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EXPERIMENTAL INVESTIGATIONS ON FIBER REINFORCED CONCRETE FOR SUSTAINABLE CONSTRUCTION

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Abstract: The fundamental mechanical properties of concrete reinforced with PVC fibers are described in this work. Plastic fibers from clear PVC sheets were used to make six distinct concrete compositions. Of them, three combinations used PVC fibers measuring 20 mm in length, and the other three made use of PVC fibers measuring 40 mm in length. For every fiber length, the fiber concentration varied from 0% to 1.5% by weight of cement. Slump tests were performed to determine the workability of new concrete mixes. Compressive strength, splitting tensile strength, flexural strength and toughness, static elastic modulus, impact resistance, and toughness were all tested for the cured concretes. Examined was the impact of fiber length and content on workability as well as the previously stated mechanical qualities. Additionally, correlations between various mechanical parameters were investigated. The findings showed that for both fiber lengths, a higher fiber content was associated with worse workability. Elastic modulus, impact resistance, compressive strength, flexural strength, and toughness all increased up to 1% fiber content before declining at 1.5% fiber content. For splitting tensile strength, a similar pattern was noted, especially when using PVC fibers that were 20 mm long. Interestingly, compared to fiber length, fiber content had a greater influence on the mechanical characteristics of concrete. The highest overall performance was found when the fiber content was optimized to 1%. With the exception of splitting tensile strength, which only somewhat correlated with compressive strength, there were strong correlations found among the mechanical parameters that were examined.

Keywords: fiber-reinforced concrete; PVC fiber; compressive strength; splitting tensile strength;

elastic modulus; flexural strength and toughness; impact resistance and toughness

1. Introduction

Plastic garbage production is rapidly increasing on a worldwide scale. Because plastics' colors include a number of dangerous trace chemicals that take hundreds of years to break down, throwing them away instead of recycling them makes them hazardous waste [1]. What is even more alarming is the fact that millions of tons of plastic debris end up in the marine ecosystem every year, having a negative impact that has been extensively studied by experts [2]. In addition, plastic trash pollutes groundwater and presents serious problems for wastewater treatment plants [3]. With considerable benefits to raw material conservation and energy savings, plastic recycling may help mitigate the aforementioned problems and lessen the quantity of garbage dumped in landfills [4]. Many types of building materials may be made from plastic fibers. Rigid pavements, shotcrete tunnel linings, concrete overlays, blast-resistant concrete, polyethylene terephthalate (PET), polyester, nylon, aramid, and high- and low-density polyethylene (PE), polyvinyl alcohol (PVA), and polyvinyl chloride (PVC) are just a few examples of the various short plastic fiber types that have been used in structural concrete members [5]. Additionally, when combined with regular asphalt, they were found to be efficient in strengthening asphaltic concrete. Concrete is strengthened against cracking and has its tensile strength increased by the use of plastic fibers. According to earlier studies, plastic fibers can help concrete's compressive strength, tensile strength, fracture toughness, ductility, absorption capacity, and resistance to blast waves. By preventing cracks from propagating and passing through fractures, plastic fibers can transport internal stresses and increase the splitting tensile and flexural strengths of concrete [6].

The ability of concrete to withstand flexural stress is enhanced by the addition of plastic fibers. However, a number of studies found that adding plastic fibers to concrete decreased its compressive strength. According to Mohammed and Rahim [7], fractures arise from the different volume and length of plastic fibers creating holes and defects in the concrete matrix. Because the new concrete was not properly poured and compacted, Nili and Afroughsabet [8,9] found that the hardened concrete specimens had a comparatively high number of pores, which led to significant decreases in their compressive and flexural strengths. Concrete's declining tensile strength may also be caused by a poor fiber-cement matrix contact. In general, plastic fibers are supposed to increase the mechanical performance of concrete even under challenging exposure circumstances if the concrete is correctly mixed, poured, compacted, and cured. It was discovered that adding PP fibers to concrete reduces the flexural strength loss brought on by heat shock and high temperatures; Nevertheless, incorporating a large amount of plastic fibers into concrete raises the risk of a weak plane developing, which may negatively impact the overall behavior of the composite [10].

