

Influence of waste PET fibres on mechanical and durability properties of polyester concrete for tension members

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Abstract:

In the northern areas of Pakistan, the fabric mostly used for wearing purposes is polyester (polyethylene terephthalate (PET)). Due to its versatile quality, concrete is the most demanding construction material. In this study, durability & mechanical properties of polyester concrete (PC) are investigated by including raw polyester fibre (PF) with varying percentages (0,0; 0,5; 1,0; 1,5; and 2,0 %). Additionally, 1% sodium carbonate is used as a cement replacement. The results reveal that the addition of 1 % polyester (PET) fibre by weight produces 25,0 and 20,6 % increases in tensile and compressive strengths, respectively. The increased percentage of fibre also significantly reduces chloride permeability, indicating improved crack resistance in concrete. However, fibre additions of 1,5 or 2,0 % may result in reduced compressive strength and increased permeability. Therefore, 1 % polyester fibre is recommended for the application of concrete tension members and mortar in external walls. Moreover, this research focuses on the sustainable use of raw polyester as a constructive approach towards addressing environmental challenges associated with conserving resources, waste disposal, and mitigating environmental pollution.

Keywords:

PET fiber; recycling; mechanical properties; green concrete; durability



1 Introduction

The most commonly used construction materials are mortar and concrete which are composed of cement, aggregates, and raw materials that act as binders. Structural members do not fail because of their low tensile strength and brittle characteristics [1]. There is a pressing need to overcome this weakness by productively using raw fibres in concrete and mortar. Consumption of nylon (polyester) fibres (clothes, plastic bottles, and plastic household items) is continually increasing. The growing use of raw polyester fibres (20,6 %) has created many environmental problems which affect human health [2]. Raw polyester fibres can be used productively as a construction material. Concrete, a fundamental building material, plays an important role in the construction industry [3]. Cement is a primary component in concrete. It is widely used as a building material for various structural elements. The ubiquity of concrete is attributed to its abundant resources, cost-effectiveness, and exceptional compressive strength [4].

In recent years, several types of innovative reinforcements have been used for advancements in concrete [5]. These innovative reinforcements have been used to address the limitations of concrete, such as its brittleness and load-bearing capacity. Fibre-reinforced concrete has gained considerable attention as a means of enhancing tensile and flexural performance [6; 7]. Synthetic fibres such as polyethylene terephthalate (PET), polyamide (PA), polyethylene (PE), polyvinyl alcohol (PVA) and hybrid fibres have been explored as alternatives to steel fibres, which are widely used as reinforcement materials [8]. An intriguing development in this domain involves the recycling of polyester fibres such as shredded recycled polyethylene terephthalate (PET) in concrete production, showcasing the potential for reusing plastic waste [9]. Waste polyester fibre clothing is a direct source of microplastics and old pollutants at both micro- and macro-environmental levels [10]. The degradation of polyester fibres under the influence of environmental factors such as temperature, humidity, and salinity pose a risk to human health [11; 12]. The production of polyester fibre increases daily. After retreatment, the fibres cannot be used for clothing, it is preferable to treat, recycle, and use them for another beneficial application [13; 14]. The use of polyester fibres in concrete is not difficult. Therefore, polyester fibres have the can be a valuable resource for fortifying concrete to improve its flexural properties and whilst offering a compelling avenue for mitigating the environmental challenges posed by textile waste [15; 16].

This study experimentally demonstrates the utilisation of raw polyester fibres in concrete and mortar. An urgent demand is addressed by proposing an innovative approach: converting waste-polyester-based clothing into a resource that can significantly enhance the mechanical and durability attributes of concrete [17; 18]. This study is significant because of its dual focus on addressing the pressing environmental issues linked to textile waste while simultaneously enhancing the mechanical properties of concrete. This not only strives to enhance the strength and performance of concrete but also underscores the importance of addressing the escalating issue of textile waste in a sustainable and eco-friendly manner [19]. Furthermore, the question of whether the impact of incorporating other materials into the reinforced structure continues to be significant is examined.

