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Assessment of Concrete Compressive Strength with Polyacrylonitrile and Basalt Fibers

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Abstract The use of concrete in construction has remained relevant over time. However, advocates for sustainable construction and structural innovation prove that there could be more in concrete. Studies have particularly focused on improving its durability and strength. In line with these, this study aims to evaluate the compressive strength of M25 and M50-grade concrete cylinders reinforced with basalt and PAN fibers. Moreover, it aims to design and test fiber mixtures, assess their sustainability, and develop a structural model to optimize performance. The researchers first determined the properties of polyacrylonitrile and basalt fibers subjected to test and compare theoretical models. Then, the researchers performed a structural performance optimization of fiber-reinforced concrete. Concrete specimens have been cured and tested in compression through the Universal Testing Machine (UTM). Aiding in the gathering and analysis of data, the study adopted descriptive statistics, central tendency measures, student t-tests, and cost-benefit analysis as statistical treatments. Four simulations were run, and variables such as Poisson's ratio and Young's modulus were held constant due to limitations in equipment and literature. The garnered concrete compressive strengths concluded with their reduction, specifically found in specimens with added PAN and basalt fibers. Stress simulations and structural models also validated this reduction. Furthermore, fiber-reinforced concrete was more costly with the addition of required steel rebars, thus increasing the cost of materials. It was also found that these fibers provided no structural benefit, as the statistical analysis showed no significant difference between fiber-reinforced and regular concrete mixtures. In addition, they could not enhance crack resistance and durability. Since material selection and production monitoring are as essential as fiber dispersion and curing conditions, engineers focus on these variables as they affect performance. This meant higher construction costs due to the reduced compressive strength of the concrete. With these, the researchers recommend further studying PAN and basalt fiber to clarify their effect on compressive strength. Furthermore, long-period evaluation must be done on fiber-reinforced concrete's structural durability for environmental conditions.

Keywords M25 and M50 Concrete Grade, Sustainability of Polyacrylonitrile and Basalt Fiber, Structural Analysis and Design Software

1. Introduction

Integrating fibers into concrete marks a transformative step forward in construction materials, addressing the mechanical shortcomings of traditional concrete and the pressing environmental concerns of modern infrastructure. These fibers enhance concrete's structural performance and contribute to sustainable building practices, making them a

compelling choice for future construction projects.

1.1. Polyacrylonitrile (PAN) & Basalt Fibers

PAN fibers are recognized for their high tensile strength and elastic modulus, significantly improving the compressive strength, fracture resistance, and overall toughness of concrete. A 2021 study highlights PAN's ability to enhance stress-strain behavior, reduce brittleness, and increase ductility, particularly when combined with recycled aggregates (RA) instead of natural aggregates (NA). This makes PAN fibers versatile in improving concrete performance in various applications [1].

On the other hand, basalt fibers, derived from volcanic rocks, offer exceptional tensile strength (up to 5000 MPa), elastic moduli ranging from 90 GPa to 120 GPa, and remarkable resistance to corrosion and thermal degradation. These properties make basalt fibers a sustainable and high-performance alternative to traditional reinforcements like steel. Their energy-efficient production process and recyclability further enhance their appeal as an eco-friendly material [2, 3].

1.2. Polyacrylonitrile (PAN) & Basalt Fibers in Concrete

Studies consistently demonstrate the benefits of incorporating PAN and basalt fibers into concrete. For instance, fiber-reinforced concrete with 1-1.5% fiber content shows significant improvements in compressive strength and ductility, particularly in high-strength applications such as M50-grade concrete [4, 5]. Basalt fibers have been shown to increase tensile strength by up to 34.45% and compressive strength by 23.8%, making them ideal for applications requiring enhanced durability and mechanical reliability [6].

While PAN fibers have some limitations in thermal resistance, they perform well under freeze-thaw cycles and fatigue conditions, further proving their adaptability in fiber-reinforced concrete [7].

Beyond mechanical improvements, the environmental advantages of PAN and basalt fibers are equally noteworthy. Basalt fiber production has a minimal ecological footprint, utilizing abundant volcanic rock resources without chemical additives. Incorporating basalt fibers into concrete reduces life-cycle emissions and enhances resistance to autogenous shrinkage, chloride penetration, and abrasion, thereby extending the material's service life [8].

