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Effect of PET Resin as Cement Substitute on Properties of Cement Mortar Subjected to Different During Conditions

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Abstract
Polyethylene terephthalate (PET) has many advantageous properties required for the packaging industry. However, the safe disposal of PET waste is an environmental challenge. The present study investigates the feasibility of using PET resin prepared through glycolysis in polypropylene glycol (20:80 and 30:70 PET-to-glycol ratios) as a replacement for cement (5%, 10%, and 15%) in cement mortar. The effect of PET resin with melamine-formaldehyde as a hardener replacement on the consistency, setting time, soundness, compressive strength, tensile strength, and abrasion resistance was experimentally studied at two different curing conditions viz. under water curing and oven-dry curing. Findings of the present investigation infer that the compressive, tensile strength, and abrasion resistance improves upon oven-dry curing. The study concludes that the use of PET resins improves the attributes of cement mortar and at the same time provides an environmentally friendly way to dispose of the PET waste.

Author Keywords. PET, Glycolysis, Curing, Compressive strength, Tensile strength

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1. Introduction

Polyethylene terephthalate (PET) is a semi-crystalline thermoplastic widely used in the packaging industry for food containers, soft drink bottles, and similar applications. Over the past few years, the use of PET in the industry has increased extensively; according to a 2019 report of plastic in Europe, plastic production reached 360 million tonnes in 2018. Of the total plastic, 39.9% was used for the packaging industry. Of the total plastic used in the packaging industry, 7.7% of the PET was used for soft drink bottles (Shukla and Kulkarni 2002; Al-Sabagh et al. 2016; Park and Kim 2014). Therefore, managing this plastic waste becomes crucial, especially because PET is not suitable for reuse. The only methods available to control the amount of PET waste are reducing consumption and recycling. A reduction in PET consumption is not currently possible because of its advantages in the packaging industry, and there are no alternative materials available. The recycling of PET is a possible method to manage the burden on the environment to avoid severe problems in the environment. The quantity of recycling of PET through the traditional way of mechanical recycling is deficient compared to the consumption of PET in the industry. An approach to recycle the PET would be beneficial if this material could be returned to its initial state (Cruz and Zanin 2006; Bedi, Chandra, and Singh 2013; Geyer, Lorenz, and Kandelbauer 2016). One of the approaches is performing PET de-polymerization and converting it into a functional product utilized in other applications. This glycolysis product can be used as a polymer in the construction industry, which would make it one of the most economical polymers. Polymer cement concrete is one of the most valuable materials because it improves the durability and flexibility of structures (Nair et al. 2010; Rashid, Wang, and Ueda 2019). The world's most recyclable material is polyester, and PET is a polyester with a functional group that some reagents can separate via hydrolysis, glycolysis, methanolysis, and other processes (Sinha, Patel, and Patel 2010; Al-Sabagh et al. 2016; Oberbeckmann, Osborn, and Duhaime 2016). The glycolysis is performed with glycol; a new type of unsaturated polyester has thus been developed. There is increased interest in producing unsaturated polyester resin as this can be used in molding applications (Atta 2003; Katoch, Sharma, and Kundu 2013; Ikladious et al. 2017).

Another approach is mechanical shredding of PET waste and utilizing it as an acceptable fine aggregate substitute in concrete. The addition of PET fibers in circular and long strips in concrete has shown improved ductility (Saikia and De Brito 2012; Foti 2013; Gu and Ozbakkaloglu 2016). The physical and mechanical properties of PET particles as a substitute for fine aggregate confirm that it is entirely possible to use these in small quantities and improve the ductility and durability of concrete (Foti 2011; Fraternali et al. 2013). This would be a new, attractive composite material. The addition of PET fibers in concrete affected the new property of concrete (Hama and Hilal 2017). The PET used in self-compacted concrete has improved strength for 15% replacement, and there was a reduction in strength beyond 15% (Yang et al. 2015). This research work prepared PET resins with PET particle polypropylene glycol. This was added in various percentages in cement mortar, and its effect on fresh and hardened properties was studied.

2. Materials and methods

2.1. Materials

Polymer mortar mixtures were prepared by mixing PET resin in cement mortar with 5%, 10%, and 15% cement replacement for both 20:80 and 70:30 PET-to-glycol ratios. The mix proportion is shown in Table 1. The resin was prepared by the glycolysis process, where polypropylene glycol (PPG) was used as glycol. PET was collected and cut into pieces around 3 to 5 mm and was added in PPG at 20:80 and 70:30 PET-to-glycol ratios. Then, zinc acetate was used as a catalyst with its weight equivalent to 0.5% of the weight of PET, and this mixture then underwent glycolysis. Glycolysis was performed in three-necked bottom flasks where the mixture of PET and PPG was heated at 180°C for an hour, after which the temperature was further raised to 210°C and then maintained until all the particles disappeared. The Styrene monomer was added at a 1:1 ratio with PET resin to reduce its viscosity (Purohit et al. 2012). The specific gravity of the PET resin was 1.03. Melamine-formaldehyde (MF) was used as an initiator for curing the PET resin. The cement used for this work was 53grade Ordinary Portland Cement (OPC) of Ultratech make. River sand was used as a fine aggregate from Tapi River Saranghkheda, Maharashtra, India. The specific gravity of the fine aggregate was 2.62, water absorption was 1.10%, and the fine aggregate complies with the specifications for Zone I of Indian Standard (IS) 383'. Potable water was used for curing and casting.