2 Methodology

2.1 Materials and sample preparation

Ordinary Portland cement (OPC) was used according to the ASTM-C150 standard. In addition, sand with a fineness modulus of 2,40 was used [20]. All the ingredients of the concrete, including OPC, sand, coarse aggregates, and polycarboxylic-ultra-accelerator 727, were acquired from a local market. M20 grade concrete was prepared according to the procedure recommended by the American Concrete Institute (ACI 211,1,91) [21; 22]. The physical properties of cement and polyester fibre are presented in Table 1 and Table 2 respectively. A mix ratio of 1:1,5:3 was used to prepare concrete with the addition of different cement weight concentrations of polyester fibres (0,0; 0,5; 1,0; 1,5; 2,0) as a reinforcement. 1 % sodium bicarbonate was used as a minor healing source with replacement for cement for all mixes [23;

8]. A constant water-cement ratio of 0,5 was maintained for all mixes. Also, three-layer nylon is a type of packaging film made up of three layers of nylon. This three-layer structure consists of two layers of nylon with a middle layer of spun bond of high-density polyethylene (HDPE). However, in some cases, spun-bond high-density polyethylene may be used in all three layers to reduce costs [24]. The material used to produce polyester fabric is water-resistant and thermal resistant due to a plastic base, showing less thermal conductivity. All these properties are desirable in construction materials.

Table 1. Physical properties of cement

No.	Description	Values	ASTM
1	specific gravity	3,12	ASTM C188
2	normal consistency	28%	ASTM C187
3	initial setting time	65 minutes	ASTM C191
4	final setting time	320 minutes	ASTM C191
5	bulk density	830-1650 kg/m ³	ASTM C29/C29M

Table 2. Physical properties of polyester fibres

Sr. No.	Properties	Polyester fibre (PET)
1	shape	longitudinal & crushed
2	specific gravity	1,33
3	melting point (°C)	245-268
4	tensile strength (kg/cm ²)	4000-6000
5	alkali resistance	very good
6	electrical & thermal conductivity	low
7	acid and salt resistance	excellent

2.2 Waste polyester fibre treatment

Polyester fabrics were obtained from a local market as waste material and left in an open space for seven days to remove all impurities [25; 26]. Chlorine- and alcohol-based disinfectant sprays were used for treatment to make the material usable for construction purposes [27]. The polyester fabric was cut into longitudinal shapes and crushed into fibres using a cutting machine, as shown in Figure 1. The treated polyester fibres were mixed with other concrete ingredients [28].

First, dried mixtures of cement, sand, coarse aggregate, and polyester fibres were prepared. Water was then mixed after the addition of 0,5 % polycarboxylate-based superplasticiser (Ultra-Accelerator 727) [29]. Mixing continued for 3 min. The mixing was stopped for 1 min, after which it was restarted for two minutes. The slump of all the mixtures was observed to be within the range of 82-130 mm. Cylindrical blocks (6" diameter and 12" height) were cast for testing [29].

After casting, the samples were dried at room temperature for 24 h. Finally, all samples were cured in water at room temperature for 28 days. The quantities of the mixtures are listed in Table 3. [30].



Figure 1. Procedure to use polyester waste fabric for green concrete

Table 3. Concrete proportions with and without fibre reinforcement

Sample name	Cement (kg/m ³)	Sand (kg/m ³)	Aggregates (kg/m ³)	Water (kg/m ³)	Plasticizer (wt.%)	Polyester fibres (wt.%)	Sodium carbonate (%)
M1	178,5	270	540	172	0,5	0,0	1
M2	178,0	270	540	170	0,5	0,5	1
M3	177,5	270	540	170	0,5	1,0	1
M4	177,0	270	540	170	0,5	1,5	1
M5	176,5	270	540	170	0,5	2,0	1

3 Experimental program

Mechanical testing of split tensile and compression tests were performed according to ASTM C496M and ASTM C39M, respectively, on the cylindrical samples, as shown in Figure 2. Compression tests were performed on different concrete samples with varying polyester fibres (polyethylene terephthalate (PET) using a Control Compression Testing machine [31]. All the tests were performed with a loading rate of 0,25 MPa/s.

