased slump of self-compacting mortar (SCM) [19].

Furthermore, the thixotropic nature of any material would be the reason for less energy amount and excess water to achieve the required flow in a blended mortar mix [20]. A similar trend was obtained through the water/cement ratio (presented in Figure 8) by the inclusion of PET plastic in the control lean mortar mix. The water/cement ratio improved continuously as the PET plastic substitution increased for lean mortar mixes. However, the water/cement ratio was enhanced by upto 20% substitution compared with the control mortar for lean mortar mixes. The reason behind enhancement is fineness, high specific surface area and less specific gravity of various sizes of PET particles favors

Figure 7. Fourier transform infrared spectroscopy setup

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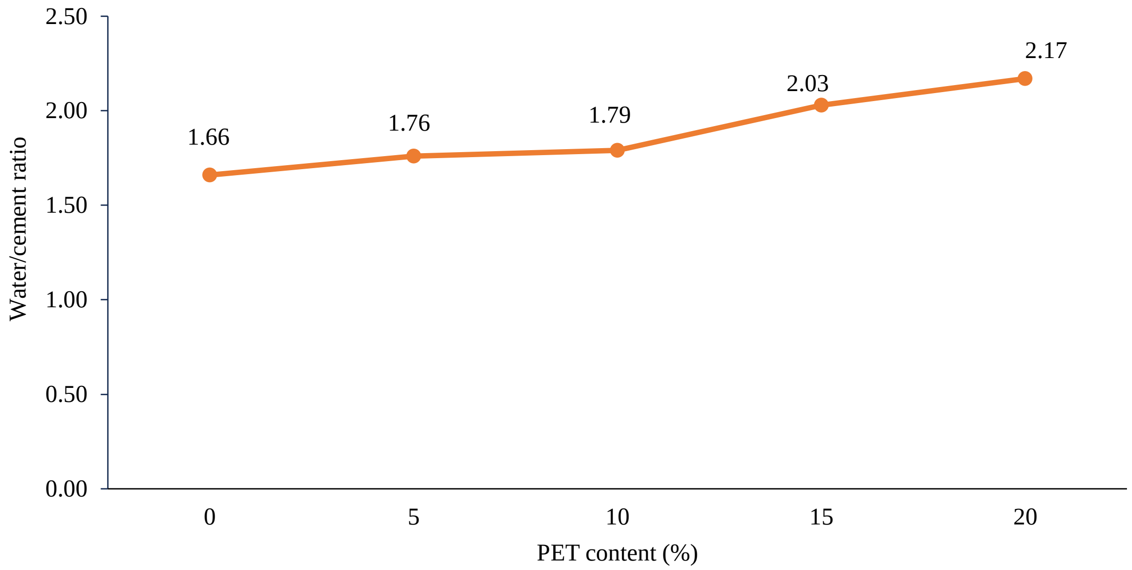

Figure 8. Change in water/cement ratio vs PET content (%).

the workability of blended lean mortar mixes compared to control lean mortar mixes. After executing the regression analysis through investigational statistics, Equation 4 is expressed. It represents the relation between the PET content mixed with the mortar and the amount of ingredients used.

$$AQ_{(PET\%)} = AQ_{cm}\left\{1.016 - 0.215\left(\frac{PET\%}{100}\right) + 0.24\left(\frac{PET\%^2}{100}\right)\right\} \tag{4}$$

Compressive and Flexural Strength for Mechanical Traits

Compressive and flexural strength are pivotal characteristics in judging the qualities of the mix. The strength was found satisfactory outcomes through the PET inclusion at a lesser substitution. The maximum strength was achieved on 5% PET replacing sand (Figures 9 and 10). However, the presence of several forms of polyethylene terephthalate caused a reduction of the strength parameters [21]. Additionally, a sample consisting PET denotes the same flexural strength as the control mixes [22]. The development of strength obtained through filling pores with fine ingredients caused fair interaction among mixed constituents.

