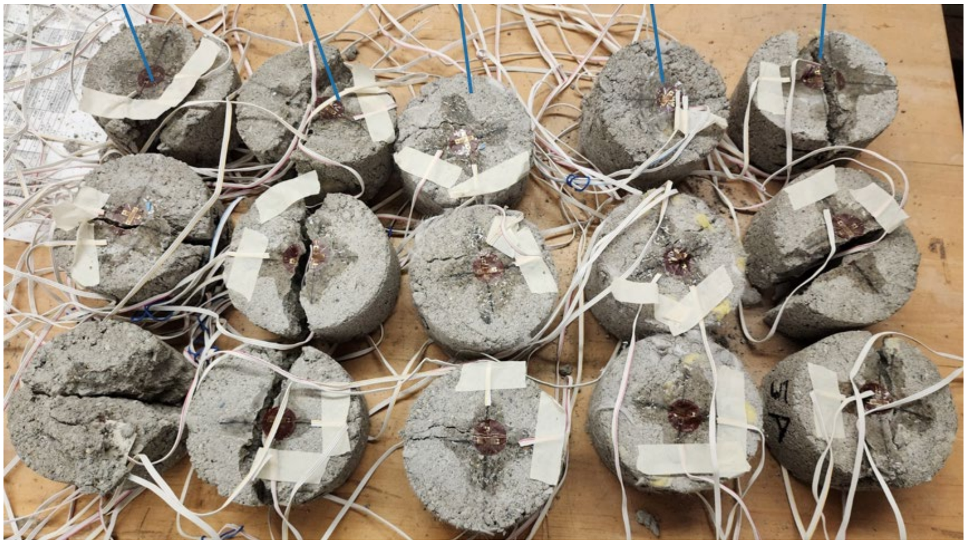
Ohio's Research Initiative for Locals (ORIL) Research On-Call Task 6 – An Experimental Study On The Influence Of Polyester Fibers, Plastic, Glass, And Tire Waste On Low-Strength Concrete Performance



Prepared by Issam Khoury, Roger Green, and Abdul Basit Dahar

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September 2023

Final Report

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<tr><td colspan="3">16. Abstract
Spearheaded by Defiance County, the research to develop a cost-efficient, flexible concrete mix was carried out by Ohio University's Departments of Civil and Environmental Engineering. The study explored the integration of locally-sourced waste materials—tire shreds, fiberglass, polyester fiber, and plastic waste—into the concrete mix. Rigorous testing protocols, aligned with ASTM C39/C39M and C496/C496M-17 standards, were employed to measure the compressive strength, split tensile strength and elastic modulus of the modified concrete. The results were compelling: inclusion of polyester fibers resulted in a 60% improvement in compressive strength and a 141% enhancement in elastic modulus. Tire shreds also positively influenced the mix, with an 84% increase in compressive strength and a 138% boost in elastic modulus. However, these figures come with a cautionary note regarding the uniform distribution of tire shreds in real-world applications. Additionally, these materials led to significant increases in split tensile strength, with polyester fibers and tire waste showing gains of 17% and 130%, respectively. Glass fibers also contributed positively but to a lesser extent. In contrast, plastic waste had a detrimental effect, causing a 40% decrease in compressive strength and a 62% reduction in elastic modulus. Strain at failure varied significantly among the mixes. Glass fiber exhibited the highest strain, 254% relative to the control, while polyester had a 94% increase, and the combined mixes ranged from 45% to 128% relative to the control. The study uncovered the nuanced challenges and opportunities of using waste materials in concrete, presenting avenues for sustainable construction solutions.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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Federal Highway Administration

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Executive Summary

Defiance County developed a flexible concrete mix beginning in 2007 to mimic the behavior of asphalt but at a lower placement cost. Lab testing was developed in 2014 to verify mix design. The material has around 300 lbs./yd^3 (178 kg/m^3) of cementitious material per cubic yard (CY) with fiber to add flexibility. Suitable locally available waste materials include 2 in (50 mm) tire shreds, scrap fiberglass insulation, and shredded recycled plastic.

Samples of the proposed added materials were acquired from Defiance County. In addition, aggregates previously used and any other fibers and admixtures were obtained from Defiance County or from the source of the earlier tests. The substituted materials tested included: tires, polyester fiber, glass fiber, plastic, and combinations of the polyester fiber with plastic or with glass fiber. Mixes were prepared with each added material and test cylinders subjected to compressive strength and split tensile strength tests following ASTM C39/C39M and ASTM C496/C496M-17, respectively.

Conclusions

The experimental study has illuminated the effects of various additives on the compressive strength, elastic modulus, and tensile strength of concrete. While controlled laboratory tests indicated that the incorporation of polyester fibers and tire waste led to significant improvements—with increases of around 60% and 84% in compressive strength, and elastic modulus increases of 141% and 138%, respectively—these results should be interpreted cautiously for tire waste. The uniform distribution of tire waste achieved in a controlled setting may not be easily replicated in actual construction sites, potentially affecting the accuracy of these percentage increases.

In both sets of split tensile strength tests, all additives resulted in increased strength compared to the control mix. Notably, the first set saw increases of 17% for polyester fibers, 164% for glass fiber, and 130% for tire waste. However, the polyester fiber results showed a notably higher standard deviation, suggesting potential variability. In the second set of tests after 7 days, all mixes displayed higher maximum stress, ranging from 8% for glass fiber to 82% for the plastic and polyester combination. Strain at failure varied significantly among the mixes. Glass fiber exhibited the highest strain, 254% relative to the control, while polyester had a 94% increase, and the combined mixes ranged from 45% to 128% relative to the control.

These findings underscore the potential for specific waste materials and fibers to enhance the mechanical properties of concrete, providing opportunities for more sustainable and environmentally friendly construction materials. However, the results also highlight the complexity of these interactions, as not all waste materials contribute positively.

