Effect of waste polyethylene terephthalate bottle fibers on the mechanical properties of recycled concrete

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Abstract:
The use of beverage containers, most of which are made of polyethylene terephthalate bottles, results in several problems with regard to sustainability. The purpose of this study was to evaluate and contrast the impact on the mechanical characteristics of concrete caused by the incorporation of polyethylene terephthalate bottle fibres in varying amounts. These fibres were generated by cutting bottles into precise dimensions (width of 5 mm and length of 25 mm), and they were used in various concentrations such as 0,25 %; 0,5 % and 1,0 % by volume of concrete with different amounts of recycled aggregate. To verify the reliability of the outcomes of the experiment, a statistical analysis was performed. According to the results, the concrete that contained 0 % recycled coarse aggregate and varying amounts of plastic fibres had a greater degree of workability compared with concrete that had either 50 % or 100 % recycled coarse aggregate. The comprehensive test findings demonstrated that the addition of polyethylene terephthalate fibres decreased compressive and split tensile strength. The study concluded that certain parameters, such as plastic fibres, curing days, and recycled aggregate, interacted together in a synergistic manner to impact the compressive and splitting tensile strengths of the concrete, with proposed equations for their prediction.

Keywords:
PET Fiber; statistical analysis; slump test; compressive strength test; indirect tension test

1 Introduction

Waste management is an important global concern. Researchers have investigated the possibility of cost reduction, quality enhancement, and sustainability by reusing waste materials such as plastic, glass, and wood in the production of concrete [1, 2]. Today, more than seven billion people live worldwide, necessitating the development of numerous housing structures. Therefore, high quality and efficient concrete is increasingly required. Consequently, the concrete components may become scarce or depleted [3, 4]. For the construction sector, both the monetary and conservational expenses associated with manufacturing, as well as the eminence of concrete by considering its resilience and physical and motorised capabilities, are very important. These variables are affected by the primary types and percentages of ingredients used in the concrete matrix, including water, cement, aggregates, and optional additional additives. However, recent years have seen a rise in the price and scarcity of materials owing to the loss of natural preservatives such as sand and gravel [1]. Plastics are among the significant advances in manufacturing materials engineering that can significantly improve the standards of living. Plastics now permeate almost every area of the human body, from water bottles to electrical devices. Plastic products that are discarded after they have served their intended use have resulted in a massive build-up of solid waste in almost every developing nation [5].

One of the most produced and used polymers in the world is polythene terephthalate (PET) that is used to package soft drinks, drinking water, food, and other consumer items [5-7]; accordingly, this is the most disposed plastic material.

The manufacture of PET bottles has grown significantly because of the sharp increase in beverage consumption. This is because of the advantages of plastics that include low density, strong stability, cost effectiveness, high resistance to mass fraction, and ease of formation and production [8]. However, recycling waste materials of all types is a problem that will continue to affect society in the future and has to be handled and resolved in a practical manner [9]. These materials are disposed of with enduring environmental issues because they degrade considerably slowly and remain in the environment [10, 11].

Recycling concrete by using waste products from the plastic industry has been the subject of extensive investigation. The incorporation of plastic waste into concrete represents a shift in research activity by fusing environmental and concrete technologies [12]. Plastic debris from plastic containers is ground to produce shredded particles that are used in concrete as a replacement for aggregates. Only the body of the plastic bottle is used, removing the neck and bottom, to obtain homogeneous dimensions and facilitate cutting. Pellets made from industrial heating and extrusion operations that behave as coarse plastic aggregates are another option. Fibrous concrete can be created using waste plastic containers shaped into fibres of various sizes and aspect ratios [13].

When making recycled aggregate concrete (RAC), recycled aggregates (RAs) can partly or completely replace coarse and fine particles. Despite using RAC, low-level construction projects can be economical, preserve environmental sustainability, and reduce landfill management issues. Several researchers have investigated the effects of RA on concrete strength and workability. Their findings indicated that the compressive strength and workability of the concrete decreased as the percentage of RA replacement increased. Further research found that replacing up to 25 % of natural coarse aggregates (NCAs) with recycled coarse aggregates (RCAs) did not improve workability and strength of concrete [14, 15].

In this study, the influence of PET waste fibres on the mechanical properties of freshly poured and fully cured concrete using RAs was investigated. To date, no studies have been conducted on the properties of PET strips as fibres (width of 5 mm and length of 25 mm) in concrete containing RCAs. For this purpose, fibres were used in specific dimensions and volumetric proportions such as 0,25 %; 0,5 % and 1,0 % to obtain compressive and splitting tensile strengths and workability of concrete containing RCAs.