Similarly, PAN fibers contribute to sustainability by reducing reliance on non-renewable resources. They can be sourced from recycled materials, supporting eco-friendly construction practices and lowering the environmental impact of concrete production [9].

It is important to note that the self-compaction of high-strength concrete is significantly influenced by the properties and proportions of its components, yet it often falls short of its designed compressive strength due to various internal and external factors affecting its structure and curing process. M50 concrete, intended for a compressive strength of 50 MPa, may fail to reach this target due to embrittlement, incorrect mix proportions, and external mechanisms such as carbonation, freeze-thaw cycles, and sulfate attacks, which accelerate microstructural deterioration and weaken the bond between aggregate and cement paste [10]. Poor curing conditions, including insufficient moisture retention and exposure to extreme temperatures, hinder hydration and prevent full strength development. Variations in cement type, inconsistency in the water-cement ratio, improper admixture dosage, and batching inaccuracies further contribute to strength deviation, often resulting in M50 concrete achieving barely 40 MPa in real applications [11]. Additionally, poor aggregate quality and improper mix designs significantly impact compressive strength, as aggregates with uneven grading, excessive fineness, or high moisture content disturb the internal matrix, weakening bonding and strength development [12]. An excessive water-cement ratio creates voids, increasing the likelihood of cracking, while long-term fluctuations in temperature and moisture levels exacerbate internal stresses, leading to microcracking and deterioration. Implementing rigorous quality control during manufacturing, installation, and curing is crucial to ensuring the desired performance of high-strength concrete mixtures.

High-strength concrete aims to achieve ultra-high compressive strength, but the addition of basalt fibers (BF) can sometimes negatively impact this property. Studies have shown that while BFs improve tensile and flexural strength, they often have little to no positive effect on compressive strength and can even cause reductions under certain conditions. A 2023 study noted that higher BF dosages reduce flowability, requiring more water and paste, which leads to delayed strength development [13]. One study found that excessive BF content, especially at 0.40% to 0.50% volume with 24 mm fibers, caused clumping and balling, resulting in inconsistent or decreased compressive strength [14]. Furthermore, another study also observed that in M50 grade concrete, increasing BF concentration to 0.9% initially enhanced tensile and flexural strength but eventually led to compressive strength reductions due to fiber buildup and nonuniform distribution [15]. Moreover, a recent study highlighted that beyond the optimal 1.5% fiber concentration, fiber agglomeration created localized stiffness and poor bonding, which induced microcracking and stress concentration, further compromising compressive capacity [4].

Other studies have also studied the integration of PAN and Basalt Fibers with other fibers and design mixtures. Table 1 is made to summarize the different findings from each respective design mixture and its integrated fibers.

Table 1. Material Quantity per Specimen

Design Mixture	Fibers	Percentage of Fibers Incorporated	Results
C30	Basalt Fiber & Polypropylene (PPTF) Fiber	0.3%, 0.6%, 0.9% and 1.2%	Decrease in compressive strength: • Basalt fiber- 9%, 19%, 1%, and 18% respectively • Polypropylene fibre -8%, 7%, 17% and 24% respectively
C40	Steel Fiber & Basalt Fiber	S15B6 • 1.5% Steel • 0.6% Basalt S15B20 • 1.5% Steel • 2.0% Basalt	S15B6 (3 samples) • Compressive strength increased by 5.9%, 7.17%, and 6.75% compared to C40. S15B20 (3 samples) • Compressive strength decreased by 35.12%, 22.61% and 33.60% concerning C40
M30 & M60	Basalt Fiber	1.5% (12mm:30mm) • 100:0 • 75:25 • 50:50 • 25:75 • 10:100	The hybrid fiber volume fraction of 1.5% with a 25-75 basalt fiber combination of 12mm to 30mm exhibits a considerable increase in compressive strength, amounting to 1.29% and 4.48% for M30 and M60, respectively. A 3.63% and 2.81% decrease was observed for M30 and M60, respectively, with only 12 mm of basalt fiber. A 6.22% and 5.231% decrease was observed for M30 and M60, respectively, with only 30 mm of basalt fiber.
C55	Polyacrylonitrile (PAN) Fiber & Basalt Fiber	Basalt: 0.15% PAN: 0.09%	The splitting tensile performance of concrete for basalt fiber is up to 5.5%, and 12.9% for polyacrylonitrile (PAN) fiber. The flexural peak value is up to 18.3% for basalt fiber, and 29.9% for polyacrylonitrile (PAN) fiber. The compressive strength of the axial center is increased by −3.9% for basalt fiber, and 2.8% for polyacrylonitrile fiber.
C30	Polyacrylonitrile (PAN) Fiber & Polypropylene (PPTF) Fiber	PAN: 0.15% PPTF: 0.15%	The compressive strength decreased. F0(without adding): 65.60 MPa F1 (⅙): 53.97 MPa F2 (2/6): 61.91 MPa F3 (3/6): 55.82 MPa F4 (4/6): 57.26 MPa F5 (⅚): 50.40 MPa F6 (6/6): 48.27 MPa