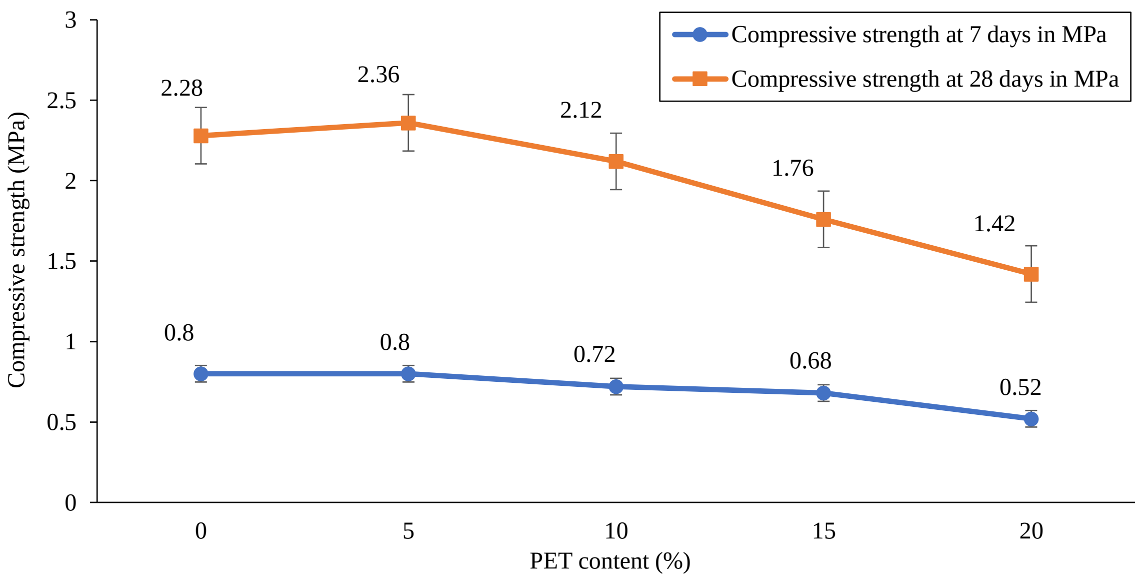

Figure 9. Comparative analysis of compressive strength vs PET content (%).

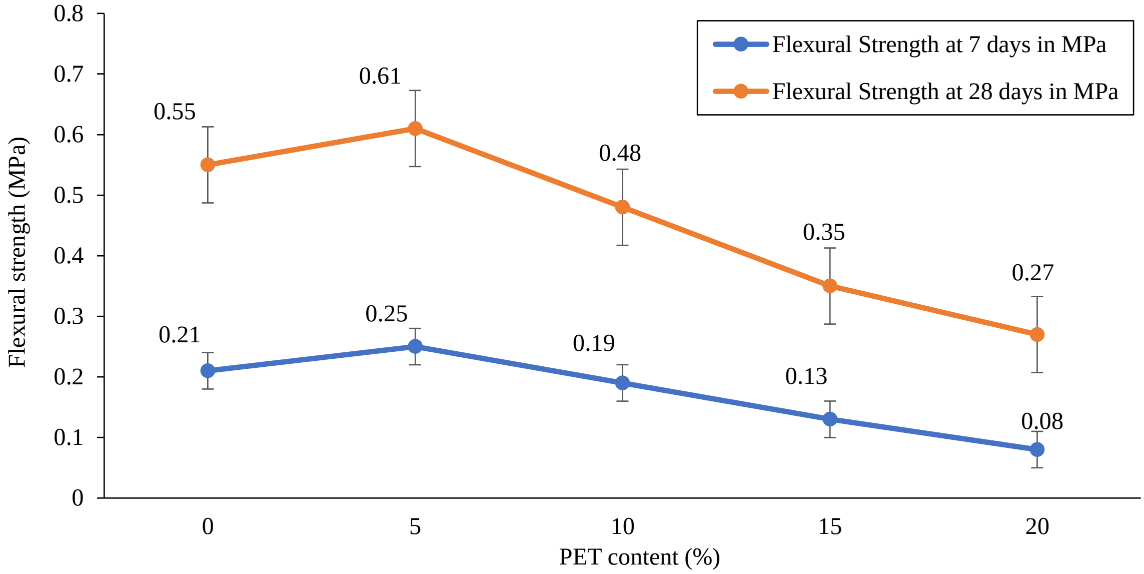

Figure 10. Comparative analysis of flexural strength vs PET content (%).