2 Concrete mixtures preparation and component properties

All the components of the concrete mixture were previously tested according to the standards. The tests were conducted on the aggregates and a binder (Portland cement) in the laboratory to determine the appropriate parameters for use in concrete.
The fineness of cement was determined using the ASTM C430-17 standard and having value of 95 %. The initial and final setting times were determined according to the ASTM C191-13 standard, and the calculated values were 40 min and 228 min, respectively.
Lawrencpur sand was used to produce the concrete. Tests were conducted to determine the specific gravity and bulk density according to the ASTM C127-14 and ASTM C29 standards. Sargodha crush was used as the NCA with an optimum size of 20 mm, as determined by sieve analysis.
To obtain the RCA, prestressed high-strength cracked girders were used. Factories produce a large quantity of prestressed girders in their daily production; however, some of the members can crack during the transportation and handling process of the girders and therefore can be used for the production of RAs. Figure 1 shows the demolished prestressed concrete girder and the RCA obtained.

Figure 1. Production of recycled coarse aggregate from demolished waste

RCA of up to 20 mm were extracted from the demolished prestressed concrete, and their size was determined by sieve analysis (ASTM C 116-04, C 117-05). Table 1 presents the aggregate properties. The specific gravity of RCA is 7 % lower whereas, fineness modulus and bulk density is 3 % lower approximately in accordance with those of NCAs. However, water absorption was almost four times higher for RAs.

Table 1. Physical properties of aggregates

Material properties	Fine aggregates	Natural coarse aggregates	Recycled coarse aggregates
Specific gravity (SSD) (g/cm^3)	2,48	2,57	2,38
Water absorption (%)	2,90	1,05	4,10
Fineness modulus (mm)	2,54	7,21	7,08
Bulk density (kg/m^3)	1630	1416	1370

The size distribution of NCAs and RCAs is shown in Figure 2. Recycled PET fibres were made from PET bottles collected and trimmed manually into a rectangular shape with a length of 25 mm and a width of 5 mm.

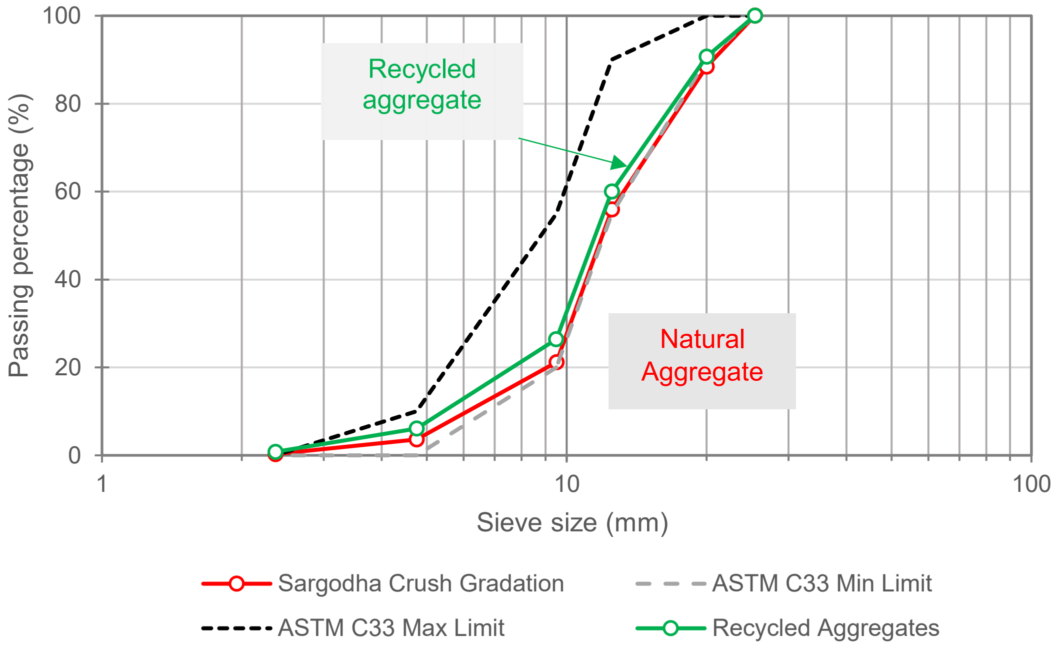


Figure 2. Size distribution of natural and recycled coarse aggregates

PET bottle fibres with RAs were used to evaluate and improve the tensile strength of concrete. The properties of PET fibres (PETFs) are presented in Table 2.

Table 2. Physical properties of PET fibres

	Material properties	Values
	Specific gravity (SSD)(g/cm³)	1,29
	Water absorption (%)	0
	Bulk density (kg/m³)	1100
	Thickness (mm)	0,2
	Size (rectangular shape)	25/5 mm
	Colour	white and green

After material testing, the concrete was manufactured with a nominal design strength of 21 MPa and W/C of 0,55.