In the first study, the addition of polypropylene and basalt fibers to a concrete mix impacts compressive strength to varying extents. However, the optimal proportions for increasing splitting tensile strength have been discovered to be 0.6% for basalt fiber and 0.3% for polypropylene [16].

Secondly, a difference in compressive strength is observed between S15B6 and S15B20. Although the steel fibers were kept constant at 1.5%, the compressive strength differences were significantly impacted by the volume fraction of basalt fibers [17].

Another study demonstrated that the compressive strength increases and decreases depending on the dimension of the basalt incorporated. The use of basalt fibers did not significantly improve compressive strength values. Hence, given the same amount of basalt fiber content, the compressive strength of hybrid fiber-reinforced samples of varying lengths is much better than that of samples integrated with single-length fibers [18].

Furthermore, the incorporation of fibers can significantly improve the mechanical properties of the concrete matrix, such as splitting tensile and bending toughness, but, at the same time, it also reduces the compressive strength of the concrete matrix to a certain extent. Based on all the experimental data and calculation results, the optimal blending amounts of basalt and polyacrylonitrile fiber obtained in this paper are VB = 0.15% and VP = 0.11% [19].

Lastly, the results from 2020 study showed that the compressive strength of concrete test blocks decreased with the increase of the thickness of PAN-PPTF concrete, but the split-tensile strength and bending strength of test blocks both increased. When PAN-PPTF concrete was 1/3 of the test block, the compressive strength decreased by 5.62%, but the split-tensile strength increased by 36.08%, and the bending strength increased by 38.48% [20].

1.3. Fibers in Structural Analysis & Design Software

Structural Analysis and Design Software further amplifies the advancements in fiber-reinforced concrete—tools like STAAD.Pro and ETABS, supported by ACI 318-11 standards and NSCP 2016, enable precise assessments of compressive strength, fracture resistance, and load distribution [21, 22]. Integrating machine learning algorithms with these software tools has enhanced predictive accuracy, allowing for more efficient and refined structural evaluations [23]. This hybrid approach is particularly valuable for optimizing the performance of fiber-reinforced materials, bridging the gap between innovative materials and sustainable engineering solutions [24].

2. Objectives

The research's main objective is to investigate the Compressive Strength of the Concrete Cylinder Integrated Polyacrylonitrile fiber and Basalt fiber.

Specifically, the study will address the following:

1. Design, mix, and test the additive impact of Polyacrylonitrile and Basalt Fiber with the M25 and M50 concrete grade mixtures;
2. Evaluate and contrast the sustainability of polyacrylonitrile and basalt Fiber with traditional concrete mixtures; and
3. Model and analyze structural columns using Structural Analysis and Design Software to generate a cost-benefit analysis on the mix ratios tested.

3. Scope and Limitations

This study focuses on optimizing the compressive strength of Grade M25 and M50 concrete cylinders by integrating polyacrylonitrile and basalt fibers while also conducting a comparative evaluation of their sustainability implications in concrete mixtures. Additionally, structural models are developed to analyze applied loads, assessing the benefits, feasibility, and cost-effectiveness of fiber-reinforced concrete.