The majority of the study articles by the aforementioned scholars concentrated on the splitting tensile, flexural, and compressive strengths of concrete reinforced with plastic fibers. Comparatively, not much research has been done on how plastic fibers affect the hardness and impact resistance of concrete. Concrete containing PP fibers was studied for impact resistance by Bayasi and Zeng [11]. According to their research, concrete containing up to 0.5 vol.% of PP fibers significantly enhanced the impact resistance of the mixture. This was especially true for fibers measuring 12.7 mm in length.

This is because the fibers provide a three-dimensional mesh reinforcement by being able to intercept fractures and limit the spread of cracks inside the concrete matrix. Nevertheless, as the fiber volume level in concrete exceeded 0.5%, its impact resistance dropped. According to Foti and Paparella's [12] analysis of the concrete reinforced with PET strips, the impact strength was increased and the slab exhibited ductile behavior that prevented total failure. Additionally, In their analysis of the impact resistance of recycled plastic fibers, Soroushian et al. [13] found that the impact strength increased until the fiber aspect ratio reached 50, at which point it decreased. Greater impact strength was achieved at an aspect ratio of 50 due to the tight interlocking of fibers with aggregates, which reduced voids. From this angle, more investigation is required to fully comprehend the impact resistance of concrete reinforced with PVC fibers.

In conclusion, the examination of the literature showed that the majority of earlier research looked at the non-PVC plastic fiber-reinforced concrete's compressive, tensile, and flexural strength properties. Comparatively, not much study has been done on the impact resistance of concretes reinforced with PVC fiber and those that aren't. This study looked at the workability, splitting and compressive tensile strengths, flexural strength, toughness, and impact behavior of concrete reinforced with PVC fibers. The resistance of concrete to the initial fracture and its eventual collapse under repeated dynamic loads were evaluated in order to assess its impact performance. Furthermore, an investigation was conducted into the correlations among various mechanical parameters.

2. Materials and Methods

2.1. Constituent Materials

In this work, Portland composite cement (PCC) with a strength grade of 42.5 N was utilized. This cement took 160 minutes to set initially, and after three days, its early strength was 20 MPa. PCC has a specific gravity of 3.13. With a 0–5% gypsum concentration, it is composed of 65–79% clinker and 21–35% slag, fly ash, and limestone. According to ASTM C33/C33M−18 requirements, coarse river sand (4.75 maximum size) and crushed stone (19 mm nominal maximum size) were employed. While crushed stone was used as coarse aggregate (CA), river sand was used as fine aggregate (FA). The aggregates' primary physical characteristics and particle size distributions are shown in Table 1, respectively. The concrete mixes were prepared using regular tap water in addition to cement and aggregates. Additionally, tiny plastic fibers were cut from transparent PVC sheets (0.45 mm thick) that were gathered from a nearby clothing industry. The fibers had a width of 2 mm and lengths of 20 and 40 mm. By weight of cement, they were included into the concrete compositions. In all concrete formulations, a third-generation superplasticizer based on polycarboxylate and having a specific gravity of 1.07 was also utilized.

Table1. Physical properties of aggregates.

Physical Properties	**FA (River Sand)**	**CA (Crushed Stone)**
Fineness modulus	3.05	7.50

Unit weight (kg/m^3)	1778	1535
Voids (vol.%)	31.06	38.96
Bulk specific gravity (OD *)	2.50	2.50
Bulk specific gravity (SSD †)	2.58	2.51
Apparent specific gravity	2.73	2.54
Absorption (wt.%)	3.03	0.60

2.2. Mixture Proportions

ACI Committee 211.1 [14] was followed in the mixture design of the concretes in order to achieve the desired compressive strength of 20 MPa. We determined the water-to-cement ratio to be 0.58. Seven different concrete mixes were made, varying in the amount of PVC fiber per weight of cement from 0% to 1.5%. One weight percent of cement was added to the polycarboxylate-based superplasticizer in order to render the concrete mixes suitable for the casting of test specimens.