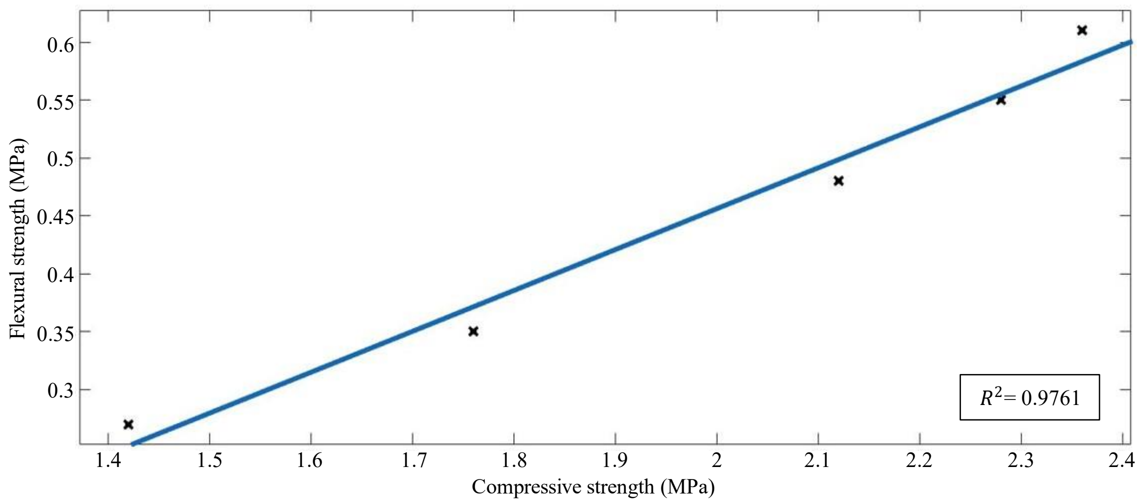

Figure 11. Correlation among strength for lean mortar mixes.

Mathematical equation 5 shows creating the interrelationship amid the strength traits (Figure 11) of PET comprising lean mortar mixes.

$$FS_{PET} = 0.3536*CS_{PET} - 0.251 \quad (5)$$

Fire Resistance Test for Durability Traits

The fire resistance test results for change in compressive strength at 200 to 800 degrees when PET was partially replaced by sand is described in Figure 12. The compressive strength slightly increased for each PET substitution from room temperature to 200°C, then 200°C to 800°C at an interval of 200°C. The internal thermal stress adjacent to voids might cause microcracks, the consequence of the control mix expanding whereas blended lean mortar mixes create a thick film thermally causing the formation of interaction among ingredients resulting in higher bonding capacity and an increase in compressive strength. At temperatures changing after 200°C to 800°C, 20% PET replacement had the maximum whereas control specimens had the minimum compressive strength when exposed to high temperatures. However, the mortar and concrete cubes were observed to be damaged by the effect of temperature. Cracking, change in weight, and corner breaks were revealed to deteriorate as the rise in temperature occurred [23].