However, the study presents certain limitations. It primarily investigates compressive strength and does not extensively analyze other mechanical properties, such as tensile strength or flexural behavior. Also, only one optimal fiber ratio was used from a referenced study [25]. The sustainability evaluation mainly focuses on environmental factors, potentially overlooking broader socio-economic considerations. And, only the short-term behavior was analyzed due to the short study duration. Lastly, constraints related to data availability, computational resources, and the complexity of structural model development may affect predictive accuracy.

4. Methods

To see their impact, this study involves creating two types of concrete mixes, with and without fibers. The research combines laboratory tests with modern computer techniques to connect theory and real-world applications. It also looks at fiber-reinforced concrete's cost-effectiveness and environmental impact, aiming to advance sustainable construction methods. This study assesses how Polyacrylonitrile and Basalt Fibers affect the strength and sustainability of M25 and M50 concrete mixes.

Figure 1 presents the conceptual framework, detailing the various phases and corresponding steps that summarize the methodology section.

4.1. Research Design

The researchers will use a systematic experimental procedure to assess concrete mix components, fibers such as polyacrylonitrile and basalt, and equipment needed, including cylindrical molds and a compression testing machine. Specifically, all the controlled variables, such as concrete mix proportions, curing conditions, and testing protocols, will be adhered to systematically to enhance analysis. Furthermore, control samples of concrete will be included alongside concrete samples integrated with PAN and basalt fibers, using the M25 and M50 concrete mix ratios. Subsequently, compression tests will be performed on concrete to assess and determine compressive strength. As a result, the statistical analysis will be conducted to enhance the comparison of results between all specimens.

4.2. Research Setting

The assessment will take place at Mapúa University, which is situated in Intramuros, Manila, Philippines, at 658 Muralla St. Here, the researchers conducted literature reviews, meetings, and modifications based on adviser recommendations. Furthermore, all the necessary testing and forming of concrete cylinders will also be undertaken. The goal of this study, which is being carried out at Mapúa University, is to gain an improved grasp of how emerging substances can affect the structural properties of concrete. This knowledge could have an impact on future building methods and material choices for applications in civil engineering.

4.3. Methodology

4.3.1. ACI M25 & M50 Mix Design

In preparation of concrete specimens, the researchers utilized ACI mix design methodology for proportioning cement, water, and aggregates. Following the said mix design methodology, what can be found in Table 2 is the required number of materials by weight for each specimen – note that one specimen accumulates into a meter cube of right cylindrical volume.