2.3. Methods for Testing

2.3.1. Workability Test

In compliance with ASTM C143, the slump test was used to evaluate the freshly mixed concretes' workability [15]. A flat, stable platform was used to set up a slump cone, and three layers of concrete sample were poured into it. Using the designated rod, the individual concrete layer was compacted by tamping it 25 times. Slump was measured by taking the vertical displacement between the concrete sample's beginning and final heights.

2.3.2. Compressive Strength, Splitting Tensile Strength, and Static Elastic Modulus Tests

A cylinder specimen of about 100 mm by 200 mm was subjected to tests for splitting tensile strength, static elastic modulus, and compressive strength. For the compression and splitting tension tests, specimens were utilized in triplicate, whereas the elastic modulus test used duplicate specimens. Before testing, every prepared specimen was constantly water-cured in a curing tank for 28 days. for figuring out the elastic modulus that is static.

2.3.3. Flexure Strength and Toughness Test

According to ASTM C293/C293M, simple beam specimens of 150 mm by 150 mm by 600 mm were constructed and evaluated for flexural strength and load-deflection behavior. For every concrete, three beam specimens underwent testing. A dial gauge was positioned at the center bottom line of the beam specimen to measure the mid-point deflection. The toughness of concrete was estimated graphically by calculating the area beneath the load-deflection behavior diagram.

2.3.4. Impact Resistance and Toughness Test

According to the test protocol established by ACI Committee 544 [16], duplicate Ø150 mm × 62.5 mm cylinder specimens were used to evaluate the impact resistance of concrete. A standard compaction hammer weighing 4.5 kg and with a drop of 45.7 cm, a steel ball with a diameter of 65.3 mm, and a positioning mechanism to hold the specimen were all part of the test apparatus. In order to conduct the experiment, it was necessary to repeatedly drop the hammer on top of the concrete specimen while closely monitoring the specimen's development of fractures and final failure. Both the total number of hammer blows required until the final failure occurred and the number of blows required before the first fracture emerged were recorded.

3. Results and Discussion

3.1. Workability of Concretes

Slump values were used to evaluate the workability of different concrete mixes. The 75–100 mm planned slump range was used. Slump rose to 140 mm when 1 weight percent of a polycarboxylate-based superplasticizer was added to the control concrete. Lower slump values are indicative of a deterioration in workability caused by the introduction of PVC fibers. When PVC fibers (20 mm and 40 mm lengths) were added up to 1 weight percent, the droop reduced to 80–95 mm and stayed within the intended range. At 1.5 weight percent, there was a noticeable decrease in droop, with 20 mm fibers showing the largest drop. Increased water requirement from a higher fiber concentration limits mortar fluidity, which impedes concrete flow [8]. Additionally, smaller fibers require more water, and PVC fibers may cluster at greater concentration, which further lessens droop. In this study, it is advised to employ PVC fibers up to 1 weight percent of cement for maximum workability.

3.2. Compressive Strength of Concretes

Slump values were used to evaluate the workability of different concrete mixes. The 75–100 mm planned slump range was used. Slump rose to 140 mm when 1 weight percent of a polycarboxylate-based superplasticizer was added to the control concrete. Lower slump values are indicative of a deterioration in workability caused by the introduction of PVC fibers. When PVC fibers (20 mm and 40 mm lengths) were added up to 1 weight percent, the droop reduced to 80–95 mm and stayed within the intended range. At 1.5 weight percent, there was a noticeable decrease in droop, with 20 mm fibers showing the largest drop. Increased water requirement from a higher fiber concentration limits mortar fluidity, which impedes concrete flow. Additionally, smaller fibers require more water, and PVC fibers may cluster at greater concentration, which further lessens droop. In this study, it is advised to employ PVC fibers up to 1 weight percent of cement for maximum workability.

Table 2. Compressive, splitting tensile, and flexural strengths along with the elastic modulus and flexural toughness of different concretes.