Recommendations

Further study is recommended to address the following issues:

- *Further Research on Plastic Waste*: Given the negative impact of plastic waste, further research should be conducted to determine if different types or proportions might yield more favorable results. Exploring various treatments or bonding agents might also enhance the compatibility of plastic waste with concrete.

- *Long-term Strength and Durability Tests*: To validate the initial findings, long-term strength and durability tests should be performed. This would provide insights into how these materials perform under sustained loads and environmental conditions.
- *Investigation of Cost and Environmental Impact*: An analysis of the cost-effectiveness and overall environmental impact of using these additives should be undertaken. This would ensure that the proposed solutions are not only technically viable but also economically and environmentally sustainable. In particular, can this concrete be reclaimed at the end of life and does the presence of plastics in the concrete lead to increased microplastic emissions into the environment.
- *Development of Standards and Guidelines*: Based on the findings of further research, industry standards and guidelines could be developed for the use of these materials in construction. This would facilitate their broader adoption and ensure quality control.

In conclusion, the study opens promising avenues for enhancing concrete's mechanical properties through the use of specific waste materials and fibers. The results call for nuanced approaches, integrating further research, long-term testing, economic analysis, standardization, and industry collaboration to fully realize the potential of these innovative materials.

1 Project Background

Defiance County developed a flexible concrete mix beginning in 2007 to mimic the behavior of asphalt but at a lower placement cost. Lab testing was developed in 2014 to verify mix design. The material has around 300 lbs./yd^3(178 kg/m^3) of cementitious material with fiber to add flexibility. Suitable locally available waste materials include 2 in (50 mm) tire shreds, scrap fiberglass insulation, and shredded recycled plastic.

2 Research Goals and Objectives

Defiance County would like to add tire shreds, scrap fiberglass insulation and shredded recycled plastic materials to the existing flexible PCC mix. These mixes need to be tested to see if they provide a benefit compared to the current mix in either properties or cost.

3 Research Approach

To fulfill the objectives listed above, the following tasks were undertaken:

- Conduct a literature search to find information on mix designs for flexible concrete incorporating these recycled materials.
- Select mix designs suitable for Defiance County that show the most promise for use.
- Obtain and characterize recycled material samples from Defiance County.
- Develop a test matrix for the selected mix designs, create test specimens for each mix, and conduct tests.
- Prepare this report.

3.1 Literature Search

The literature was reviewed for information relating to the addition of tire shreds, fiberglass, and recycled plastic to concrete mixtures. This review provided information on the mix proportions for flexible concrete and how to achieve it with these materials.

3.2 Material Characterization

Samples of the proposed added materials were acquired from Defiance County. In addition, aggregates previously used and any other fibers and admixtures were obtained from Defiance County or from the source of the earlier tests. It is important for this research to use the same materials previously tested so an informed comparison can be made. The substituted materials tested included: tires, polyester fiber, glass fiber, plastic, and combinations of the polyester fiber with plastic or with glass fiber.

3.3 Create Mix Design Tables

A 5-mix matrix was designed, reviewed by the TAC, and modified as necessary. Upon agreement with the TAC on the mix designs to be tested, a minimum of 3 concrete cylinders were cast for each test mix. Strain gauges were installed to measure the strain response when tested in compression in ORITE laboratories. Stress-strain curves were generated for comparison to results previously collected by Defiance County.

Table 1 shows the mix designs used in the first round of tests. For each mix approximately 1.4 ft^3 (39.6 l) of concrete was prepared. For the second set of mixes, the added materials tested included glass fiber, polyester, a combination of both, and polyester + plastic, with the additives maintained at consistent quantities by weight. In both sets of mixes, a control batch without any additives was prepared.

Table 1. Material proportions for first set of tests making 1.4 ft^3 (39.6 l) of concrete.

Mix	Control		10% tire waste		0.3% polyester fiber		5% plastic		0.3% glass fiber	
Material	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**
Cement	6.218	2820	6.218	2820	6.218	2820	6.218	2820	6.218	2820
Class F fly ash	4.708	2136	4.708	2136	4.708	2136	4.708	2136	4.708	2136
Slag	4.708	2136	4.708	2136	4.708	2136	4.708	2136	4.708	2136
C-33 Sand	91.614	41555	91.614	41555	91.614	41555	91.614	41555	91.614	41555
AASHTO #8 aggregate	49.548	22475	49.548	22475	49.548	22475	49.548	22475	49.548	22475
AASHTO #57 aggregate	27.887	12649	27.887	12649	27.887	12649	27.887	12649	27.887	12649
Water	13.342	6052	13.342	6052	13.342	6052	13.342	6052	13.342	6052
Air entrainment	0.186	84	0.186	84	0.186	84	0.186	84	0.186	84
Added material	-	-	0.916	416	0.428	194	4.234	1920	0.662	300
Total	198.211	89907	199.127	90323	198.638	90101	202.445	91827	198.873	90207

Material proportions for first set of tests making 1.4 ft^3 (39.6 l) of concrete.

Mix	Control		glass fiber		polyester		polyester + glass		polyester + plastic	
Material	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**	**(lb)**	**(g)**
Cement	6.218	2820	6.218	2820	6.218	2820	6.218	2820	6.218	2820
Class F fly ash	4.708	2136	4.708	2136	4.708	2136	4.708	2136	4.708	2136
Slag	4.708	2136	4.708	2136	4.708	2136	4.708	2136	4.708	2136
C-33 Sand	91.614	41555	91.614	41555	91.614	41555	91.614	41555	91.614	41555
AASHTO #8 aggregate	49.548	22475	49.548	22475	49.548	22475	49.548	22475	49.548	22475
AASHTO #57 aggregate	27.887	12649	27.887	12649	27.887	12649	27.887	12649	27.887	12649
Water	13.342	6052	13.342	6052	13.342	6052	13.342	6052	13.342	6052
Air entrainment	0.186	84	0.186	84	0.186	84	0.186	84	0.186	84
Added material 1	-	-	0.6614	300	0.6614	300	0.6614	150	0.6614	150
Added material 2	-	-	-	-	-	-	0.6614	150	0.6614	150
Total	198.211	89907	198.872	89907	198.872	89907	199.534	89907	199.534	89907

3.4 Create and Test Specimens

Three 6 in (150 mm) diameter and 12 in (300 mm) length cylindrical test specimens were prepared for the compressive strength and split tensile tests for each mix. Figure 1 shows the test setups used for the first set of mixes. Compressive strength testing was conducted after 28 days of curing conforming to ASTM C39/C39M. Split tensile testing was conducted following ASTM C496/496M-17.