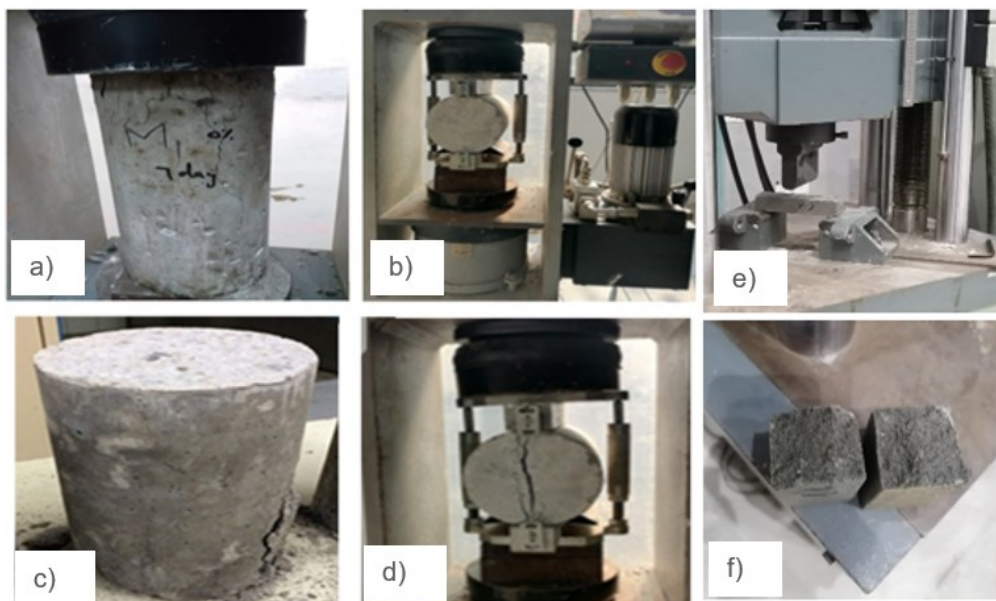


Figure 2. Mechanical testing: a) compression test configuration; b) tensile testing configuration; c) sample after the compression test; d) sample after the tensile test; e) flexural Test configuration; and f) sample after flexural test

The penetration and interconnectivity of the pores in the concrete were evaluated using the Rapid Chloride Permeability Test (RCPT). RCPT procedure was performed according to ASTM C 1202 to determine the ion penetration [32; 33]. Concrete durability decreases in cold environments [34; 35]. The freezing and thawing of water are common issues in cold environments. For this purpose, the cylindrical concrete specimens were placed in a frozen state for 6 h and left at room temperature for another 6 h [36]. Subsequently, the RCPT test was used to compare the freeze–thaw resistance. A higher risk of cracks and permeability was expected in more deteriorated samples. Furthermore, energy-dispersive X-ray spectroscopy (EDAX) was performed to analyse the composition and morphological conditions of the concrete specimens [37; 38].

4 Results and discussion

4.1 Mechanical results

Figure 3 presents compression test results after 28 days of curing. The results show that the compressive strength increased by 20,6 % for concrete containing 1 wt.% polyester fibre content as compared to the control samples. The compressive strength decreases by up to 4% for samples containing 2 wt.% polyethylene terephthalate (PET) fibre content probably due to the formation of air voids in concrete [39; 40]. At lower fibre volumes, the mixing of polymer-modified polyester concrete (PMPC) is more effective in reducing issues such as fibre entanglement, clumping (conglomeration), and air entrapment. This leads to improved strength because the clumped fibres create larger interfacial transition zones (ITZ), which weaken the material [41; 42].

Idress et al. observed the same trend in the compressive strengths of polypropylene and waste PET fibre-based concrete [43]. Qin et al. studied the compressive behaviour of both plain and waste polypropylene fibre-incorporated concrete [44]. The research study concluded that waste fabric-incorporated concrete has a higher compressive strength than the control mix, which shows the better performance of waste polyester (polyethylene terephthalate) in concrete. Sodium bicarbonate acts as an alkaline activator. It is environmentally friendly and contributes to the formation of calcium-aluminosilicate hydrate (C-A-S-H) or sodium aluminosilicate hydrate (N-A-S-H) gels, which account for the strength of the hardened samples.

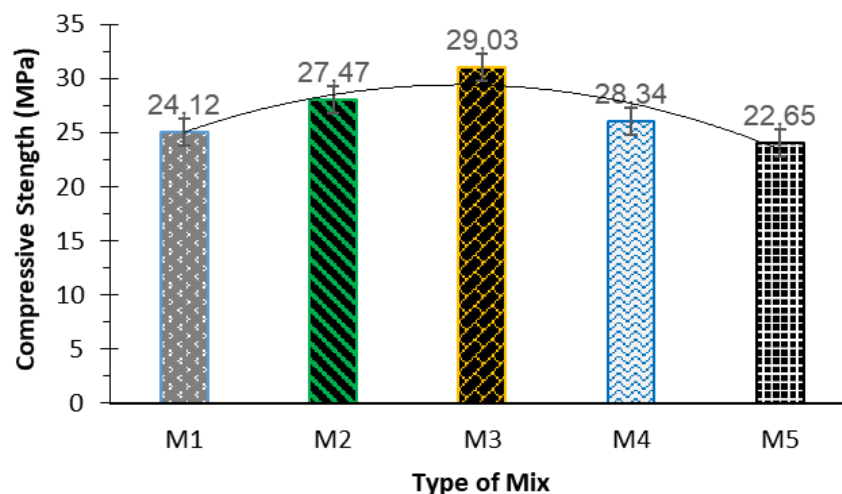


Figure 3. Results of compressive strength versus different concrete samples with and without polyester fibre