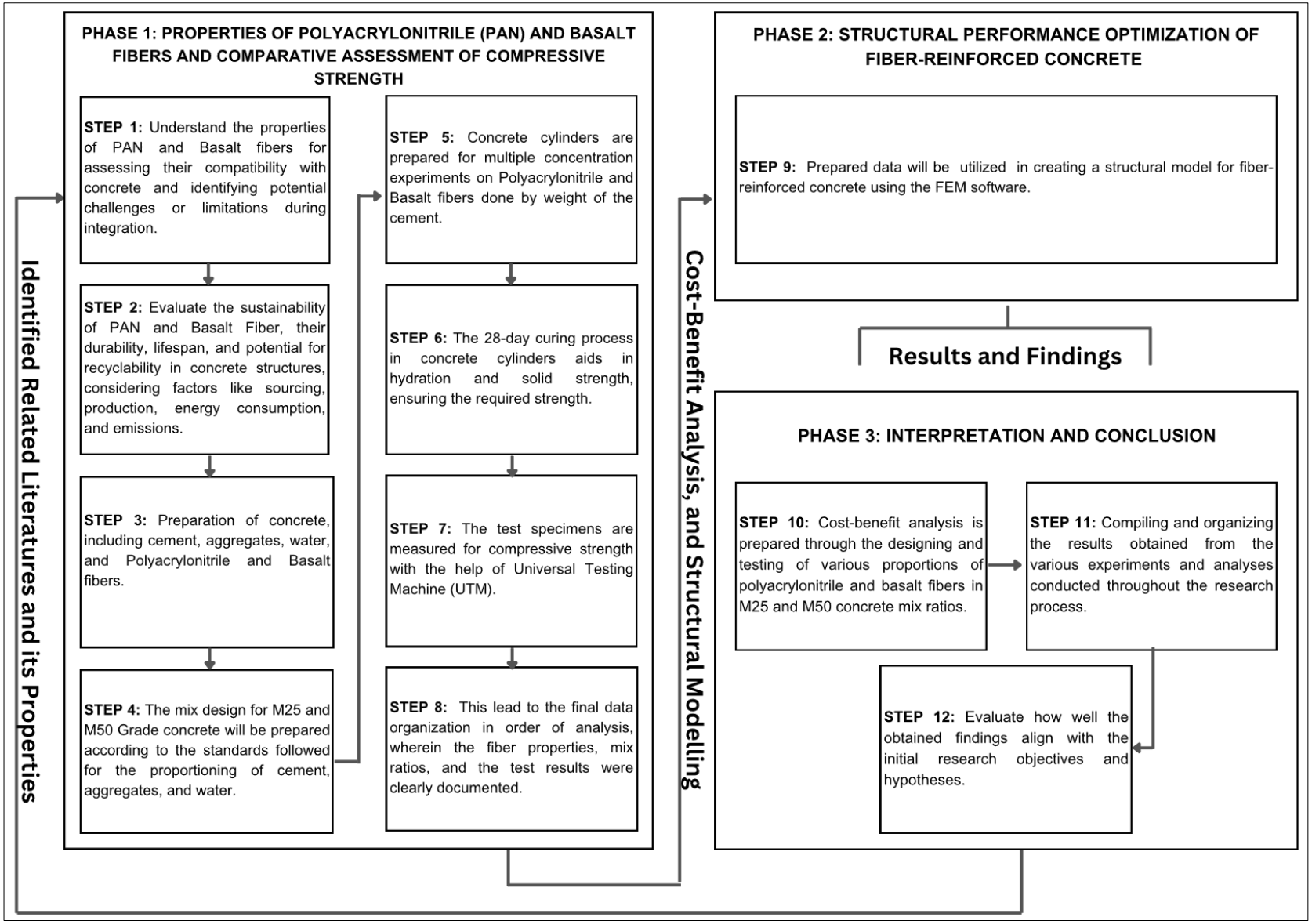

Figure 1. Conceptual Framework

Table 2. Material Quantity per Specimen

Mix Design	Materials	Quantity (in kg)
M25 w/ Fiber	Cement	2.0200
	Water	1.0700
	Sand	2.3500
	Gravel	7.9000
	Polyacrylonitrile Fiber	~0.0190
	Basalt Fiber	~0.0140
M25 w/o Fiber	Cement	2.0200
	Water	1.0700
	Sand	2.3500
	Gravel	7.9000
M50 w/ Fiber	Cement	3.3600
	Water	1.0700
	Sand	0.9400
	Gravel	7.9000
	Polyacrylonitrile Fiber	~0.0190
	Basalt Fiber	~0.0140
M50 w/o Fiber	Cement	3.3600
	Water	1.0700
	Sand	0.9400
	Gravel	7.9000

With the base mix established, polyacrylonitrile and basalt fibers will be added to the mix in volume percentages. The highest compressive strength included a volume fraction of 0.4% with a mixture of 75% and 25% of the fibers, the latter being utilized as Basalt fiber [25].

Curing the sample for 28 days, concrete cylinders are placed in water for curing, which assists the hydration process and allows the cement to attain solid strength. Proper curing is essential to ensure that the concrete achieves the necessary stability. If curing is not done correctly, it can lead to misleading results, making the concrete seem weaker.

4.3.2. UTM Concrete Compressive Testing

After curing, the test specimens are measured for compressive strength with the help of a Universal Testing Machine (UTM). The machine applies an incremental load to the cylinder until it fails, and the data is taken regarding the maximum load it can bear.

Testing for compressive strength is the primary measure by which concrete's ability to bear structural loads is assessed. The results will answer how diverse types and percentages of fibers affect the load-carrying capacity of concrete.