Three main groups of concrete mixtures were produced using 0 % RCA, 50 % RCA, and 100 % RCA. For each of these groups, three different fractions of PETFs (0,25 %; 0,50 %, and 1,00 %) were used and tested at the ages of 7, 14, 21, and 28 days.

Therefore, the mixture names were defined according to the percentage of RAs, R(0 / 50 / 100), and percentage of PETFs, PETF(0 / 0,25 / 0,5 / 1). Hence, 288 cylinders (144 for compression and 144 for splitting tensile strength tests) were casted and tested. The mixing proportions for all the mixes are listed in Table 3.

Table 3. Mix proportions of concrete type mixtures

Concrete type mixture	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregates (kg/m^3)	Recycled aggregates (kg/m^3)	Water (kg/m^3)	PET fibres (kg/m^3)
R0PETF0	180	270	540	0	99	0,000
R0PETF0,25	180	270	540	0	99	0,119
R0PETF0,5	180	270	540	0	99	0,239
R0PETF1	180	270	540	0	99	0,479
R50PETF0	180	270	270	270	99	0,000
R50PETF0,25	180	270	270	270	99	0,119
R50PETF0,5	180	270	270	270	99	0,239
R50PETF1	180	270	270	270	99	0,479
R100PETF0	180	270	0	540	99	0,000
R100PETF0,25	180	270	0	540	99	0,119
R100PETF0,5	180	270	0	540	99	0,239
R100PETF1	180	270	0	540	99	0,479

3 Results and discussion of experimental tests

The purpose of the experimental tests was to ascertain the workability, compressive strength, and splitting tensile strength of conventional and recycled course aggregate-based concretes using varying proportions of PET bottle fibres.

3.1 Slump test

The workability of the new concrete was evaluated to determine the ease of laying it. A slump test was conducted in accordance with the requirements outlined in the ASTM C 143 standard. A W/C ratio of 0,55 was used. The slump values obtained for the various mixes are depicted in Figure 3.

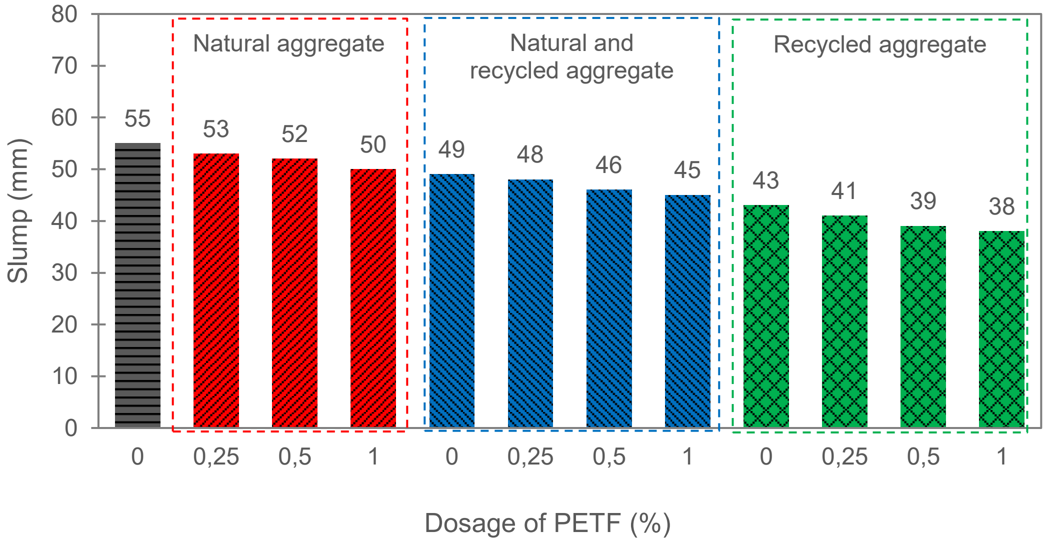


Figure 3. Slump test results

The slump test results indicated that the workability of the control mix R0PETF0, was higher than that of the other mixtures. Notably, slump values were decreased for mixtures with 100 % NCAs, and ratios of PETFs varied up to 9 % when compared to those of a reference mixture. This reduction in workability was increased from 11 % to 18 % by using 50 % RCA and 50 % NCA and further reduction was observed from 22 % to 31 % when 100 % RCA was used, in comparison to the reference mix slump value. The workability of concrete was considerably influenced by the addition of waste plastic fibres in any form, and its value continuously decreased with an increase in the quantity of unwanted plastic fibres in concrete [1]. The reason for the decreased slump value is based on the assumption that RCAs absorb more water than NCAs. Certain studies have recommended that, to remedy this predicament, the RCA should be submerged in water for approximately 20-30 min before mixing the concrete [14]. In addition, the test findings showed that the workability of all combinations ranged from medium to low (55-38 mm).