For the second set of mixes, the split tensile test setup was as shown in Figure 2, and the curing period reduced to 7 days. Figure 3 shows what the specimens looked like after testing.

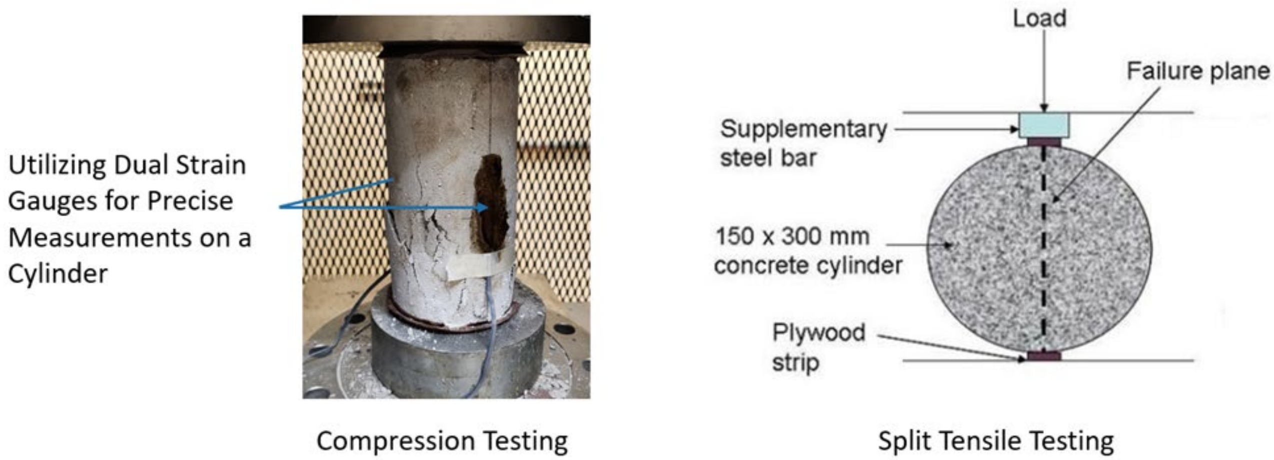

Figure 1. Test setups for compression testing (left) and split tensile testing (right).

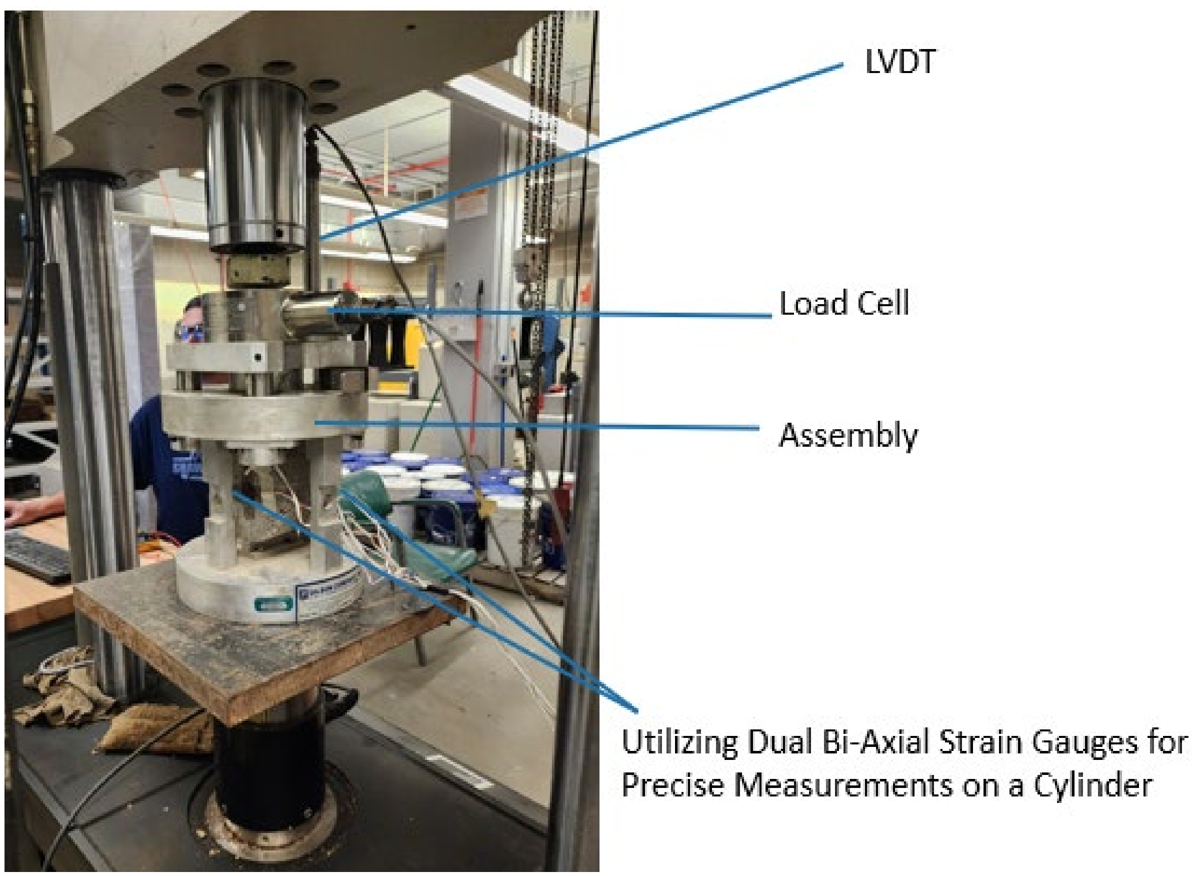

Figure 2. Setup for split tensile test used in second set of tests.