Cement	PET resin %	Weight of PET resin	Fine aggregate
788	0	–	1965
748	5	12.80	1965
709	10	25.75	1965
669	15	38.60	1965

Table 1: Mix Proportion for Mortar (1:3) in kg/m^3

2.2. Fourier Transformed Infrared Spectroscopy (FTIR)

Glycolysis of PET waste and the formation of polyester polyols was confirmed using FTIR spectroscopy (Figure 1). FTIR was used to obtain the structure corresponding to the material in the hydroxyl stretching region (3700–3500 cm^{-1}): symmetric stretching of the ester carbonyl (1750–1700 cm^{-1}), stretched C–O of ester (1600–1400 cm^{-1}), C=C conjugated into an aromatic ring (1450–1680 cm^{-1}) and stretching of aliphatic C=C (1620–1680 cm^{-1}) (Vidales et al. 2014). FTIR confirmed that major functional groups were retained in PET after reaction and corresponded to the stretching O–H bond formed during the glycolysis reaction.

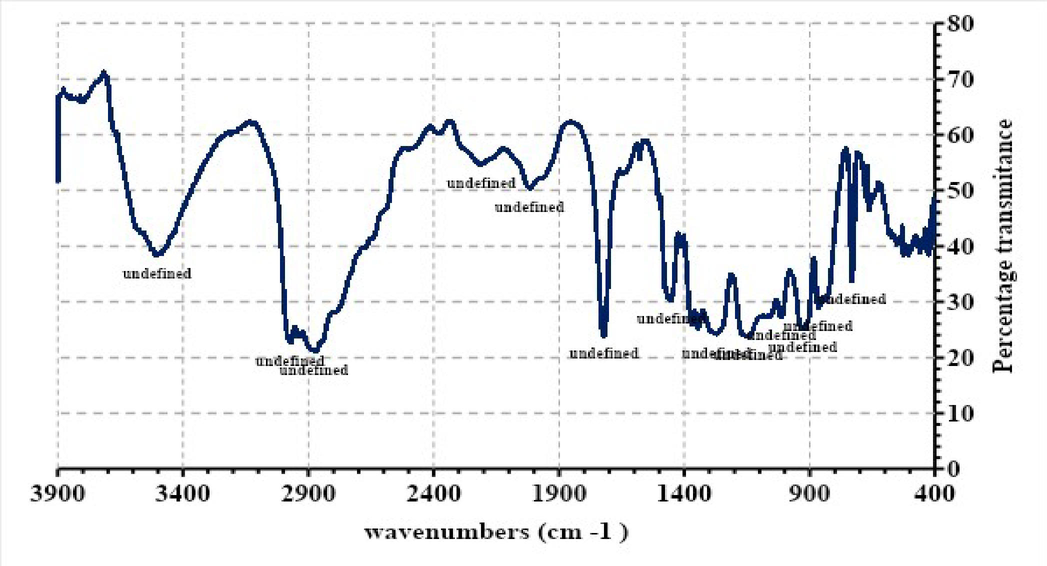

Figure 1: FTIR of PET

2.3. Mix Proportion

The mix proportion and replacement of material for this work are shown in Table 1.

2.4. Testing

Polymer mortar specimens were cast and tested under different curing conditions. The fresh and hardened properties were determined for various mixes of polymer mortar. PET resin was used as a binder in this work, so the effects of this binder on the properties of initial setting time (IST), final setting time (FST), consistency, and soundness were determined using IS 4031-1968 and IS 269-1976. The slump flow test was carried out following IS 4031 part 4, 2005. The cement-to-sand ratio was taken as 1:3, and the water quantity was taken based on the standard consistency $(4 + 3)$ percent of the combined weight of cement and sand mix for the casting of all the specimens. IS 4031 part 4, 2005 was used for compressive strength and tensile strength, IS 269-2013, American Society for Testing and Material (ASTM) C307, and IS 4031; part 8 were used. PET resin was added in 5%, 10%, and 15% as a substitute for cement in the mortar at 80:20 and 70:30 PET-to-glycol ratios, and its effect on the strength for 1, 7, and 28 days of water curing and oven-dry curing was studied. Abrasion resistance was determined for 28 days of oven curing. Compressive strength was performed on a cube of 70.7 mm × 70.7 mm × 70.7 mm, and for tensile strength, a briquette mold was used for casting. Abrasion resistance was performed on a 70.7 mm × 70.7 mm × 20 mm specimen. The cement mortar specimen curing was performed using the water and the oven-dry methods; after casting and de-moulding, all the specimens tested for oven-dry curing were kept in the oven for 1 hour at 90°C and then tested (Jo, Park, and Park 2008). This study cast and tested 126 specimens for the compression test, 126 specimens for the tensile strength test, and 21 specimens for the abrasion test (Figure 2).