The split tensile test results presented in Figure 4 at 28 days of curing show that the tensile strength increased for concrete with polyester fibre content compared to the control concrete samples. The concrete samples containing 1 wt.% polyester fibre content exhibited maximum 25 % enhancement in tensile strength and then decreased as the fibre content further increased [45]. The results show that the tensile strength and crack resistance were significantly improved by the addition of up to 1 % polyester fibres [46; 47].

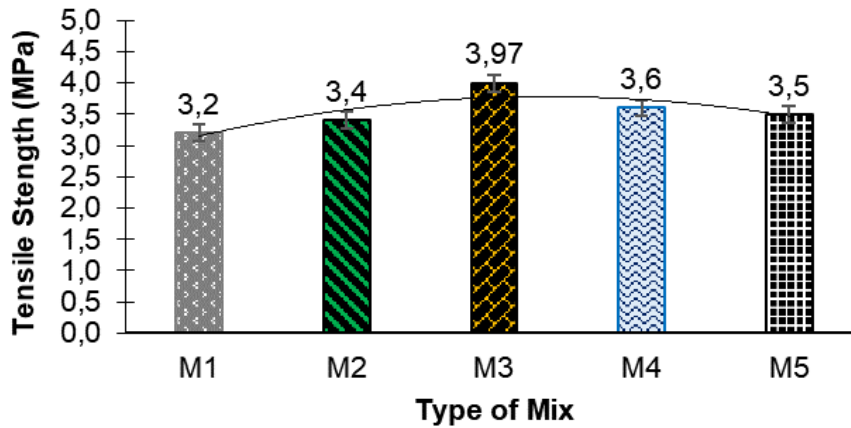


Figure 4. Results of tensile strength verses different concrete samples with and without polyester fibre

The flexural test results for 28 curing days are shown in Figure 5. This illustrates the increase in the flexural strength with a polyester fibre content up to 1 %, followed by a decrease with additional fibre [48; 49].

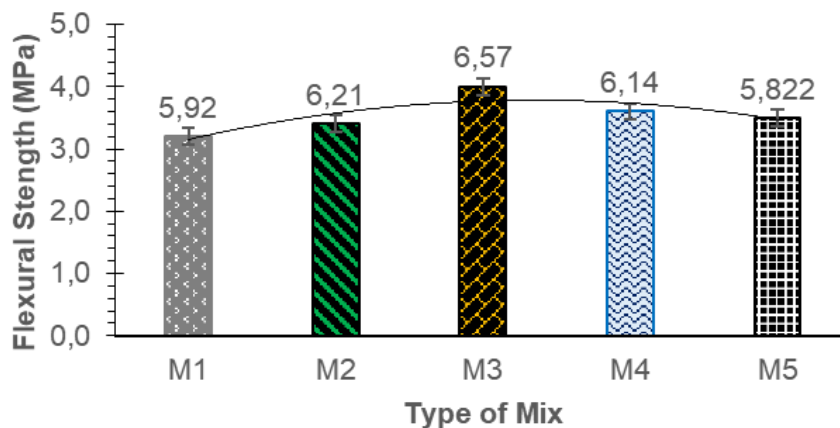


Figure 5. Results of flexural strength of different concrete samples with and without polyester fibre

After testing the samples, varying strengths at different percentages were calculated at 28 d. The decreases in the compressive, tensile, and flexural strengths are presented in Table 4. The analysis showed that with 1 % addition of the (PET) fibres, the compressive strength

increased by 20,60 % increase in compressive strength, 19,08 % in tensile strength and 15,17 % in flexural strength. A significant reduction was observed with an increase in the PET fibre content [50].

Table 4. Percentage variation in compressive, tensile and flexural strength with control mix

Type of mix	28 days compressive strength			28 days split tensile strength			28 days flexural strength		
	Mean value (MPa)	STD	Decrease in compressive strength (%)	Mean value (MPa)	STD	Decrease in compressive strength (%)	Mean value (MPa)	STD	Decrease in compressive strength (%)
M1	24,85	0,672	0,00	3,20	0,35	0,00	5,20	0,62	0,00
M2	27,01	0,891	8,69	3,02	0,35	-5,62	6,13	0,20	1,88
M3	29,97	0,105	20,60	3,81	0,55	19,08	5,98	0,59	15,17
M4	28,16	0,241	13,31	3,16	0,41	-1,25	6,06	0,27	16,53
M5	23,21	0,492	-6,59	2,95	0,61	-7,80	5,78	0,30	11,15

Table 5 shows that flexural strength of each mix of concrete was approximately 4 % of the compressive strength and tensile strength was 8 % of the compressive strength.