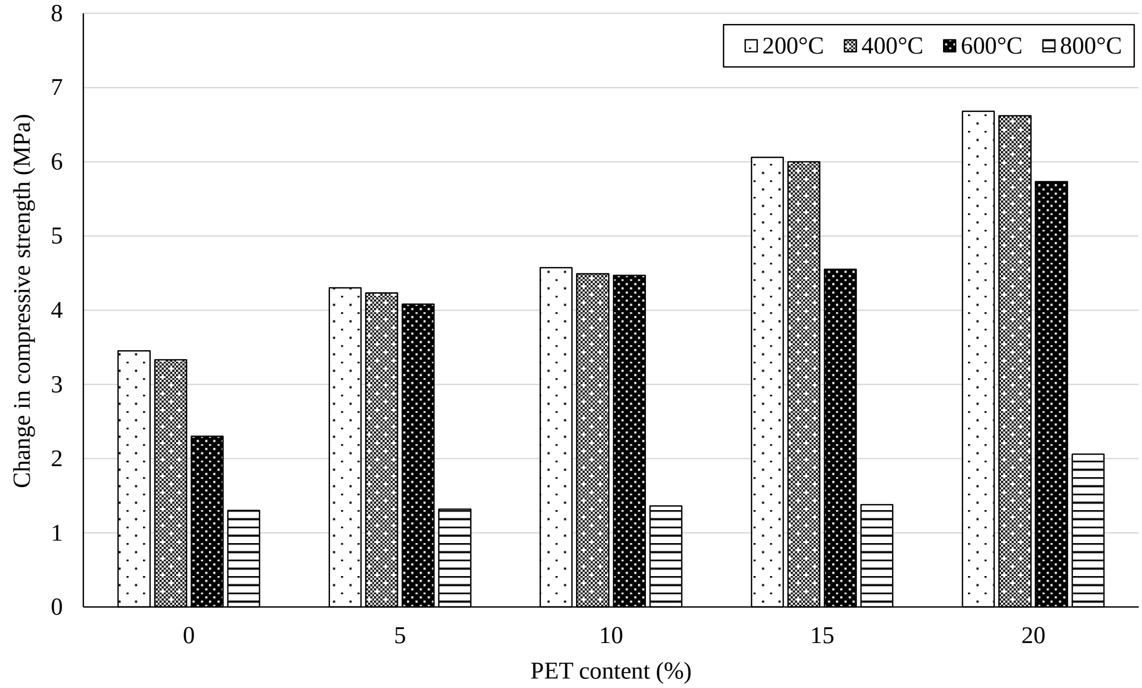

Figure 12. Change in compressive strength with PET content (%)

Fourier Transform Infrared Spectroscopy for Microstructural Analysis

Fourier transform infrared spectroscopy (FTIR) investigation executed with an instrument 'Spectrum Two' having a potassium-bromide splitter of pixels 4 cm^{-1} and 8 shots. A powdered sample was necessary to conduct the test and the pattern was denoted in Figures 13 and 14. Solid thin absorptions at band 1424.07 cm^{-1}–1420.10 cm^{-1}, and piercing deep band between 873.30–874.14 cm^{-1} were mainly by the presence of $CaCO_3$ [24]. Additionally, the presence of calcite peaks was found between 2926.28 cm^{-1} (C–H) [25]. Similarly, peaks were obtained between 460.11-462.96 cm^{-1}(Al-O), 793.11 cm^{-1}(Si), and approx. 1000 cm^{-1}(Si-O-Si) because of the presence of alumina, quartz, and silicates in mixes [26, 27]. An extended band seemed 3436.26-3449.43 cm^{-1} by the existence of water particles in the specimen. The peaks originating around 1000 cm^{-1} were moved between 971.65 by the inclusion of polyethylene terephthalate plastic in mixes. Furthermore, high-intensity peaks were observed for blended lean mortar mixes, whereas low-intensity peaks were in the control mortar lean mix. This result confirms an enhancement in strength parameters specified in Figures 9 and 10.