3.2 Hardened concrete properties

The compression strength test results showed a decreasing trend in the compressive strength of all the mixes compared to that of the control mix, as shown in Figure 4. Notably, at 28 days of curing, the compressive strength of concrete mixes with 50 % and 100 % RCA without PETF was decreased by 5,32 % and 10,13 %, respectively, compared with that of the reference mix. Similarly, when 0,25 % and 0,50 % PETFs were used in all mixes of RCA concrete, the compressive strength reduced compared with that of the mixtures without PETFs. Additionally, when compared with mixes R0PETF0,25, R50PETF0,25, and R100PETF0,25, the 28-day compressive strengths of R0PETF0,50, R50PETF0,50, and R100PETF0,50 increased by 0,26 %, 2,14 %, and 1,39 %, respectively. As observed from the experimental results, the compressive strength was reduced as the percentage of PETFs was increased either in NCA- or RCA-based concrete. However, the compressive strength was enhanced in the case of NCA rather than RCA concrete.

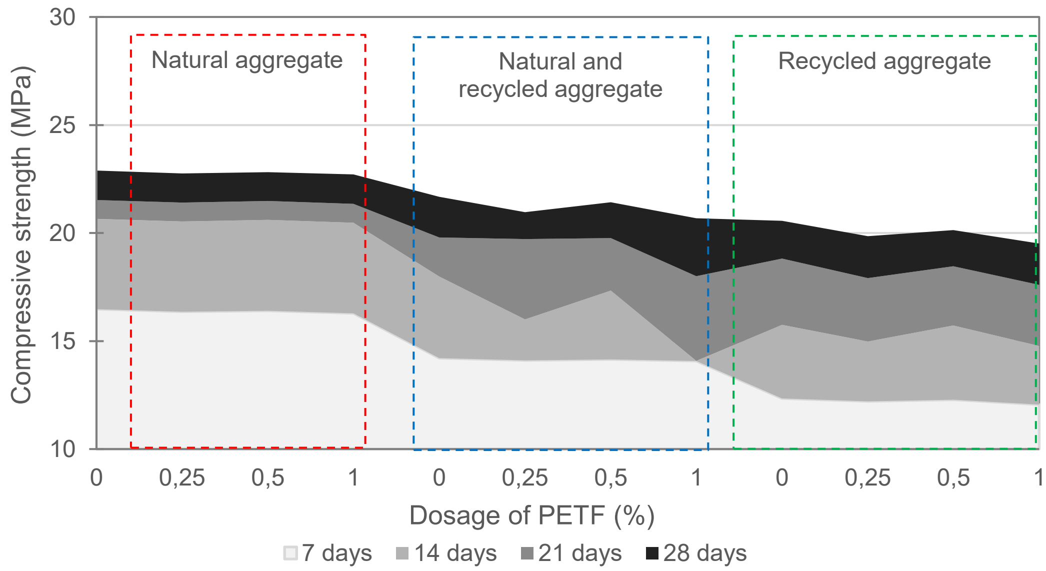


Figure 4. Compressive strength of all mixtures depending on time, PETF percentage, and type of aggregate

Because establishing the direct tensile strength is exceedingly difficult, an indirect testing method was used to estimate the splitting tensile strength of the concrete. This test was conducted using the ASTM C496 and BS 1881 117-83 standards. The splitting tensile strength test was conducted on all mixes, and the observed values are shown in Figure 5. The test results showed that by increasing the quantity of PETFs in 0 %; 50 % and 100 % RCA concrete, the splitting tensile strength decreased. At 28 days of curing, the splitting tensile strength of mixes with 50 % and 100 % RCA without PETF was decreased by 7,27 % and 14,09 %, respectively, compared with that of the reference control mix. Additionally, the 28-day splitting tensile strengths of mixes R0PETF0,50, R50PETF0,50, and R100PETF0,50 were enhanced by 0,29 %; 3,03 % and 5,40 %, respectively, compared with those of mixes R0PETF0,25, R50PETF0,25, and R100PETF0,25. Consequently, an improvement in splitting tensile strength was observed when 0,50 %, PETFs were added to all mixes of RAC, compared with mix having natural aggregate.