Table 5. Percentage variation in compressive, tensile, and flexural strength with control mix

Type of mix	28 days compressive strength (MPa)	28 days tensile strength (MPa)	Compressive strength// split tensile capacity	28 days compressive strength (MPa)	28 days flexural strength (MPa)	Compressive strength/ flexural capacity
M1	24,85	3,20	7,70	24,85	5,92	4,19
M2	27,01	3,02	8,20	27,01	6,21	4,34
M3	29,97	3,81	7,80	29,97	6,57	4,56
M4	28,16	3,16	8,30	28,16	6,14	4,58
M5	23,21	2,95	7,94	23,21	5,82	3,98

4.2 Regression analysis of compressive strength, splitting tensile strength, and flexural strength

In this study, the effects of sodium carbonate (Na_2CO_3) and PET polymer on the flexural, tensile, and compressive strengths of concrete were explored via regression analysis using Origin software. This is an effective technique for determining relationships between one or more input and output variables [51].

Tables 6, 7, and 8 represent the coefficient variations in the regression model for the input variables. PET × Time, PET × PET, PET × Na_2CO_3 , Time × Time, Time × Na_2CO_3 , Na_2CO_3 × Na_2CO_3 describe two-way and quadratic expressions where single variables as PET, Time, Na_2CO_3 , are linear. The regression coefficient provides statistics on the strength and relationship between the independent and dependent variables. The sign of the coefficient indicates the direction of this relationship. The standard error of the coefficient is denoted as SE Coef. This illustrates that exact coefficients were measured. The significance of each term in the regression equation is shown by the "p" values, which are based on a 95 % confidence range [52]. A parameter is significant and significantly affects the intended outcomes if its "p" value is less than 0,05. All combinations of compressive strength are significant because $p < 0,05$ as shown in Table 6. The effect on tensile strength of PET fibre incorporation in all combinations were not significant as shown in Table 7. The p value for all combinations with regard to flexural strength were greater than 0,05, indicating that all the fibre and other

polymeric admixtures additions were not significant [52]. The T value, either positive or negative, is considered significant for both the input and output factors.

Table 6. Regression analysis of compressive strength verses PET, Na₂CO₃ and time

Term	Coefficient (Coef)	SE Coef	T-Value	P-Value	VIF
PET	0,0143	0,0021	6,7588	0,0212	∞
Na ₂ CO ₃	0,0000	0,0000	34,0626	0,0009	0,0000
Time	0,0011	0,0000	34,0626	0,0009	0,0000
PET × PET	-5,8086	0,7947	-7,3088	0,0182	12,4286
Na ₂ CO ₃ × Na ₂ CO ₃	0,0000	0,0000	34,0626	0,0009	0,0000
Time × Time	0,0303	0,0009	34,0626	0,0009	0,0000
PET × Na ₂ CO ₃	0,0143	0,0021	6,7588	0,0212	∞
PET × Time	0,3991	0,0590	6,7588	0,0212	∞
Na ₂ CO ₃ × Time	0,0011	0,0000	34,0626	0,0009	0,0000

Table 7. Regression analysis of tensile strength verses PET, Na₂CO₃ and time

Term	Coefficient (Coef)	SE Coef	T-Value	P-Value	VIF
PET (x1)	-0,96100	0,44500	-2,16	0,1630	∞
Na ₂ CO ₃ (x2)	0,00401	0,00024	16,75	0,0035	~ 0,00
Time (x3)	0,11230	0,00670	16,75	0,0035	~ 000
PET × PET	442,86000	167,58000	2,64	0,1180	12,43
Na ₂ CO ₃ × Na ₂ CO ₃	0,00401	0,00024	16,75	0,0035	~ 0,00
Time × Time	3,14000	0,18800	16,75	0,0035	~ 0,00
PET × Na ₂ CO ₃	-0,96100	0,44500	-2,16	0,1630	∞
PET × Time	-26,92000	12,45000	-2,16	0,1630	∞
Na ₂ CO ₃ × Time	0,11230	0,00670	16,75	0,0035	~ 0,00