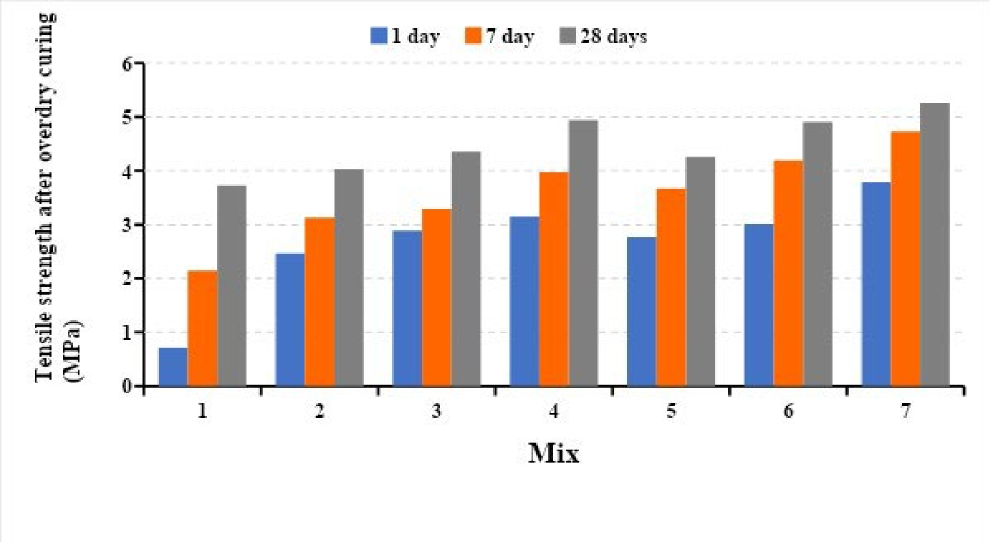

Figure 2: Tensile Strength Under Oven-Dry Curing

3. Results and Discussion

3.1. Consistency

The results of the standard consistency test are shown in Table 2. Standard consistency is an important parameter for cement paste and concerns the quantity of water required to form a paste to complete the hydration process. Consistency was determined according to IS 4031, part 4, using Vicat's apparatus. The standard consistency of cement paste was determined with and without adding PET resin. The PET resin content was 5%, 10%, and 15% for PET-to-glycol ratios of 20:80 and 30:70. The standard consistency for normal cement was 30.5% as PET resin was added to cement, reducing the standard consistency of cement for all PET resin content and both PET-to-glycol ratios. Compared with standard cement paste, the standard consistency of 20: 80 PET-to-glycol ratio was reduced by 1.63% and 4.91% for 10% and 15% resin content, respectively. However, the samples with 5% PET resin content did not show any changes in consistency. The 30:70 PET-to-glycol ratio and 5%, 10%, and 15% PET resin content reduced the consistency 1.63%, 4.91%, and 8.19%, respectively compared with standard cement consistency. The PET-to-glycol ratio affected the consistency of cement, but this effect was minimal. The standard consistency was affected by the PET resin content because as the percentage of PET resin increases in cement, the water required for consistency reduces. This effect was because PET resin and styrene monomer in cement help paste formation, reducing the water required for consistency. In addition, an increase in PET content increased the effect of glycol on consistency.

PET-to-glyco l ratio	Specimen	IST in minutes	FST in minutes	Soundness in mm	Standard consistency in %	Abrasion (mm)
0	Cement	75	460	1	30.5	2.68
20:80	5% resin	160	585	1	30.5	2.41
	10% resin	185	630	2	30	2.19
	15% resin	210	670	2	29	1.96
30:70	5% resin	175	590	2	30	2.18
	10% resin	205	645	2	29	1.93
	15% resin	215	680	2	28	1.78