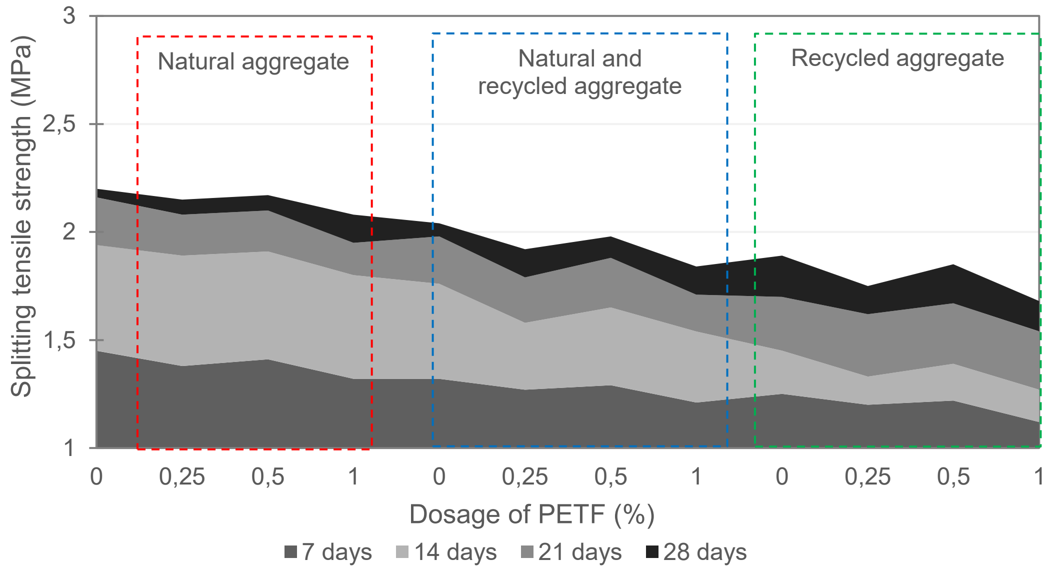


Figure 5. Splitting tensile strength of all mixtures depending on time, PETF percentage, and type of aggregate

The failure patterns of the various concrete specimens under compression are shown in Figure 6. The concrete specimens with NCA and RCA with PETF content showed multiple cracks compared with specimens shown in Figure 6(a) and (d). This is because the concrete specimens with fibres had more ductility than the specimens without fibres.

(a) (b) (c) (d)

Figure 6. Failure pattern of specimens: (a) NAC without fibre; (b) NAC with fibre; (c) RAC with fibre; (d) RAC without fibre

After testing, the strengths were compared statistically; 28-days compressive and tensile strengths were evaluated by calculating the percentage reduction, as presented in Table 4. This analysis showed that the mix of 0,50 % PETFs and 0,00 % RCA provided 0,26 % increase in compressive and 0,92 % increase in splitting tensile strengths compared with those of 0,25 % PETF. Similarly, when 1,00 % fibre was used, the strength was reduced compared with that when 0,25 % and 0,50 % PETFs were used.

Table 4. Percentage variations in compressive and splitting tensile strength test results with control mix (R0PETF0)

	28 days compressive strength			28 days split tensile strength		
Concrete type mixture	**Mean value** (MPa)	**Standard deviation**	**Decrease in compressive strength** (%)	**Mean value** (MPa)	**Standard deviation**	**Decrease in splitting tensile strength** (%)
R0PETF0	22,89	1,10	0,00	2,2	0,17	0,00
R0PETF0,25	21,67	1,01	-5,32	2,04	0,13	-7,27
R0PETF0,5	20,57	1,05	-10,13	1,89	0,15	-14,09
R0PETF1	22,76	0,98	-0,56	2,15	0,08	-2,27
R50PETF0	20,97	0,24	-8,38	1,92	0,05	-12,72
R50PETF0,25	19,85	0,29	-13,28	1,75	0,03	-20,45
R50PETF0,5	22,82	0,07	-0,31	2,17	0,01	-1,36
R50PETF1	21,43	0,46	-6,38	1,98	0,09	-10,00
R100PETF0	20,13	0,54	-12,06	1,85	0,05	-15,90
R100PETF0,25	22,71	1,05	-0,79	2,08	0,15	-5,45
R100PETF0,5	20,68	0,85	-9,65	1,84	0,08	-16,36
R100PETF1	19,52	1,28	-14,70	1,68	0,20	-23,64

Table 5 clarified the fact that the splitting tensile strength of each batch of concrete was approximately 11 % of the compressive strength.