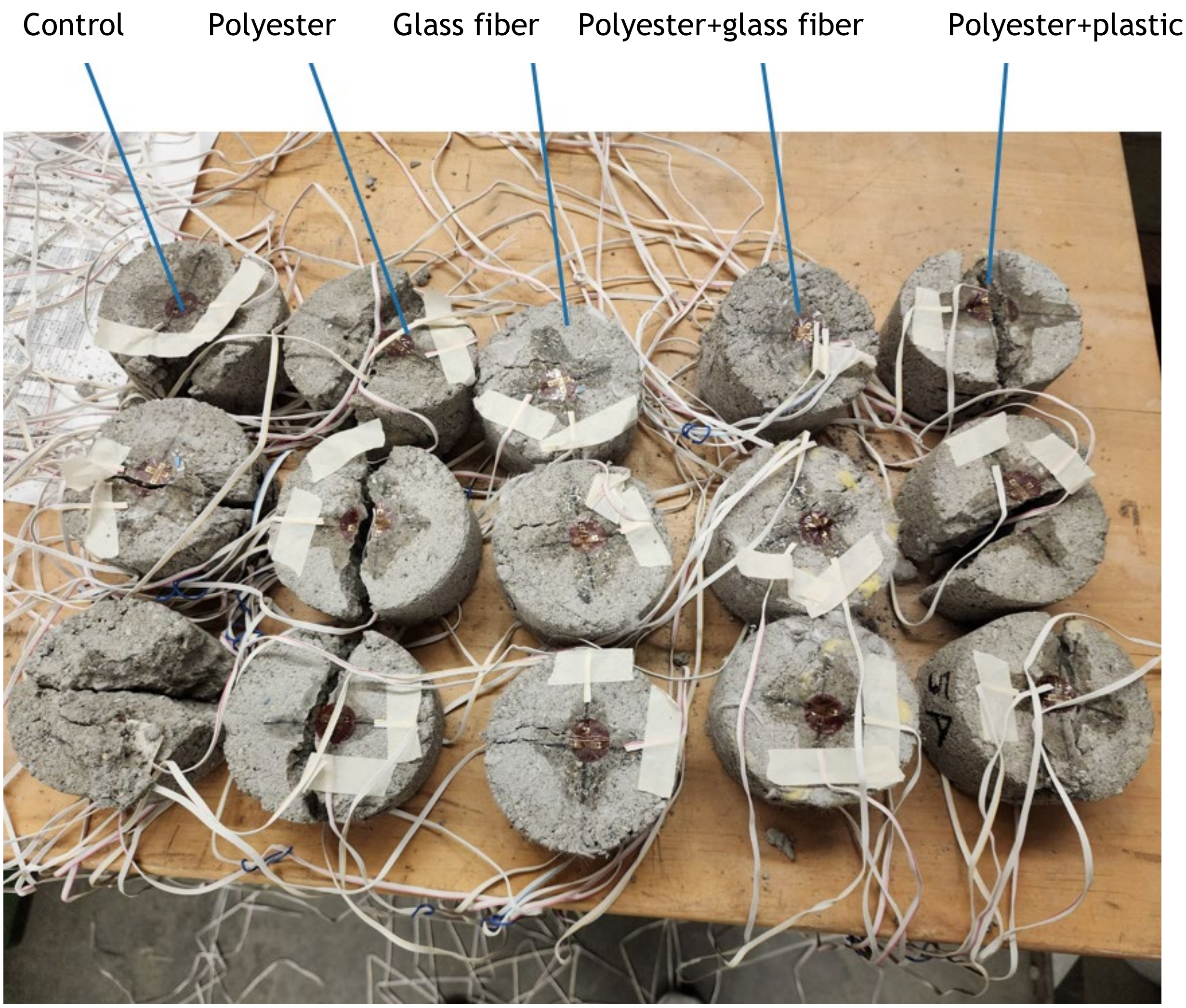

Figure 3. Split tensile test specimens for second set of mixes after testing.

4 Literature Review

While many research studies have been conducted on fibers and waste in structural concrete, only a few exist on flexible concrete as a pavement material [Ortega-López et al., 2018]. The growing interest in flexible concrete is driven by recent increases in asphalt and bitumen prices. According to reports, the United States (US) alone uses more than 320 million tons of raw materials each year to build, renovate, and maintain the nation's road network, at a cost of more than $150 billion [USDOT, 2006; FHWA, 2009]. About 300 million waste tires are produced in the US each year, and a mere 5.5% of them are utilized in civil engineering [Rubber Manufacturers Association, 2011].

Recycling waste, such as fibers and plastics, is an effective strategy for protecting the environment and supplying the high and rising demand for construction materials [Ahmed and Lim, 2020]. This practice will protect natural aggregate reservoirs, avoid greenhouse gas emissions, use less energy to produce aggregates, and save valuable land from being turned into a dumping ground, all of which will improve the sustainability and efficiency of the construction sector [Jacobi, Haas, Wiedenhofer, and Mayer, 2018; Rodríguez, et al., 2016]. The majority of studies demonstrate that the presence of fibers and waste influences workability, compressive strength, elastic modulus, split tensile strength, and thermal conductivity, and somewhat improves abrasion and flexural strength [Sharma and Bansal, 2016]. Additional research reveals potential applications for these materials in paving systems, concrete formulations, and asphalt binders [Lee, 2008; Siddique, Khatib, and Kaur, 2008].