Mixture Designation	PVC Fiber		Compressive Strength (MPa)	Elastic Modulus (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Flexural Toughness (N-mm)
	Fiber Length (mm)	Fiber Content (wt.%)					
Control	-	0	21.40	19,462	2.55	4.69	2887.45
PVCFRC 1	20	0.5	25.00	26,800	2.80	5.69	6467.63
PVCFRC 2		1	26.80	27,062	2.90	6.25	8385.51
PVCFRC 3		1.5	20.50	25,614	2.76	5.52	6410.53
PVCFRC 4	40	0.5	23.20	26,167	2.87	5.21	5951.22
PVCFRC 5		1	25.70	26,899	2.82	6.04	8109.57
PVCFRC 6		1.5	22.10	26,071	2.74	5.60	6810.15

3.3. Elastic Modulus of Concretes

One important characteristic of concrete that shows its capacity to withstand strain is the elastic modulus, or Ec. Table 2 displays the impact of PVC fibers on the static elastic modulus of various concretes. A reduction in the modulus of elasticity was discovered after a few investigations into the modulus of elasticity of plastic fiber-reinforced concrete. On the other hand, several researchers also discovered an increase in the elastic modulus. The elastic modulus of concrete was found to be improved by PVC fibers up to a 1 weight percent fiber content in this investigation. In comparison to the control concrete, the highest increase in elastic modulus for each length of PVC fibers happened at a 1 weight percent fiber concentration. Conversely, the concrete containing 1.5 weight percent of 20 or 40 mm long PVC fibers had a decrease in its elastic modulus; nonetheless, it remained greater than that of the control concrete. The same explanations that were covered in the case of compressive strength are responsible for this influence of PVC fibers on the elastic modulus of concrete. Additionally, as can be seen from the compressive strength data, the addition of fibers reduces pre-cracked elastic deformation and hence increases the load-carrying capacity of concrete [7]. This also leads in an increase in the static elastic modulus.

3.4. Splitting Tensile Strength of Concretes

Because fibers have a stronger strength under tension than other materials, they may efficiently transfer the tensile stress from weaker and fractured places to themselves, which often improves the splitting tensile strength of concrete. The splitting tensile strength of concrete was shown to be greatly increased by non-PVC plastic fibers, according to several previous investigations. Table 2 displays the splitting tension test findings as well as the PVC fibers' related impact that was noted throughout this investigation. According to the test findings, the concrete with the maximum splitting tensile strength was that which contained 1 weight percent of 20 mm long PVC fibers. In contrast, the addition of 40 mm long PVC fibers resulted in a modest reduction in splitting tensile strength beyond 0.5 weight percent fiber content. For 20 mm long PVC fibers, the splitting tensile strength increased by around 13.7% at 1 weight percent fiber content. The perpendicular fibers in the specimen's dividing section serve as bridges to allow stress to be transferred between the concrete components. Consequently, when the tensile strength of fiber-reinforced concrete increases, the tensile stresses that were created in the splitting section are gradually maintained [19]. Moreover, the proportion of splitting tensile strengths to compressive strengths. This proportion ranges from 7.4% to 9.2%. For both 20 mm and 40 mm long PVC fibers, the 1 weight percent fiber content showed the greatest percentage. Furthermore, it was observed that the aforementioned percentage increased for PVC fibers 20 mm in length as opposed to 40.