Table 5. Percentage variations in compressive and splitting tensile strength test results with control mix (R0PETF0)

Concrete type mixture	**28 days compressive strength** (MPa)	**28 days split tensile strength** (MPa)	**Compressive strength/splitting tensile capacity** (%)
R0PETF0	22,89	2,2	10,4
R0PETF0,25	21,67	2,04	10,6
R0PETF0,5	20,57	1,89	10,9
R0PETF1	22,76	2,15	10,5
R50PETF0	20,97	1,92	10,9
R50PETF0,25	19,85	1,75	11,3
R50PETF0,5	22,82	2,17	10,5
R50PETF1	21,43	1,98	10,8
R100PETF0	20,13	1,85	10,9
R100PETF0,25	22,71	2,08	10,9
R100PETF0,5	20,68	1,84	11,2
R100PETF1	19,52	1,68	11,6

4 Regression analysis of compressive strength and splitting tensile strength models

In this study, the effects of RCA and PETF on the compressive and tensile strengths of concrete were evaluated via Taguchi analysis using Minitab software. It is an effective technique for determining the relationship between one or more input and output variables.

Tables 6 and 7 present the coded coefficients of the regression model for the input variables. PETF × Time, PETF × RCA, RCA × Time, RCA × RCA, Time × Time, and PETF × PETF illustrate two-way and quadratic interactions, whereas single terms, such as PETF, RCA, and Time, are linear. Regression coefficients often known as ‘Coef’, provide information on the strength and way of the link between the dependent and independent variables. These quantities are also multiplied by the continuous terms in the regression equation. The coefficient proportions depend on the extent of impact a term has on the response factors, whereas the sign indicates the direction of the relationship. The standard error of the coefficients is referred to as ‘SE Coef’. This demonstrates the accuracy with which the coefficients can be measured: the fewer the mistakes, the more accurately the coefficients can be ascertained. Based on a 95 % confidence interval, the ‘p’ values demonstrate the relevance of each term in the regression equation. A ‘p’ value less than 0,05 indicates that a parameter is significant and has a considerable impact on the desired results.

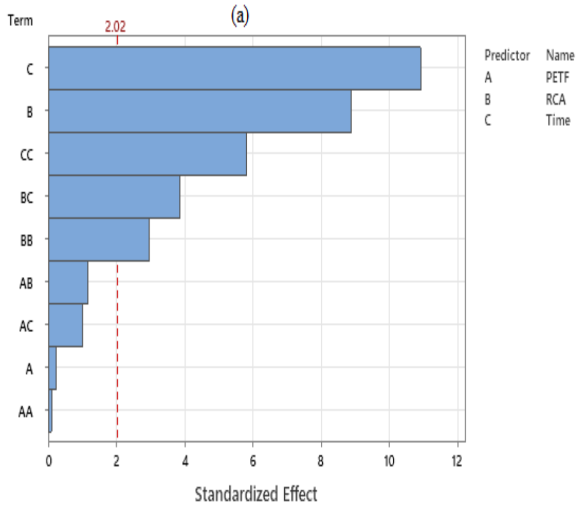
Table 6. Regression analysis of compressive strength verses PETF, RCA, and time

Term	Coef	SE Coef	T Value	P Value	VIF
Regression constant	13,053	0,527	24,77	0,000	
PETF	0,211	0,869	0,24	0,810	19,45
RCA	-0,06983	0,00786	-8,88	0,000	19,40
Time	0,6028	0,0552	10,92	0,000	35,13
PETF × PETF	-0,064	0,658	-0,10	0,923	12,95
RCA × RCA	0,000183	0,000062	2,95	0,005	13,00
Time × Time	-0,00866	0,00149	-5,82	0,000	32,23
PETF × RCA	-0,00564	0,00483	-1,17	0,250	3,90
PETF × Time	-0,0252	0,0252	-1,00	0,324	7,40
RCA × Time	0,000881	0,000228	3,86	0,000	7,50

Table 7. Regression analysis of splitting tensile strength verses PETF, RCA, and time

Term	Coef	SE Coef	T Value	P Value	VIF
Regression constant	1,0238	0,0702	14,57	0,000	
PETF	-0,085	0,116	-0,73	0,467	19,45
RCA	-0,00323	0,00105	-3,08	0,004	19,40
Time	0,07621	0,00736	10,35	0,000	35,13
PETF × PETF	-0,0218	0,0877	-0,25	0,805	12,95
RCA × RCA	0,000005	0,000008	0,61	0,548	13,00
Time × Time	-0,001148	0,000198	-5,79	0,000	32,25
PETF × RCA	-0,000086	0,000644	-0,13	0,895	3,90
PETF × Time	-0,00220	0,00336	-0,65	0,517	7,40
RCA × Time	0,000059	0,000030	-1,93	0,062	7,50