The Transportation Research Board released Special Report 347 [TRB, 2023] entitled *Recycled Plastics in Infrastructure* in August 2023, a comprehensive survey of using recycled plastic in infrastructure. Most of the report examines the production of plastic and handling of the waste stream, as well as regulations and policy impacts. Chapter 6 concerns use of recycled plastics in pavements, specifically in asphalt concrete pavements and in subbase layers, rather than Portland cement concrete (PCC). The use of plastics in asphalt concrete pavement has been studied in recent years, with assessments ranging from optimistic [Lombardo, 2023; Craig, 2023; Sasidharan, Eskandri Torbaghan, and Burrow, 2019] to pessimistic [Conlon, 2021; Winters, 2023]. A primary problem is the "downcycling" of waste plastic into construction materials does not create a closed use cycle or fully solve the issues of waste plastic generation [Cirino et al., 2023]. It should be noted that the most successful use of recycled plastics has been with thermoplastic pipes, where an NCHRP study addressed the feasibility of this application [Pluimer et al., 2018].

4.1 Compressive Strength

Rubberized concrete (RuC) typically has a lower compressive strength than plain concrete (PC) [Aslani, 2016]. With a rubber content between 5 and 50 percent of natural particles, ranging in size from 6 mm to 0.075 mm, concrete's strength was reduced by around 40 to 70 percent [Najim and Hall, 2012]. The literature's findings on compressive strength loss are given in Table 2. The size, shape, mechanical characteristics, and amount of RA replacement all affect the overall decline in RuC strength [Ganjian, Khorami, and Maghsoudi, 2009]. Numerous studies have provided many examples of the reasons why the compressive strength of RuC has been trending downward with increasing rubber content. One of the main reasons for this downward tendency is the extremely poor adhesion between the cement paste and rubber in concrete, which functions as a gap in the matrix of concrete and decreases the density of the concrete matrix [Aslani, 2016]. Cement paste adheres poorly to rubber's slick surface. An SEM test conducted by Thomas and Gupta [2009] verified the existence of gaps and fissures in the cement paste-rubber interface, suggesting a weak bonding condition. Another factor that contributed to the loss in strength was the fact that early RuC cracking occurs as a result of tensile strains developing in the corresponding cement paste and along the surface of the rubber particle when RuC is under compressive stress.

Table 2. Compressive strength of mixes using recycled tires studied in the literature (25.4 mm = 1 in).

References	Replacement level	Recycled Aggregate size (mm)	Properties of Specimens	Compressive strength variations	Modulus of elasticity variation	Remarks
Noaman, Abu Bakar, and Akil [2016]	5-15% Fine Aggregate	1.18-2.36	Cube (1:1.7:2.1 with w/c = 0.47)	Reduced 12.7%-26%	Reduced 9.4%-18.5%	With increasing size and RA content, compressive strength falls.
Li, Zhuge, Gravina, and Mills [2018]	6-18% Fine Aggregate	1.18, 2.36	Cylinder (1:1.7:2.7 with w/c = 0.5)	Reduced 11.5%-31.9%	Reduced 4.4%-13.7%	Concrete's ability to absorb energy and hardness were both enhanced by RA.
Ganjian, Khorami, and Maghsoudi [2009]	5-10% Coarse Aggregate 5-10% Binder	<10 0.045-1.2	Cylinder (1:2.26:2.44 with w/c = 0.5)	Reduced 10%-23% Reduced 20%-40%	Reduced 17%-25% Reduced 18%-36%	Any focused load in the ITZ caused concrete to crumble rapidly because rubber acted as a cavity.
Hassanli, Mills, Li, and Benn [2017]	6-18% Fine Aggregate	average 1.18	Cylinder (1:1.5:2.7 with w/c = 0.5)	Reduced 10.9%-30.9%	Reduced 2.2%-10.1%	Rubber addition promotes ductility.

Al-Manaseer and Dalal [1997] looked at how plastic aggregate inclusion affected concrete's compressive strength. Varied w/cm and distinct proportions of plastic particles were used to create different concrete compositions. As the content of aggregates increased, compressive strength fell. When the w/cm was raised, it was discovered that the compressive strength decreased at any given level of plastic aggregate concentration. In general, it was found that as the concentration of aggregates made of plastic increased, the strength-gain rate loss decreased. For concrete that has plastic particles at percentages of 10%, 30%, and 50%, there was found a 34%, 51%, and 67% reduction in compressive strength, respectively. The lower strength that is typical of aggregates made of plastic or a weak connection between the plastic aggregates and the cement paste may be to blame for the decrease in compressive strength brought on by the inclusion of plastic aggregates. Table 3 shows the results of work carried out by Choi, Moon, Chung, and Cho [2005].

Table 3. Mechanical properties of PCC made with lightweight plastic aggregate in proportions by weight of 0%, 25%, 50%, and 75%. Adapted from Choi, Moon, Chung, and Cho [2005].

Water-cement ratio	Plastic replacement ratio	Density (pcy)	Compressive strength		Splitting tensile strength (ksi)	Modulus of elasticity (ksi)	Slump (in)
			at 7 days (ksi)	at 28 days (ksi)			
0.53	0%	3877	3.48	4.57	0.474	3408	3.9
	25%	3742	3.39	4.31	0.384	3336	6.0
	50%	3590	3.12	3.81	0.326	3075	7.8
	75%	3388	2.78	3.16	0.296	2683	8.8
0.49	0%	3877	4.03	5.02	0.474	3379	4.1
	25%	3759	3.87	4.89	0.400	3307	6.1
	50%	3573	3.52	4.22	0.341	2625	7.1
	75%	3371	3.13	3.36	0.281	2422	8.4