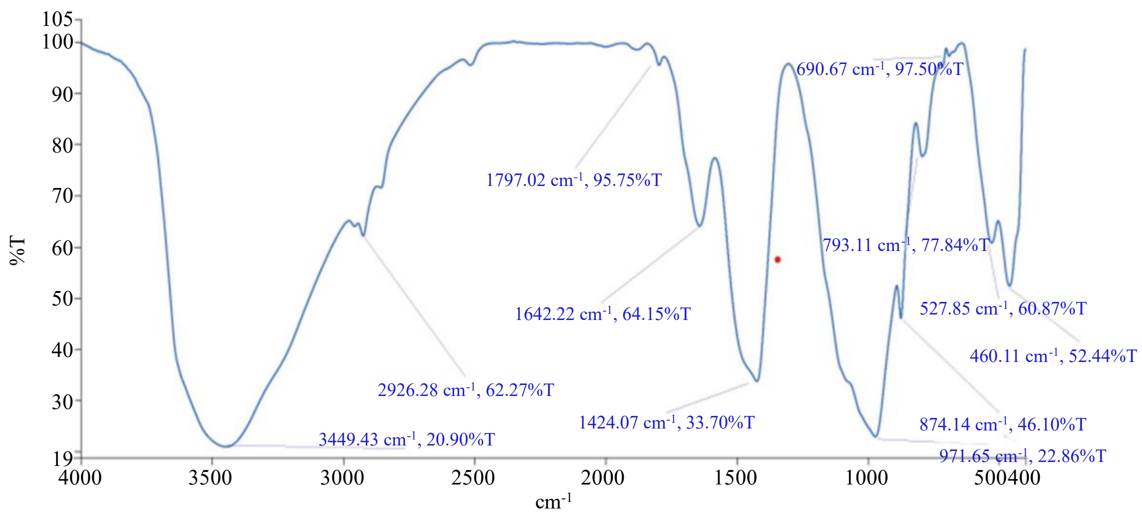

Figure 13. FTIR spectra for control lean mix.

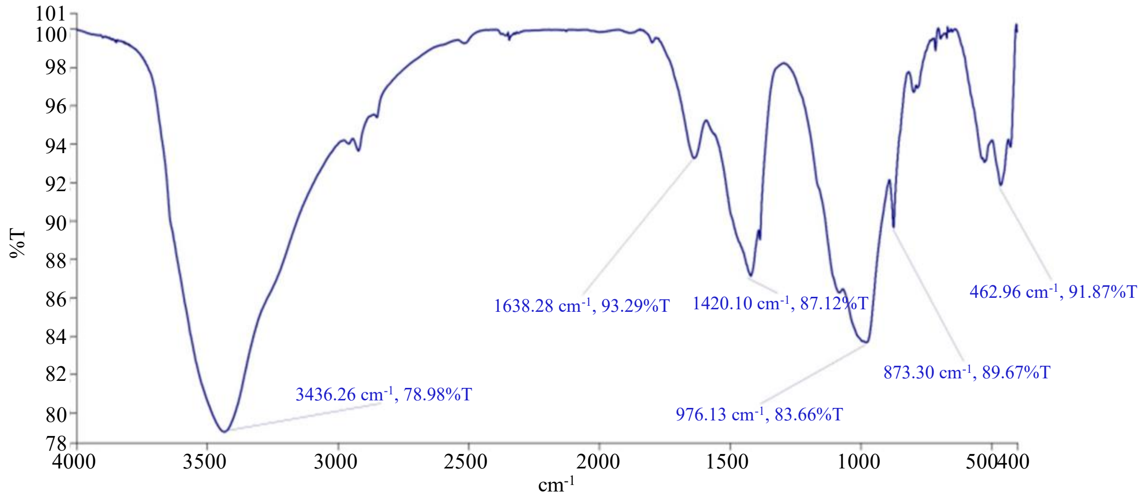

Figure 14. FTIR spectra for blended lean mix with 5% PET substitution.

CONCLUSIONS

- The fineness, large surface area, and lower specific gravity of polyethylene terephthalate particles are favorable in enhancing the workability.
- Till 5% substitution of PET over river sand leads to the highest compressive and flexural strength and later reduced at 20%. This improvement was ascribed to pores filling in blended lean mortar mixes. Furthermore, these characters are authenticated through regression analysis and mathematical simulations.
- Result comparison in mechanical properties especially compressive strength at 28 days for 5%, 10%, 15%, and 20% replacement were observed as approax 3.51% more, 7.02%, 22.81%, and 37.72% respectively less as compared to the control mortar mix. Similarly, flexural strength at 28 days for 5%, 10%, 15%, and 20% replacement was observed as approax 10.91% more, 12.73%, 36.36%, and 50.91% respectively less as compared to the control mortar mix.
- Fire attack exposure investigation proves that PET waste may be effectively used to make blended lean mortar mixes that can resist at high temperatures over control lean mortar mix through the development of fair interaction between ingredients resulting in higher bonding capacity.
- The microstructural assessment like FTIR enhanced in strength for lesser substitution in blended lean mortar mixes.

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I would honestly acknowledge MRC, MNIT Jaipur, Rajasthan for their contribution to this study.

ABBREVIATIONS

PET: Polyethylene Terephthalate;
FTIR: Fourier Transform Infrared Spectroscopy;
PPC: Portland Pozzolana Cement;
FA: Fine Aggregate

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