For the output variable of compressive strength (CS), the analysis of variance showed that the PETF had a ‘p’ value greater than 0,005. This indicated that the PETF factor had no effect on the CS. Similarly, the influence of RCA and time/curing days on the output variable of CS was significant; p < 0,005. This implied that by replacing the coarse aggregate with different percentages of RCA, the CS was improved. Moreover, the CS of concrete increased with time. The linear relationship between factors PETF × PETF was insignificant at level of 5 % (p > 0,005), whereas the factors RCA × RCA, Time × Time, PETF × RCA, PETF × Time, and RCA × time had statistically significant influence on output variable CS. Similarly, for output variable splitting tensile strength (STS), the analysis of input variables showed that the PETF did not have a significant influence (p < 0,005), whereas Time and RCA had significant influence on this output variable. This indicated that the PETF element had no effect on the tensile strength of the concrete. Moreover, the STS of concrete increased with time and varying percentages of RCA. The linear relationship between factors PETF × PETF and PETF × RCA was insignificant at level of 5 % (p > 0,005), whereas the factors RCA × RCA, time × time, PETF × time, and RCA × Time had statistically significant influence on output variable STS. To investigate the influence of input variables PETF, RCA, and time/curing days on CS of concrete in quadratic and linear settings, the outcomes were presented through a Pareto plot, as shown in Figure 7.



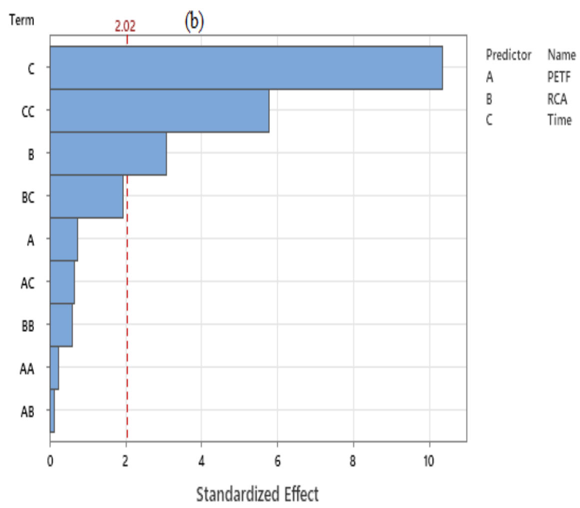


Figure 7. Pareto plot variation: (a) compressive strength; (b) splitting tensile strength

A regression equation for the compressive and tensile strengths was generated to determine the influence of PETF and curing time on RCA concrete. Equation (1) was generated using software to correlate the factors of CS versus PETF, RCA, and curing days on concrete.

$$\text{Compressive strength} = 13{,}053 + 0{,}211 \times \text{PETF} - 0{,}06983 \times \text{RCA} + 0{,}6028 \times \text{time} - 0{,}064 \times \text{PETF} \times \text{PETF} + 0{,}000183 \times \text{RCA} \times \text{RCA} - 0{,}00866 \times \text{time} \times \text{time} - 0{,}00564 \times \text{PETF} \times \text{RCA} - 0{,}0292 \times \text{PETF} \times \text{time} + 0{,}000881 \times \text{RCA} \times \text{time} \quad (1)$$

The CS value, R^2, after the regression analysis was 97,95 %, and the R^2 adjusted value was 97,46 %; this provides an excellent example of a regression model. The coefficient of determination, or R^2, always has a value between 0 and 100 %; a greater R^2 number indicates a better fit [16]. The variations between the STS and the variable components PETF, RCA, and time are also shown in Equation (2):

$$\text{Splitting tensile strength} = 1{,}0238 - 0{,}085 \times \text{PETF} - 0{,}00323 \times \text{RCA} + 0{,}07621 \times \text{time} - 0{,}0218 \times \text{PETF} \times \text{PETF} + 0{,}000005 \times \text{RCA} \times \text{RCA} - 0{,}001148 \times \text{time} \times \text{time} - 0{,}000086 \times \text{PETF} \times \text{RCA} - 0{,}00220 \times \text{PETF} \times \text{time} + 0{,}000059 \times \text{RCA} \times \text{time} \quad (2)$$

The R^2 value for STS after the regression analysis was 96,32 % and R^2 adjusted value was 95,45 %. The R^2 values were nearer to R^2 adjusted values, demonstrating the fitness of the models.