0.45	0%	3877	4.54	5.40	0.482	3698	5.3
	25%	3809	3.97	4.90	0.406	2712	6.7
	50%	3641	3.84	4.61	0.370	2509	7.2
	75%	3270	3.60	3.61	0.296	2263	8.1
		(kg/m^3)	(MPa)	(MPa)	(MPa)	(GPa)	(cm)
0.53	0%	2300	24.0	31.5	3.27	23.5	10.0
	25%	2220	23.4	29.7	2.65	23.0	15.3
	50%	2130	21.5	26.3	2.25	21.2	19.9
	75%	2010	19.2	21.8	2.04	18.5	22.3
0.49	0%	2300	27.8	34.6	3.27	23.3	10.5
	25%	2230	26.7	33.7	2.76	22.8	15.4
	50%	2120	24.3	29.1	2.35	18.1	18.0
	75%	2000	21.6	23.2	1.94	16.7	21.4
0.45	0%	2300	31.3	37.2	3.32	25.5	13.5
	25%	2260	27.4	33.8	2.80	18.7	16.9
	50%	2160	26.5	31.8	2.55	17.3	18.4
	75%	1940	24.8	24.9	2.04	15.6	20.5

4.2 Flexural strength

According to published research [Batayneh, Marie, and Asi, 2008], the declining trend of RuC's flexural strength is almost identical to the compressive and split tensile strengths. Similar results were observed by [20], who discovered a 25–27% decrease in flexural tensile strength when 20% sand was substituted with CR in concrete. Self-compacting rubberized concrete was shown to have increased flexural toughness [Najim and Hall, 2012]. The advantage is that RuC does not crack abruptly under bending as regular concrete does [Lin, et al, 2013]. Because of this, RuC fails with a certain degree of deformation but does not completely disintegrate under flexural stress [Thomas and Gupta, 2016; Sofi, 2017]. In order to reduce the strength loss of RuC under flexural stress, silica fume addition is favorable [Elchalakani, 2015]. Additionally, to increase RuC's flexural strength and fracture resistance, experts advise using steel or synthetic fibers [Park, Abolmaali, Maohammadagha, and Lee, 2014].

Both the splitting and flexural strengths of the investigated materials showed similar trends, but with a smaller influence. (iii) The lower strength of the plastic particles compared to the aggregate was the cause of the drop in strength. According to the maximum strength of the structural element to be built, both the usage of concrete containing plastic particles and the percentage of replacement should be limited.

4.3 Abrasion Resistance

RuC is more resistant to abrasion than PC [Thomas and Gupta, 2016; Sofi, 2017; Gesoğlu, Güneyisi, Khoshnaw, and İpek, 2014]. Rubber is added to concrete to further increase abrasion resistance [Kang, Zhang, and Li, 2012]. When the RA concentration was raised by 10–30%, the abrasion depth of RuC fell from 73% to 61% when compared to PC. Better abrasion resistance is usually shown by a denser matrix. With the inclusion of finer rubber particles, concrete becomes denser, increasing both abrasion resistance and density. Kang, Zhang, and Li [2012] provided an example that abrasion resistance varies with rubber content and rubber size. It also indicated that the RuC with finer CR displays reduced abrasion depth, while the RuC with greater RA concentration exhibits improved abrasion resistance. The fact that rubber is soft and works like a brush may be to blame for the increase in wear resistance. On the other hand, increased rubber content may result in more abrasion damage to RuC because the rubber might aggregate and reduce the matrix's surface stiffness [Ridgley, Abouhussien, Hassan, and Colbourne, 2018].

5 Test results

5.1 Compressive Strength

Figure 4 shows the stress-strain relationships from the compressive strength test on the first set of mixes. Table 4 has the stress and strain values recorded at the maximum stress point and at the point of failure (the maximum strain). The relative stress values recorded are as a percentage of the stress of the control mix. The mix with polyester added reached a maximum stress of 771.97 psi (5.32 MPa) or a relative value 160%, an increase of 60% above the control mix value of 483.89 psi (3.34 MPa). The maximum stress of the glass fiber mix also increased 60%, and the tire waste mix increased 83%, while the plastic mix decreased by 40%. The stress values recorded at failure followed a similar pattern.

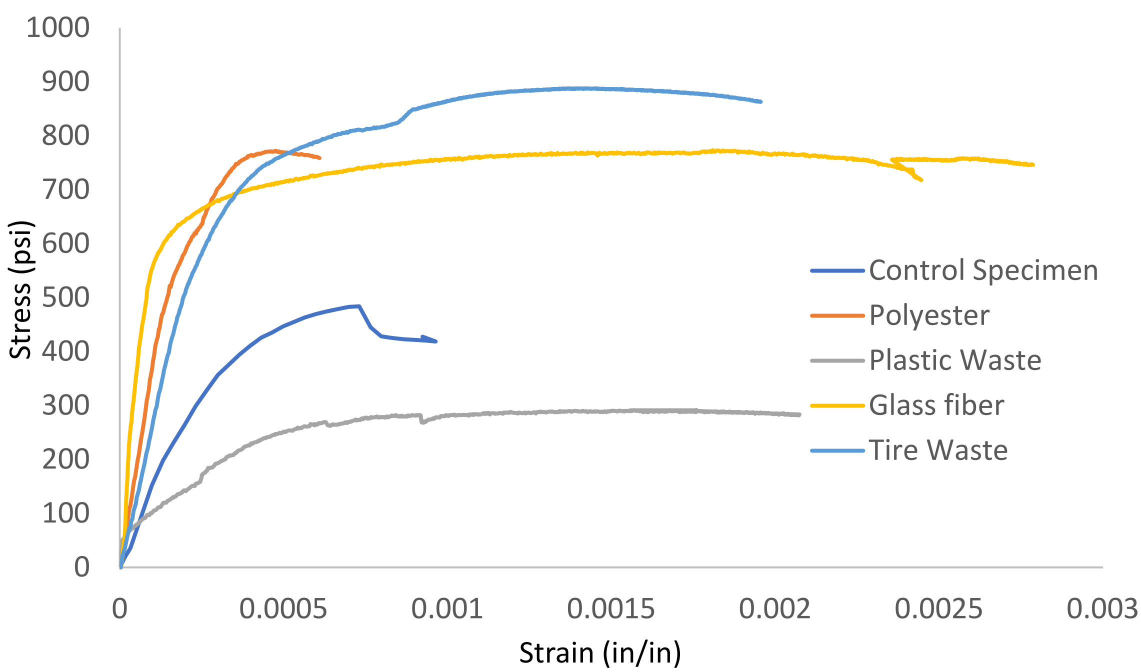

Figure 4. Stress-strain relationship from compressive strength test.