4.3.3. STAAD.Pro Concrete Column Design & Analysis

Data from the UTM Concrete Compressive Testing will be used in the STAAD.Pro design and analysis of concrete column. Utilizing the average maximum compressive strengths of each mix design, four simulations will be done, one for each mix design.

Due to the limitations on the scope of the study, laboratory equipment, and time, Table 3 summarizes the variables that remained constant throughout all simulations.

Table 3. STAAD.Pro Material, Section, and Load Values

Variable	Value
Young's Modulus (E)	23500000 kN/m^2 (for M25) 33234020 kN/m^2 (for M50)
Poisson's Ratio (n_u)	0.17
Density	23.5616 kN/m^3
Thermal Coefficient (a)	1e-05/ºC
Critical Damping	0.05
Shear Modulus (G)	10042735.04 kN/m^2 (for M25) 14202572.65 kN/m^2 (for M50)
FYMAIN *[yield strength for main reinforcement steel]*	414MPa
REINF *[select 0 (for the tied column) or 1 (for the spiral column)]*	0
Ultimate Load Applied	5000kN + SW
Concrete Area Provided	250000 mm2

Utilizing ACI 318-11, in line with NSCP 2015, the STAAD.Pro Concrete Column Design & Analysis will provide the researchers with the required steel area for each mix design, considering the load applied and the limited concrete area.

4.3.4. Cost-Benefit Analysis

Built from the STAAD.Pro Concrete Column Design & Analysis, the required steel area, will be the main deciding factor for the cost-benefit analysis of the study.

A cost-benefit analysis is crucial in the assessment of these fibers with concrete. It will give us an idea of the potential increase or decrease in material quantity and costs.

5. Results & Discussion

5.1. Objective 1: Effect of Basalt and Polyacrylonitrile (PAN) Fibers

The researchers' UTM compressive testing, shown in Table 4, summarizes each specimen's average compressive load capacity.

Table 4. UTM Testing Summary

Specimens	Average Compressive Capacity (in MPa)
M25 w/ Fiber	21.6026
M25 w/o Fiber	21.6600
M50 w/ Fiber	25.6010
M50 w/o Fiber	27.9789

The combination of basalt and polyacrylonitrile (PAN) fibers showed a nice balance of strengths, with both fibers boosting tensile strength and crack resistance, while the latter further added ductility and flexibility. However, the experiments revealed a slight compressive strength drop for M25 and M50 concrete mixes. For the M25 mix, adding the fiber blend led to a 0.26% decrease in compressive strength, from 21.6600 MPa to 21.6026 MPa. For the M50 mix, the reduction was more noticeable at 8.49%, with strength dropping from 27.9789 MPa to 25.6010 MPa compared to the control samples without fibers. These findings imply that the integration of fibers led to a lower compressive capacity compared to their conventional design mixes.

Moreover, the Student's T-test, with a 5% significance level, shows that the difference is not statistically significant. The specific values computed for each case are in Tables 5 and 6.

Table 5. Computed Data & Values for M25 T-test Analysis

Data		
Group	w/o Fiber	w/ Fiber
Mean	21.659950	21.6026
SD	0.575373	1.0030
SEM	0.406850	0.7093
N	2	2
T-Test Computational Values		
t		0.0702
df		2
standard error of difference		0.8180
difference between means of the two groups		0.0574
95% confidence interval		-3.5755 to 3.4607
two-tailed P value		0.9504

Table 6. Computed Data & Values for M50 T-test Analysis

Data		
Group	w/o Fiber	w/ Fiber
Mean	27.978850	25.6010
SD	5.300967	3.8788
SEM	3.748350	2.7427
N	2	2
T-Test Computational Values		
t		0.5120
df		2
standard error of difference		4.6450
difference between means of the two groups		2.3779
95% confidence interval		-22.3620 to 17.6063
two-tailed P value		0.6596

The decrease in compressive strength due to the integration of Basalt and PAN fibers is consistent with the results found from other studies. Exploring other design mixes, as well as fiber proportions, generally led to a decrease in compressive capacity.