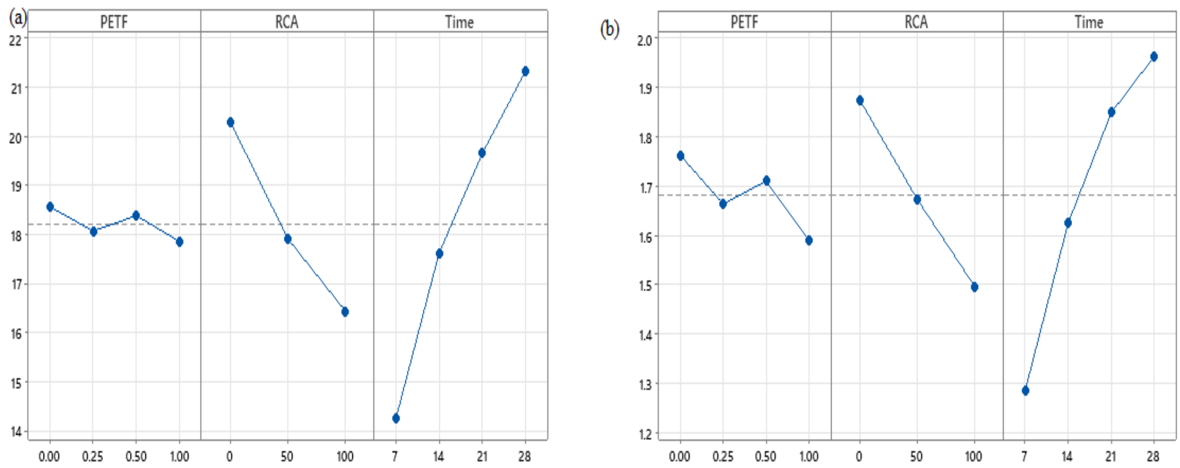


Figure 8. Main effects plots: (a) compressive strength vs PETF, RCA, and Time; (b) splitting tensile strength vs PETF, RCA, and Time

The main effect charts for the compressive and splitting tensile strengths are shown in Figure 8. These graphs demonstrate the variations in the compressive and splitting tensile strengths with the addition of PETF and RCA to concrete. As shown in the plot, the average strength was increased from 0,25 % to 0,50 % when PETF was used. When 0,50 % PETF and 100 % NCA were combined, the average strength was higher than that of the mixtures with 0,25 % PETF. Similarly, with the RCA, the strength was reduced for all mixes compared with that with the NCA. Moreover, when 1,00 % PETF was combined with RCA and NCA mixes, the strength was reduced. The compressive and splitting tensile strengths always increased with time according to the relationship between time and strength.
According to the statistical regression analysis, a prediction model for the CS was proposed to assume the required strength before the experimental test and mixture component distribution which is shown in Table 8.

Table 8. Prediction model of compressive strength for concrete with recycled coarse aggregate and PETFs

		% of recycled coarse aggregate										
		0	10	20	30	40	50	60	70	80	90	100
% of PETF	0	23,85	23,41	23,02	22,66	22,33	22,05	21,80	21,58	21,41	21,27	21,16
	0,5	23,53	23,07	22,64	22,25	21,90	21,59	21,31	21,07	20,86	20,69	20,56
	1	23,18	22,69	22,23	21,82	21,44	21,09	20,79	20,52	20,28	20,09	19,93
	1,5	22,79	22,28	21,79	21,35	20,94	20,57	20,24	19,94	19,68	19,45	19,26
	2	22,38	21,83	21,32	20,85	20,41	20,01	19,65	19,32	19,03	18,78	18,56
	2,5	21,93	21,36	20,82	20,32	19,85	19,43	19,03	18,68	18,36	18,08	17,83
	3	21,45	20,85	20,28	19,75	19,26	18,81	18,39	18,00	17,66	17,35	17,07

5 Conclusions

This paper presents the effects of PETF on NCA and RCA concrete by obtaining general material properties. The following conclusions were drawn from the test results:

- The ratio of RCAs to PETFs caused a progressive decline in the workability of concrete. Compared with specimens with 50 % and 100 % RCA, the slumps of specimens with various PETF percentages and 0 % RCA were higher.

- The experimental results indicated that by the addition of PETFs, the reduction in the CS of NCA concrete increased from 0,5 % to 0,8 % and that of RCA concrete increased from 5,0 % to 14,0 %.
- Factors such as PETFs, curing days, and RCA worked synergistically to affect the compressive and splitting tensile strength effectiveness of concrete. As a parameter, RCA had a significant impact on both material properties. Therefore, the equations for calculating the CS and STS were presented based on a regression statistical analysis. Consequently, a prediction model for the CS of RCA concrete with PETFs was proposed.

In future studies, the usability of PETFs should be investigated in terms of toughness, ductility, resistance to cracking, shrinkage, and durability issues caused by weather and aging. The potential of incorporating other types of waste or recycled materials, such as fly ash or silica fume, along with RCA and PETFs in concrete should be examined. Exploring the possibility of using advanced composite materials, such as glass or carbon fibres, in combination with RCA and PETFs to enhance the mechanical performance of concrete is an important topic for future investigations.

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