Table 4. Stress and strain values at points of maximum stress and failure. Relative values are in comparison to control mix.

Compressive Strength	Maximum stress				Stress at failure			
Treatment	(psi)	(MPa)	relative	Strain (ε)	(psi)	(MPa)	relative	Strain (ε)
Control	483.89	3.34	100%	0.00073	427.31	2.95	100%	0.00092
Polyester	771.97	5.32	160%	0.00048	758.3	5.23	177%	0.00061
Plastic	291.93	2.01	60%	0.00176	291.37	2.01	68%	0.00156
Glass Fiber	773.39	5.33	160%	0.00181	745.76	5.14	175%	0.00279
Tire Waste	887.92	6.12	183%	0.00142	864.02	5.96	202%	0.00194

5.2 Slump

Slump values for the different mixes are given in Table 5. Slump is considered a measure of workability, and low values indicate a stiff mix. The relative values indicate all the mixes were comparable (above 90%) to the control mix, except the one with plastic waste, which had a slump of only 0.5 in (13 mm), only 17% of the control mix value.

Table 5. Slump test results for the first set of mixes.

	Slump		
Treatment	(in)	(mm)	(%)
Control	3.0	76	100%
Tire waste	2.9	74	97%
Plastic waste	0.5	13	17%
Polyester fiber	2.8	71	93%
Glass fiber	2.8	70	92%

5.3 Elastic Modulus

The elastic modulus of the first set of mixes are shown in Table 6. The plastic mix has a much lower modulus, reduced by 62% from the control mix value. The glass fiber mix has a modulus 40% greater than the control, and the polyester and tire mixes show an increase of around 140%, more than double the control.

Table 6. Elastic modulus values measured for the first set of mixes

	Elastic modulus		
Treatment	(ksi)	(MPa)	relative
Control	1118	7708	100%
Polyester	2695	18581	241%
Plastic	426	2937	38%
Glass Fiber	1561	10763	140%
Tire Waste	2659	18333	238%

5.4 Split Tensile Strength

The split tensile strength test results for the first set of mixes after 28 days of curing are summarized in Table 7. All of the additives had mean split tensile strengths increase relative to the control: by 17% for the polyester fibers and the plastic, and by 164% for the glass fiber mix and 130% for the mix with the tires. However, the standard deviation of the polyester fiber results is larger than the mean, indicating either a spurious result or extreme variability.

Table 7. Split tensile strength values recorded for the first set of mixes.

Split Tensile Strength Treatment	Mean (psi)	Std dev (psi)	Mean (MPa)	Std dev (MPa)	Std dev (%)	Relative to control
Control	98.23	13	0.68	0.07	13%	100%
Polyester fibers	114.59	156	0.79	1.03	136%	117%
Plastic	114.95	31	0.79	0.21	27%	117%
Glass fibers	259.42	50	1.79	0.34	19%	264%
Tires	225.47	15	1.55	0.10	7%	230%

The second set of mixes had split tensile strength tests after only 7 days of curing. Results are graphed in Figure 5. Results are tabulated in Table 8 at the point of maximum stress. The test mixes all showed increased maximum stress relative to the control mix, with the increase as little as 8% for the glass fiber and as much as 82% for the combination of plastic and polyester. The strain at maximum stress was at 80% for the glass fiber mix, a reduction of 20% from the control, while the other mixes had increases of about 50% for polyester and polyester with glass fiber and even 105% for the polyester and plastic mix.

Results at the point of failure are tabulated in Table 9. The stress recorded at failure for the glass fiber and polyester fiber mixes decreased by 9% and 17% respectively from the control, while those for the two combined mixes, polyester with glass fiber and polyester with fabric, increased by over 80% relative to control. The maximum strain at the point of failure was all over the place, ranging from 45% of the control value for the polymer with glass fiber mix, a reduction of 55%, to a 154% increase for the glass fiber mix (more than double the control value).