Table 8. Regression analysis of flexural strength verses PET, Na₂CO₃ and time

Term	Coefficient (Coef)	SE Coef	T-Value	P-Value	VIF
Const	2,97594	3,15023	0,94474	0,50857	NaN
PET	5,60471	6,62296	0,84636	0,53848	123,9054
Na ₂ CO ₃	2,97594	3,15023	0,94474	0,50857	121,3727
Time	0,03652	0,04564	0,80022	0,55417	116,0336
Polymer × Polymer	-2,35805	2,82365	-0,83514	0,54488	89,2044
Na ₂ CO ₃ × Na ₂ CO ₃	2,97594	3,15023	0,94474	0,50857	121,3727
Time × Time	0,00047	0,00059	0,80022	0,55417	116,0336
Polymer × Na ₂ CO ₃	5,60471	6,62296	0,84636	0,53848	123,9054
Polymer × Time	0,03652	0,04564	0,80022	0,55417	116,0336
Na ₂ CO ₃ × Time	0,03652	0,04564	0,80022	0,55417	116,0336

4.3 Rapid Chloride Permeability Test (RCPT)

Adding waste polyester fibres to concrete reduces chloride permeability, which improves corrosion resistance. The permeability decreased with a fibre content of up to 1 %, with a 10 % reduction at this optimum level. Above 1 % fibre content, the permeability increased. The improvement at lower fibre levels was owing to the PET fibres filling the pores and limiting

chloride penetration [53]. When polyethylene terephthalate (PET) fibre content exceeded 1 %, air entrainment and permeability in the mixture increased. This is due to the higher air content associated with greater fibre volume and potential issues such as improper mixing and nonhomogeneous distribution. At a fibre content of 2 %, the permeability increased further because more air was trapped by the fibres. The results of RCPT are presented in Figure 6. To investigate the durability of concrete, the rapid chloride permeability test was performed. The reduced permeability resulted in better resistance. A maximum decrease of 3 % in permeability was achieved with the addition of 1 wt. % polyester fibre, and a 16 % increase in permeability was achieved for concrete containing 2 % polyester fibre content. The results showed that the permeability of concrete containing polyester fibres (0,5-1,5 %) was also reduced, and the resistance against chloride penetration increased owing to pore filling. The permeability and air entrainment increased with increasing polyester fibre content. An increased air void content may lead to inadequate mixing and handling of fibres [54]. The nonuniformity of the cut pieces of polyester fibre makes them impermeable in nature and does not allow water or ions to pass through them. This may have caused a significant decrease in the permeability of the concrete samples. Thus, the addition of 0,5 and 1,0 % polyester fibres was effective in reducing the permeability of concrete, but greater content was not [55].

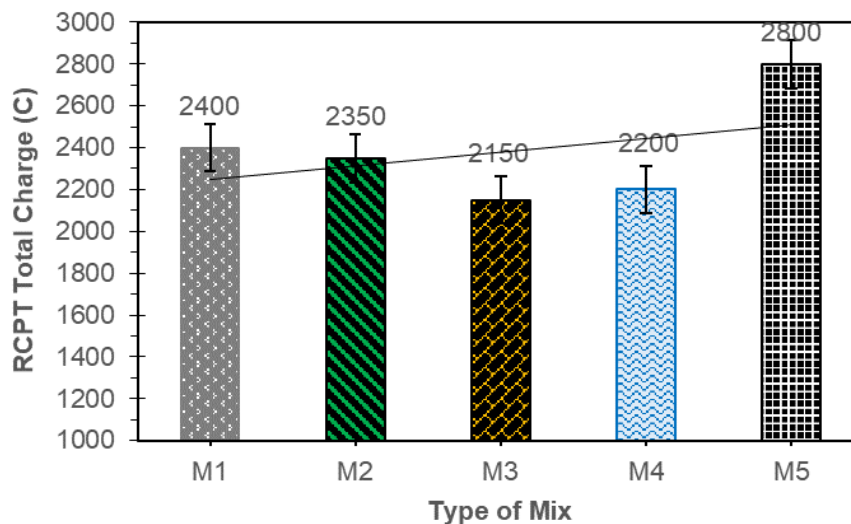


Figure 6. RCPT total charge results of different concrete samples

4.4 Energy Dispersive X-ray (EDAX) analysis

The results of the concrete samples containing polyester fibres were analysed using EDAX to determine their chemical elemental composition and the presence of layers of Calcium-Silicate-Hydrate (C-S-H) on the fibre surface, as shown in Figure 6 [43; 45]. The analysis revealed the presence of various elements derived from the concrete constituents: calcium (Ca) originating from cement and carbon (C), aluminium (Al), and silica (Si) originating from the sand and cement [54]. The quantity of each element in terms of weight % and atomic weight % is presented in Table 9 for concrete containing 1 wt. % polyester fibres [47].