Table 2: Cement Properties

3.2. Setting Time

The results for setting time are shown in Table 2. Setting time is one of the vital parameters considering all the activities in the concreting process, and it was determined according to IS-4031. The IST and FST were affected by the presence of PET in cement paste according to the dosage of PET resin content and PET-to-glycol ratio. The IST was increased by 85, 110, and 135 minutes, and the FST was delayed by 125, 170, and 210 min, respectively, for 5%, 10%, and 15% resin content of the 20:80 PET-to-glycol ratio compared with regular cement paste. The setting time for the 30:70 PET-to-glycol ratio was also affected; the IST was delayed by 100, 130, and 140 minutes; and the FST was 130, 185, and 220 minutes, respectively, for 5%, 10%, and 15% resin content. The setting time of cement depends on various factors such as fineness, temperature, salt presence, and chemicals. The nature of salts and chemicals is also one of the essential factors. The hydration of the cement paste largely depends on the temperature condition. The presence of the PET resin alters the temperature of the paste, in turn affecting the IST and FST (Mehta and Monteiro 2014; Kodur 2014; Han, Ding, and Yu 2015; Kazemian et al. 2017; Özbay, Erdemir, and Durmuş 2016). PET has a hydrophobic characteristic that affects the setting time of cement. The increase in IST may be advantageous for ready mixed concrete, but an increase in FST may delay the removal of shuttering.

3.3. Soundness

The results of soundness tests are shown in Table 2. The soundness of cement is a crucial cement property, especially when a different binding material substitutes cement. The results show that soundness was not affected by the presence of PET resin for both 20:80 and 30:70 PET-to-glycol ratios and 5%, 10%, and 15% PET resin content of all mixes.

3.4. Slump Flow

Slump flow is an important measure for the workability of concrete and mortar. The results of the slump flow test for all the mixtures are shown in Figure 3. The slump flow increased as PET resin content also increased; these results agree with the findings of Jo, Park, and Park (2008) and Vidales et al. (2014) . The slump flow for the 20:80 PET-to-glycol ratio was increased by 18.75%, 55%, and 75% for 5%, 10%, and 15% PET resin content, respectively; while for the 30:70 PET-to-glycol ratio, the slump flow increased by 31.25%, 62.5%, and 85%. The results show that the increased PET content in resin increased the slump flow. This was because of the styrene monomer's presence, which was added at a 1:1 ratio (PET resin to styrene monomer).

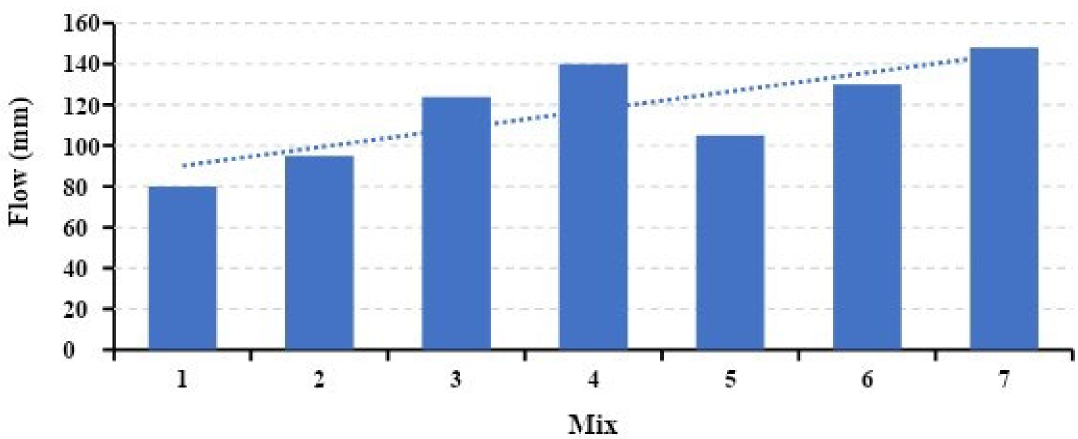

Figure 3: Slump Flow

3.5. Compressive Strength

The compressive strength of cement mortar was examined for the 20:80 and 30:70 PET-to-glycol ratios under normal curing and oven-dry curing. The reduction in compressive strength was observed for 1, 7, and 28 days of curing under normal curing conditions for both PET-to-glycol ratios and all PET resin contents. The compressive strength for the 20:80 PET-to-glycol ratio was decreased from 58.64% to 53.64%, 55.39% to 48.89%, and 43.26% to 40.11%, respectively, for 5%, 10%, and 15% PET resin content for 1, 7, and 28 days under normal water curing in comparison with standard mortar specimens. The reduction in compressive strength for the 30:70 PET-to-glycol ratio was from 56.73% to 50.40%, 51.0% to 43.46%, and 41.07% to 36.87% for 1, 7, and 28 days water curing, respectively, for 5%, 10% and 15% PET resin content. These results are shown in Figure 4. The reduction in compressive strength decreased as the PET content in resin increased, and the dosage of resin content in cement mortar also affected the compressive strength. The strength gained in cement mortar and concrete depends on the binding properties of the material and the binding action of the material. Similar to the cement hydration process, most of the binding activities of PET are temperature dependant. The presence of PET resin with styrene monomer as a viscosity agent and MF as a curing agent affected the hydration process of cement and reduced the compressive strength. The low bonding strength of the binding material consisting of cement paste with PET resin was because of the hydrophobic nature of PET that inhibits the hydration process by restricting water movement; this was a major cause for the loss of strength (Reis and Carneiro 2012). The addition of MF as a curing agent did not affect compressive strength under water curing, but in the case of oven-dry curing, it had a positive impact on the strength.