3.5. Flexural Strength and Toughness of Concretes

The load-deflection characteristics of various concretes were analyzed using beam specimens subjected to center-point loading, revealing a post-peak deflection-softening behavior in all PVC fiber-reinforced concretes. Notably, concrete reinforced with 20 mm PVC fibers exhibited a higher flexural peak load than that reinforced with 40 mm fibers, especially at 0.5 wt.% and 1 wt.% fiber contents. Load-carrying capacity and deflection increased up to 1 wt.% fiber content, but a reduction occurred beyond that. Despite this, concrete beams still showed significant post-peak deflection compared to control beams, indicating increased ductility with PVC fibers. Flexural strength increased with higher fiber content, rising by 33.3% and 28.9% for 20 mm and 40 mm fibers, respectively, at 1 wt.%. The increase remained below 20% at 1.5 wt.% but remained significantly higher than the control concrete. The enhanced flexural strength was attributed to PVC fibers resisting cracks in the tension zone, effectively distributing the load, and improving energy absorption and stress relaxation. Flexural toughness (Tf) values, calculated from load-deflection curves, increased with PVC fibers. A range of 122% to 190.4% increase was observed for 20 mm fibers (0.5–1.5 wt.%), and 106.1% to 180.9% increase for 40 mm fibers. The optimum PVC fiber content for the highest increase in flexural toughness was found to be 1 wt.%.

3.6. Impact Resistance and Toughness of Concretes

Few research have looked at how plastic fibers affect concrete's toughness and resistance to impact. Using the test equipment that the ACI committee 544 proposed, the current study evaluated the impact resistance and hardness of different PVC fiber-reinforced concretes. The average number of blows needed during impact testing to for the concrete specimens to fail and show visible cracks for the first time. Concrete's impact resistance has been improved as a result of the use of PVC fibers. As the concrete specimens needed the most blows before the first apparent break and final failure, it was determined that the ideal fiber content for both 20 mm and 40 mm long PVC fibers was 1 weight percent.

3.7. Correlations among Mechanical Properties of Concretes

The study aimed to comprehend the interdependencies inside PVC fiber-reinforced concrete by examining correlations between its various mechanical characteristics. There was a strong power connection between the elastic modulus and compressive strength, as evidenced by the high correlation value ($r = 0.9911$). Comparably, flexural and compressive strengths showed a strong linear association ($r = 0.9980$). There was an exponential relationship ($r = 0.9246$) between compressive strength and impact resistance. Flexural strength, flexural toughness, impact resistance, and impact toughness were also shown to have substantial correlations; the former showed an exponential connection ($r = 0.9751$), while the latter showed a linear correlation ($r = 0.9824$). The interconnectedness of the mechanical characteristics of PVC fiber-reinforced concrete is highlighted by these correlations, which offer important information for structural design and material optimization.

4. Conclusions

The mechanical performance of PVC fiber-reinforced concrete was evaluated in this work, with particular attention paid to its compressive, splitting tensile, flexural, and impact behaviors. The following are some important findings from the experimental investigation:

- Workability, as determined by slump, dropped when 20- and 40-mm long PVC fibers were added, reaching 80–95 mm at 1 weight percent. Because there was more water required to moisten the material surfaces, there was a noticeable reduction in slump at 1.5 weight percent, especially with 20 mm fibers.
- With 1 weight percent PVC fibers, the performance of the concrete was at its best, showing excellent splitting tensile, flexural, impact resistance, flexural, and impact toughness. This improved performance was facilitated by the PVC fiber-reinforced concrete's greater ductility and energy absorption capability.
- Mechanical characteristics decreased beyond 1 weight percent because to limited workability, which led to fiber aggregation and air spaces. Even at 1.5 weight percent, PVC-infused concrete performed better than the control.
- During flexural testing, PVC fibers enhanced the ductility of the concrete, as seen by the post-peak deflection.
- Fiber length had less of an effect on mechanical qualities than fiber content. For both lengths, the ideal fiber content was found to be 1 weight percent.
- There were significant relationships found between impact resistance, flexural strength, and elastic modulus and compressive strength. Nonetheless, a weak link between splitting tensile strength and compressive strength was discovered. There were excellent relationships found between ultimate impact resistance and flexural strength, as well as between flexural toughness and ultimate impact toughness.

Although the study offers insightful information, it is not without limits. Future studies might examine the characteristics of PVC fibers and possible chemical treatments for better adherence, which would expand our knowledge of the behavior of fiber-reinforced concrete. Notwithstanding these drawbacks, the study advances the area and offers ideas for new lines of inquiry.

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