The study examines chemical characterization of polyethylene terephthalate (PET) polyester concrete when exposed to elevated temperatures, specifically at 200 °C and 300 °C. Interestingly, the EDAX results indicate that the polyester concrete exhibits a chemical composition [48] as shown in Figure 7 and similar to that C-S-H gel and CH as shown in Figure 8 and is characterised as plain concrete. In essence, the chemical composition and characterisation remain consistent, whereas the introduction of polyester fibres enhances the mechanical and durability properties of concrete without affecting its chemical composition.

Interestingly, the EDAX results indicate that the polyester concrete exhibits a chemical composition similar to that of the C-S-H gel, as shown in Figure 7 and is characterised as plain concrete. Figure 8 represents the C-S-H gel and ettringite area. In essence, the chemical composition and characterisation remain consistent, whereas the introduction of polyester fibres enhances the mechanical and durability properties of concrete without affecting its chemical composition.

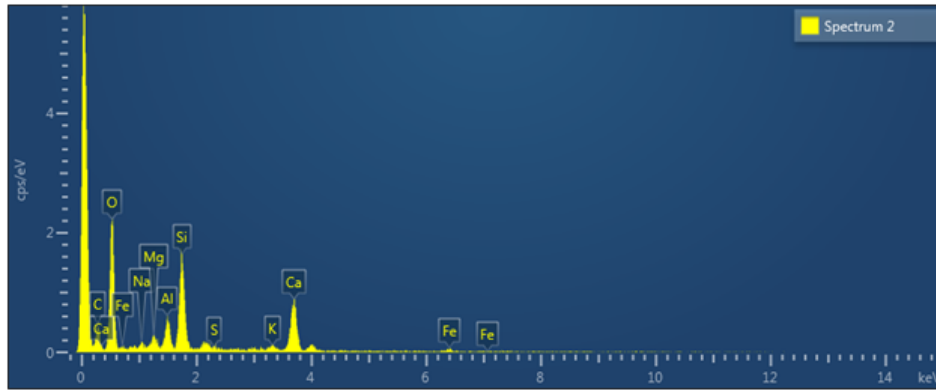


Figure 7. EDAX of concrete with its elemental analysis

Table 9. Summary of EDAX results of a concrete sample containing 1 wt. % polyester fibre with its elemental analysis

Element	Line type	Apparent concentration	k ratio	wt. %	wt. % sigma	Standard label
C	K series	6,52	0,06719	27,41	3,22	C Vit
O	K series	29,33	0,09970	46,28	2,23	SiO ₂
Na	K series	0,51	0,00216	0,62	0,19	Albite
Mg	K series	0,68	0,00478	1,02	0,18	MgO
Al	K series	2,01	0,01450	2,73	0,24	Al ₂ O ₃
Si	K series	6,14	0,04903	8,46	0,48	SiO ₂
S	K series	0,00	0,00000	0,00	0,00	FeS ₂
K	K series	0,57	0,00571	0,78	0,18	KBr
Ca	K series	7,03	0,06369	9,69	0,58	Wollastonite
Fe	K series	0,81	0,00859	1,41	0,40	Fe

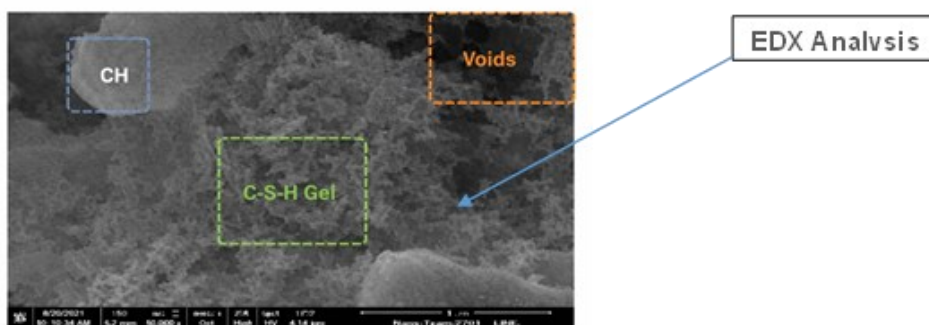


Figure 8. EDAX of polyester concrete with the formation of C-S-H gel

4.5 Scanning Electron Microscopy – SEM

Figure 9 shows SEM images of polymer modified polyester concrete (PMPC) with 1 % polyester fibre at a 5 µm scale. The images highlight the improved strength and performance achieved with the reduced voids in the concrete owing to the polymer addition [49]. Tests for chloride permeability and water absorption indicated a lower permeability, which is attributed to the presence of ultrafine sodium silicate. SBR and EVA particles blended with cement, supporting hydration and strength development. The combination of sodium silicate and polymer admixtures enhanced the strength, durability, and self-healing properties of modified mortar and concrete [49].