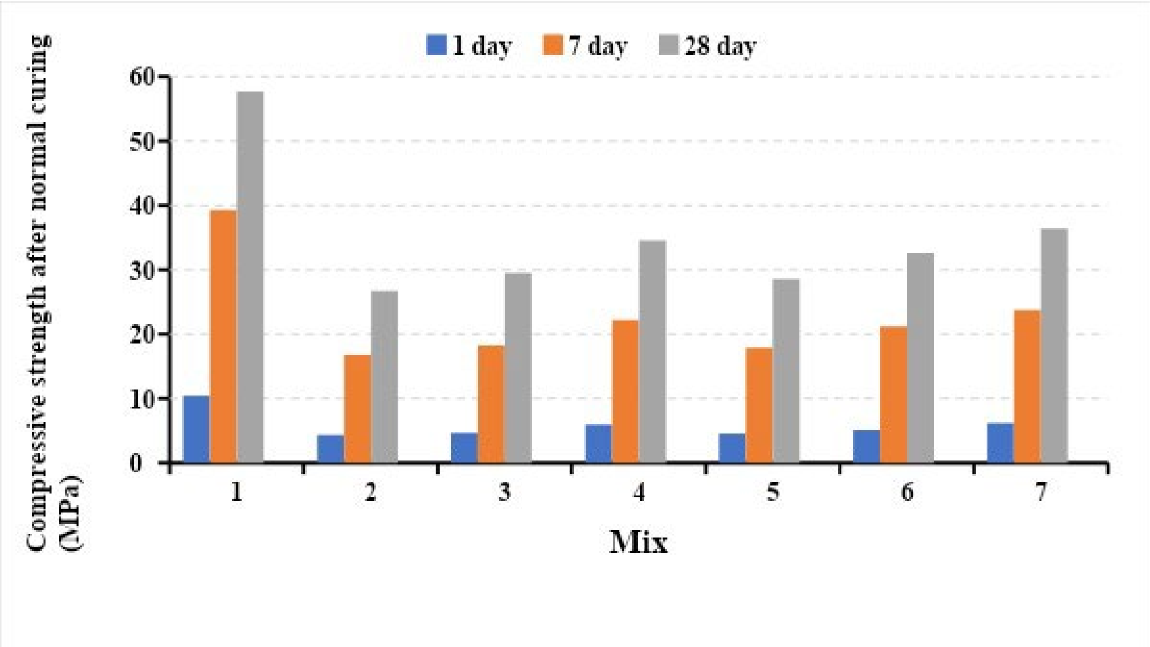

Figure 4: Compressive Strength Underwater Curing

Figure 5 shows the variation in the compressive strength of test specimens subjected to oven-dry curing. The compressive strength was increased in oven-dry curing in comparison with water curing. Under oven-dry curing, all specimens were kept in the oven for 1 hour at a temperature of 90°C. The MF acted as a curing agent at elevated temperatures. It was observed that for 1 day of oven-dry curing, the compressive strength of the cement mortar specimen with PET resin content was 80 to 90% of the targeted strength at 28 days. The increase of compressive strength for 1 day of curing for the 20:80 PET-to-glycol ratio was

327.41% to 380.38%. For the 30:70 PET-to-glycol ratio, it was 373.80% to 410.79% for the 5%, 10%, and 15% resin content compared to the standard cement mortar specimen. After 7 days of curing for the 20:80 PET-to-glycol ratio, the gain in compressive strength was 26.47% to 35.48%, and for the 30:70 PET-to-glycol ratio, it was 31.56% to 44.29% for 5%, 10%, and 15% resin content compared with the standard mortar specimen. The results show a higher gain in compressive strength for 1 day and 7 days of curing compared with the standard specimen. However, for 28-day compressive strength, this gain was equal to the targeted strength but less than the standard specimen's strength for some of the PET resin content. The compressive strength at 28 days of oven-dry curing for the 20:80 PET-to-glycol ratio varies from –5.30% to 2.89% and from –3.34% to 4.75% for the 30:70 PET-to-glycol ratio for 5%, 10%, and 15% resin content. The strength increased as resin and PET content increased in cement mortar. The reduction in compressive strength was observed for the 20:80 PET-to-glycol ratios with 5% and 10% resin content and for the 30:70 PET-to-glycol ratio with 5% resin content compared with the compressive strength of standard specimen after 28 days of curing. The compressive strength of the specimens cured in the oven increased because of the reaction of MF with PET resin. At the raised temperature, the hydroxyl group present in the PET resin reacted with MF and formed crosslinks with the polymer.