5.2. Objective 2: Sustainability Assessment of Basalt and Polyacrylonitrile (PAN) Fibers

The results in Objective 1 indicated that the incorporation of fibers increased material costs, raising concerns about economic feasibility. The fiber-reinforced concrete does not improve durability and resistance to cracking with the addition of fibers. The Post-Failure Analysis implied larger and dispersed cracks, which suggests less significant gap bridging. It maximizes crack propagation, resulting in deteriorated environmental resistance.

Furthermore, the noticeable difference between the expected strength of 50MPa and the actual strength garnered of 27.9789MPa for M50 concrete mix, as well as the difference for the M50 with fiber mix, could be attributed to various factors such as poor curing conditions, poor aggregate quality, and improper mixing conditions [11, 12]. These parameters demonstrate the complexity of acquiring the required compressive strength and how different variables affect concrete's functionality.

Table 7. Steel Area Requirements for Each Specimen Case

Specimens	Compressive Strength	Ultimate Load Applied	Concrete Area Provided	Steel Area Required
M25 w/ Fiber	21.6026	5000kN + SW	250000 mm^2	12843.7000 mm^2
M25 w/o Fiber	21.6600			12814.5000 mm^2
M50 w/ Fiber	25.6010			10788.9000 mm^2
M50 w/o Fiber	27.9789			9549.8000 mm^2

5.3. Objective 3: Modelling Using Structural Analysis and Design Software

Utilizing data garnered from Objective 1, Table 7 shows the summary of results from the STAAD.Pro ACI 318-11 concrete column analysis.

The structural models analyzed demonstrated that fiber-reinforced concrete exhibited inferior load-bearing capacity and structural integrity compared to traditional concrete.

Simulated stress distribution models further validated the fiber blends' decreased compressive strength and ductility.

Cost-benefit analysis revealed increased material costs primarily due to the fiber incorporated and the rise of steel required in its integration. M25 with fiber does not differ much from M25 without fiber. However, in the concluded testing, M50 with Fiber differed significantly from M50 without fiber.

6. Conclusions

The findings indicate that integrating basalt and PAN (polyacrylonitrile) fibers into M25 and M50 concrete grades does not improve structural compressive performance. The statistical treatment suggests that the difference in compressive strengths in the M25 and M50 categories shows no significant difference between conventional concrete and the inclusion of fibers. Thus, the results from the inclusion of fibers could be treated as conventional concrete itself.

Furthermore, the said integration of fibers did not offer any advantages. Specifically, this combination does not enhance key properties such as durability and resistance to cracking. Moreover, an in-depth study of the materials and procedures utilized in the concrete formulation is crucial. Even perfect concrete proportions as per design may not achieve the necessary strength without appropriate monitoring and control in production. Hence, various factors, such as fiber dispersion, bonding efficiency, curing conditions, and mix proportions, can significantly influence the final performance of fiber-reinforced concrete. A comprehensive understanding of these parameters is crucial to optimizing material selection and ensuring that modifications bring tangible structural benefits rather than unnecessary expenses.

Finally, the lower compressive strength suggests reduced load-bearing capacity, compromising the overall structural compressive performance. Relating this, it was found that additional steel reinforcement would be required to compensate for the performance shortfall due to this lowered strength, ultimately increasing construction costs.

7. Recommendation

This study examined the compressive strength of Grade M25 and M50 concrete cylinders combined with polyacrylonitrile and basalt fibers. Hence, the researchers make several significant recommendations to improve future studies, industry uses, and environmentally friendly building techniques.

The researchers advise further studies regarding PAN and basalt fiber to clarify how they affect compressive strength. They can also explore alternative fiber types, mix designs with higher fiber content, determine the optimal balanced integration/mixture, and the expansion of sample numbers.

While the main focus of the research is compressive strength, future studies should examine other mechanical characteristics, such as flexural behavior, tensile strength, impact resistance, and longevity, to give a complete picture of the performance of fiber-reinforced concrete.

Fiber-reinforced concrete durability and structural stability should be evaluated over a long period under various environmental conditions. This would offer important insights into possible degradation and practical uses.

Evaluating these, succeeding analyses may expand on the framework supplied by this study, resulting in an additional understanding of fiber-reinforced concrete and its function in resilient and sustainable development infrastructure.

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