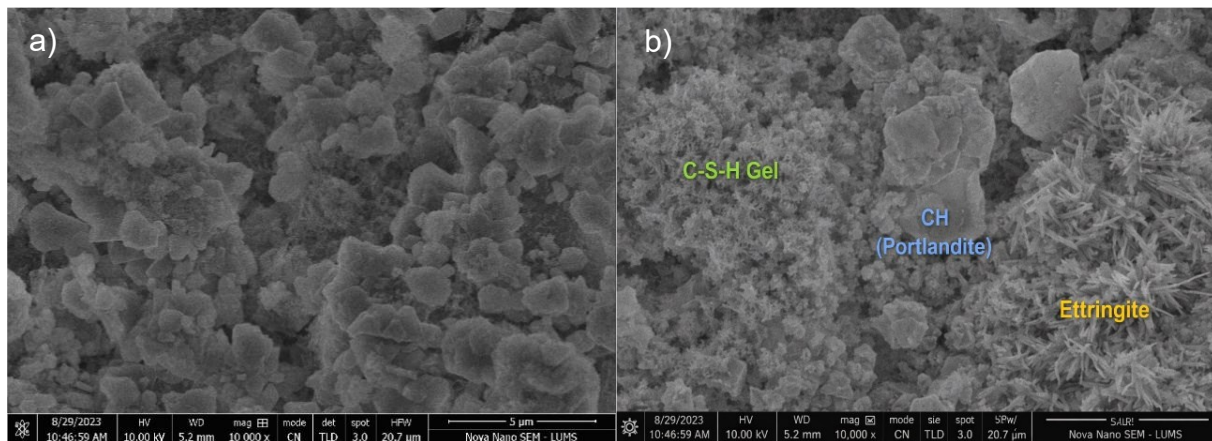


Figure 9. Scanning Electron Microscopy of concrete at 1 % Polyester Fibre & 5% EVA: a) without CSH gel; and b) with CSH gel

5 Conclusions

This study focused on the incorporation of sodium carbonate with ethylene vinyl acetate to enhance its mechanical and polyester fibres for durability properties in M20-grade concrete, particularly under freeze-thaw conditions. The key findings and conclusions of this study are as follows:

- The addition of 1 wt. % polyester fibre content led to a significant increase in compressive strength, showing a 20,6 % improvement when compared to control concrete samples. This improvement in compressive strength indicates that the incorporation of polyester fibres (PF) affects the load-bearing capacity of concrete.
- The split tensile test results revealed that the tensile strength of concrete improved when polyester fibres were introduced. Specifically, concrete samples containing 1 wt. % polyester fibre content exhibited a substantial 25 % increase in tensile strength. This improvement suggests that the polyester fibres enhanced the resistance of the concrete to cracking and tensile stresses.
- The RCPT was used to evaluate the durability of the concrete. The results established that the addition of polyester fibres may lead to a reduction in permeability, indicating an improved resistance to chloride ion penetration. A maximum decrease of 10 % in permeability was achieved with 1 % PF content and an 8 % decrease with 1,5 % PF content. This decrease in permeability may be due to the filling of voids by the polyester fibres, which enhanced the resistance of the concrete to chloride interruption.
- The EDAX results revealed that the chemical composition and characteristics of the polyester concrete remained similar to those of the plain concrete. The primary differences were in the mechanical and durability properties, which were positively influenced by the addition of polyester fibres.

Polyester fibres improve the durability of the concrete, with a reduction in permeability of 23 % at 0,5 % fibre content and 36 % at 1 % fibre content. The optimal value for incorporating waste polyester (polyethylene terephthalate, PET) fibres into concrete to improve both the durability and mechanical properties was found to be 1 %, which is recommended in the construction industry for tension members and hydraulic structures.

Because of their excellent mechanical properties, cement-based composite materials have broad application prospects in bridge piers, guardrails, shield tunnel structures, and other fields. However, further research is needed in areas such as internal structural aging, comparison of different structures, and durability testing.

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