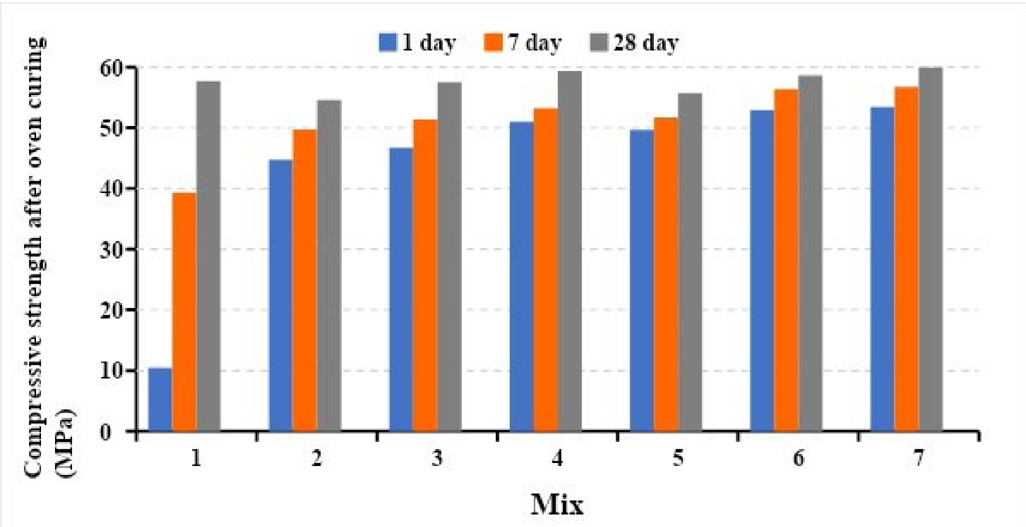

Figure 5: Compressive Strength Under the Oven-Dry Condition

3.6. Tensile Strength

The tensile strength was also determined for 1, 7, and 28-days of curing in water and in an oven for all PET resin content specimens. The results obtained for the specimens subjected to normal curing are shown in Figure 6. The tensile strength of cement mortar with water curing increased for 1 day and decreased for 7 and 28 days. The increase in tensile strength for 1 day of curing with the PET-to-glycol ratio of 20:80 was 25.35%, 59.15%, and 77.46%, and with the PET-to-glycol ratio of 30:70 it was 56.33%, 94.36%, and 108.45% for 5%, 10%, and 15% resin content in comparison with standard cement mortar. The reduction in tensile strength for 7 days of water curing with the PET-to-glycol ratio of 20:80 was 13.08%, 7.47%, and 4.67%, and for the 30:70 PET-to-glycol ratio, it was 11.68%, 8.87%, and 1.86% for the 5%, 10%, and 15% resin content. After curing for 28 days, a strength reduction of 36.44% to 18.69% was noted for the 20:80 PET-to-glycol ratio, and for the 30:70 PET-to-glycol ratio, it was 31.46% to 16.51% for 5% to 15% of resin content. The results show that the reduction in strength at 7 days was less than that for 28 days of curing compared with standard cement mortar specimen strength. The presence of PET resin affected the hydration of the cement paste and resulted in the specimens having reduced strength. However, the hydration process was completed generally in the standard specimens, and the specimens attained higher strength. The results also show that as both the PET-to-glycol ratio and PET resin content increased, the tensile strength of cement mortar also increased. On 1-day of curing, the strength of the specimens with PET was higher than that of standard cement mortar specimens. However, after 1-day of curing, this strength was lost because any further hydration was halted due to the presence of PET resin.