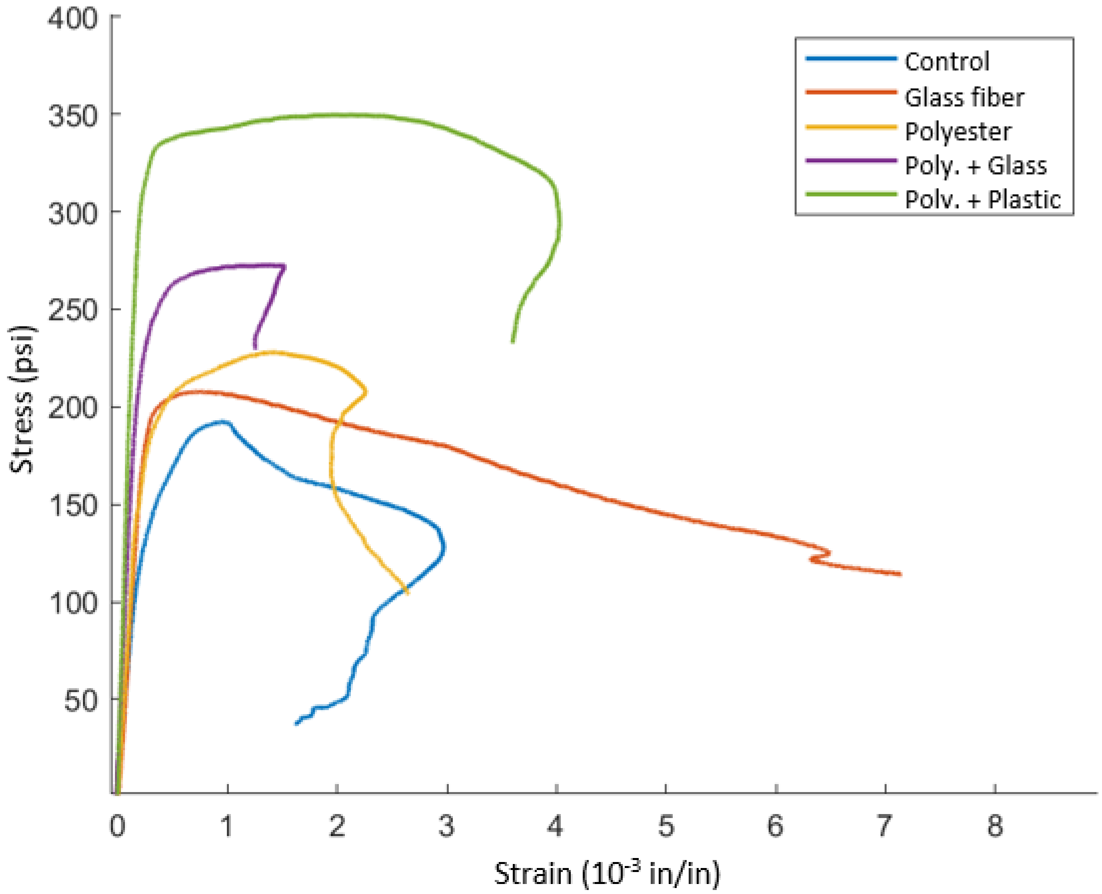

Figure 5. Stress-strain relationship after 7 days of cure for second set of mixes.

Table 8. Split tensile strength values at point of maximum stress recorded for the second set of mixes.

Split tensile strength at maximum stress Treatment	Mean (psi)	Std dev (psi)	Mean (MPa)	Std dev (MPa)	Std dev (%)	Stress relative to control	Strain	Strain relative to control
Control	192.30	19.06	1.33	0.13	10%	100%	0.00094	100%
Glass Fiber	207.87	15.14	1.43	0.10	7%	108%	0.00076	80%
Polyester	228.03	101.95	1.57	0.70	45%	119%	0.00141	150%
Poly. + Glass	272.58	64.78	1.88	0.45	24%	142%	0.00140	149%
Poly. + Plastic	349.54	101.80	2.41	0.70	29%	182%	0.00193	205%

Table 9. Split tensile strength values at point of failure recorded for the second set of mixes

Split tensile strength at point of failure Treatment	Mean (psi)	Std dev (psi)	Mean (MPa)	Std dev (MPa)	Std dev (%)	Stress relative to control	Strain	Strain relative to control
Control	125.00	16.12	0.86	0.11	13	100%	0.00281	100%
Glass Fiber	114.25	12.37	0.79	0.09	11	91%	0.00715	254%

Polyester	103.90	35.73	0.72	0.25	34	83%	0.00265	94%
Poly. + Glass	228.99	50.87	1.58	0.35	22	183%	0.00126	45%
Poly. + Plastic	232.12	88.25	1.60	0.61	38	186%	0.00360	128%

6 Conclusions

The experimental study has illuminated the effects of various additives on the compressive strength, elastic modulus, and tensile strength of concrete. While controlled laboratory tests indicated that the incorporation of polyester fibers and tire waste led to significant improvements—with increases of around 60% and 84% in compressive strength, and elastic modulus increases of 141% and 138%, respectively—these results should be interpreted cautiously for tire waste. The uniform distribution of tire waste achieved in a controlled setting may not be easily replicated in actual construction sites, potentially affecting the accuracy of these percentage increases.

In both sets of split tensile strength tests, all additives resulted in increased strength compared to the control mix. Notably, the first set saw increases of 17% for polyester fibers, 164% for glass fiber, and 130% for tire waste. However, the polyester fiber results showed a notably higher standard deviation, suggesting potential variability. In the second set of tests after 7 days, all mixes displayed higher maximum stress, ranging from 8% for glass fiber to 82% for the plastic and polyester combination. Strain at failure varied significantly among the mixes. Glass fiber exhibited the highest strain, 254% relative to the control, while polyester had a 94% increase, and the combined mixes ranged from 45% to 128% relative to the control.

These findings underscore the potential for specific waste materials and fibers to enhance the mechanical properties of concrete, providing opportunities for more sustainable and environmentally friendly construction materials. However, the results also highlight the complexity of these interactions, as not all waste materials contribute positively.

7 Recommendations

Further study is recommended to address the following issues:

- *Further Research on Plastic Waste*: Given the negative impact of plastic waste, further research should be conducted to determine if different types or proportions might yield more favorable results. Exploring various treatments or bonding agents might also enhance the compatibility of plastic waste with concrete.
- *Long-term Strength and Durability Tests*: To validate the initial findings, long-term strength and durability tests should be performed. This would provide insights into how these materials perform under sustained loads and environmental conditions.
- *Investigation of Cost and Environmental Impact*: An analysis of the cost-effectiveness and overall environmental impact of using these additives should be undertaken. This would ensure that the proposed solutions are not only technically viable but also economically and environmentally sustainable. In

particular, can this concrete be reclaimed at the end of life and does the presence of plastics in the concrete lead to increased microplastic emissions into the environment.

- *Development of Standards and Guidelines*: Based on the findings of further research, industry standards and guidelines could be developed for the use of these materials in construction. This would facilitate their broader adoption and ensure quality control.

In conclusion, the study opens promising avenues for enhancing concrete's mechanical properties through the use of specific waste materials and fibers. The results call for nuanced approaches, integrating further research, long-term testing, economic analysis, standardization, and industry collaboration to fully realize the potential of these innovative materials.

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