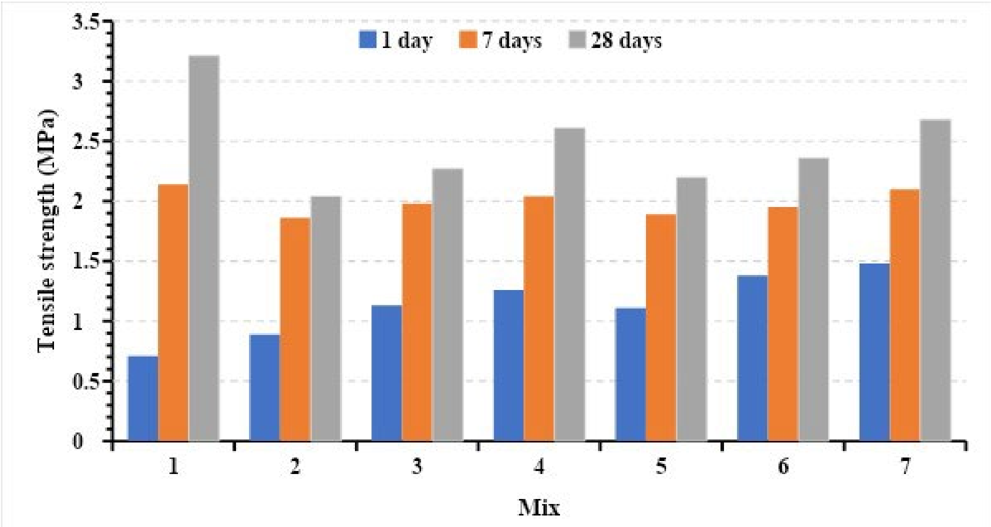

Figure 6: Tensile Strength Underwater Curing

The tensile strength under oven-dry curing increased for all specimens that contained PET resin. The increase in tensile strength for cement mortar was higher for the 1-day oven-dry curing of the specimens. For the 20:80 PET-to-glycol ratio, the 1-day tensile strength was 3.47, 4.05, and 4.43, and that for 30:70, PET-to-glycol ratio was 3.40, 4.23, and 5.32 times higher than the strength of standard cement mortar for 5%, 10%, and 15% resin content. The strength gain at 7 days curing for 20:80 ratio varies from 46.26% to 85.51%, and for the 30:70 PET-to-glycol ratio varies between 71.49% to 121.08% for 5 to 15% PET resin content in comparison with the strength of the standard mortar specimen. The variation in tensile strength for the 20:80 PET-to-glycol ratio was 8.04% to 32.43%, and for the 30:70 PET-to-glycol ratio it was 13.91% to 41.08% for 5% to 15% PET resin content. The results show that as both the PET resin content and PET-to-glycol ratio increase, the tensile strength of cement mortar also increases. The highest tensile strength was observed for 15% resin content and the 30:70 PET-to-glycol ratio in oven-dry curing. The presence of MF as a curing agent cured the PET resin and formed a long chain of the polymer, increasing the tensile strength of the specimen (Nair et al. 2010). There was an increase in the tensile strength because of the presence of this polymer chain, restricting the propagation of the fracture phase. These observations are supported by Reis et al. (2011).

3.7. Scanning Electron Microscopy (SEM)

The SEM images of the specimens cast with cement mortar and the 30:70 PET-to-glycol ratio (5%, 10%, and 15%) are shown in Figure 7. The figures show that as the percentage of PET resin in the mortar mix was increased from 0% (in cement mortar) to 15%, the number of polymer chains increased. These polymer chains act as a link that holds the components together and reduces the propagation of fracture planes. This increases the capacity of the specimen to handle tensile stress. This observation is supported by the results of the tensile strength tests.

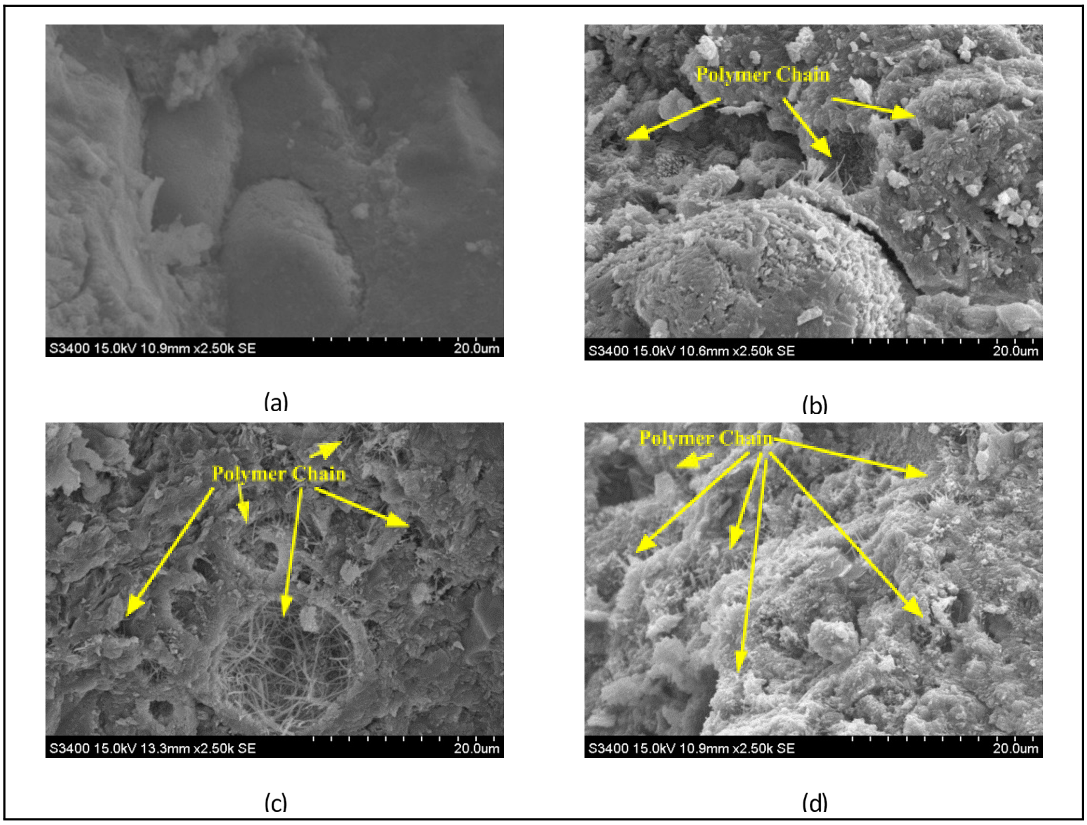

Figure 7: SEM images of the Mortar Specimens (a) Cement Mortar, (b) 5% PET Resin, (c) 10% PET Resin, and (d) 15% PET Resin

3.8. Abrasion

Abrasion resistance was determined for all the specimens subjected to oven-dry curing after 28 days of curing. These results are shown in Table 2. The table shows that as PET content in cement mortar increased, there was an increase in abrasion resistance. The increase in the abrasion resistance for the 20:80 PET-to-glycol ratio was 10.07%, 18.28%, and 26.86%, and for the 30:70 PET-to-glycol ratio it was 18.65%, 27.98%, and 33.58% for 5%, 10%, and 15% resin content, respectively. This reduction in abrasion infers that the presence of PET resin makes the cement mortar more durable. This enhancement in abrasion resistance because of the presence of PET can be utilized in situations where the mortar is used as the wearing course and where higher abrasion resistance is required (Figure 8).

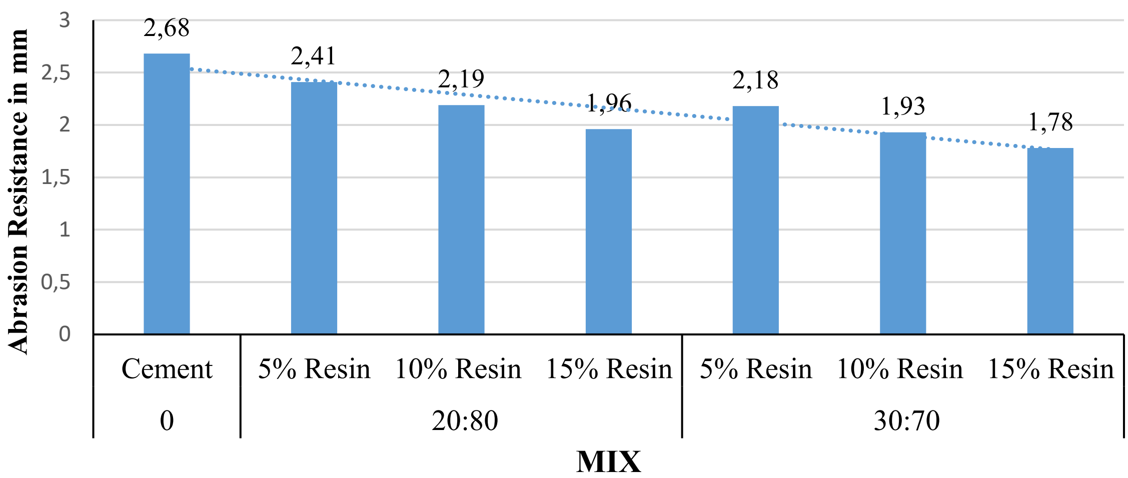

Figure 8: Abrasion Resistance at 28-Days

4. Conclusions

The following conclusions may be drawn from this study-

a) This study's results infer that adding PET resin in cement mortar results in a small reduction in the water required for consistency and increases the setting time while the soundness remains unaffected.

b) The slump flow increases as PET resin and PET content increase in cement mortar and it was maximum for 15% resin at 30:70 PET-to-glycol ratio which is 85% higher in comparison with ordinary cement mortar

c) There was a reduction in the compressive strength of specimens subjected to water curing for all PET resin content. However, there was an increase in the specimens' compressive strength when subjected to oven-dry curing for all specimens containing PET resin. The 80% of targeted strength was achieved in 1 day in the case of oven-dry curing.

d) A significant enhancement (8% to 41%) in the tensile strength was observed in the specimens subjected to oven-dry curing, making it a suitable material in situations where higher tensile strength is required. However, the tensile strength gain in the specimens cured in water was insignificant.

e) The abrasion resistance of specimens with PET resin cured in the oven-dry condition was 10% to 33.50% higher than that of normal cement mortar specimen, making it suitable for wearing courses.

This study's findings infer that replacing 15% cement by PET resin prepared with a 30:70 PET-to-polypropylene glycol ratio, with the addition of MF as a hardener, can be successfully used in the precast industry with oven curing. The utilization of PET as a binder material has significant advantages in the field of sustainable construction.

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