

# Comparative Analysis of Mechanical and Physical Properties of Cement Mortar Reinforced with Synthetic (Polypropylene) and Natural (Pine Needle) Fibers

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## Abstract

This study investigates the mechanical and physical properties of cement mortar reinforced with synthetic polypropylene (PP) and natural pine needle (PN) fibers at 1–5% by cement weight. Fresh and hardened properties including workability, flexural strength, compressive strength, ultrasonic pulse velocity, density, and water absorption were evaluated. Results identified 2% PP as an optimal dosage, giving a 7% increase in flexural strength while maintaining acceptable compressive strength and internal quality. PN fibers showed potential as a waste-derived, sustainable alternative but exhibited lower mechanical performance and higher water absorption than PP at comparable contents. For both fiber types, increasing dosage reduced workability and compressive strength and increased water absorption while reducing density in a dose-dependent manner. A strong correlation between fiber content, decreased pulse velocity, and reduced compressive strength indicated increased porosity. Overall, PP fibers provided superior reinforcement with a better balance of properties, while PN fibers require further treatment to improve compatibility with the cement matrix.

Keywords: Fiber-reinforced mortar, polypropylene fibers, pine needle fibers, mechanical properties, sustainable construction materials

## 1 Introduction

Cement-based materials form the backbone of modern construction but remain intrinsically brittle and weak in tension. Under load, shrinkage, or environmental actions, this leads to crack initiation and sudden failure, limiting service life and reliability. Incorporating discrete fibers is a well-established strategy to mitigate these drawbacks: properly designed fiber reinforcement bridges cracks, increases energy absorption, and converts a brittle matrix into a more ductile composite [1,2].

A wide range of fibers has been used in cementitious systems, including synthetic polymers (e.g. polypropylene, polyvinyl alcohol), steel, and glass or carbon fibers. Their

efficiency depends on geometry (length, diameter, aspect ratio), mechanical properties (modulus, strength), and the quality of the fiber-matrix interface, which together control stress transfer and crack-bridging capacity [3].

Synthetic fiber systems have been extensively characterized. Nataraja et al. [5] linked fiber type to composite stress-strain response under different loading conditions. Long et al. [6] showed that the matrix-to-fiber modulus ratio governs whether stiffness or ductility is improved, with high-modulus carbon fibers primarily enhancing stiffness and low-modulus polypropylene fibers improving toughness and energy dissipation. Nayak [7] reported clear mechanical benefits from polypropylene fibers, accompanied by a reduction in workability at higher dosages.

At the high-performance end, Engineered Cementitious Composites (ECC) achieve strain-hardening and tensile strains of 3–5% using carefully tailored PVA or polyethylene fibers [9]. Hybrid concepts, such as combining polypropylene fibers with nano-silica, have demonstrated improved fiber-matrix bond and more stable crack patterns [10], illustrating how microstructural tailoring can further enhance performance.

In parallel, environmental and resource considerations have renewed interest in natural and waste-derived fibers as partial substitutes for petroleum-based synthetics. Among these, pine needles are an abundant forest residue that can acidify soil and hinder vegetation if left on the forest floor. Utilizing pine needles as cementitious reinforcement offers the dual benefit of waste valorization and reduced dependence on conventional synthetic fibers [14].

Polypropylene fibers in cement-based materials have been studied in depth [12], and natural fibers have been explored in various polymer and cementitious composites [13]. However, direct, side-by-side comparisons of conventional synthetic fibers and natural waste fibers within the same mortar system, test matrix, and curing conditions remain limited. This lack of controlled comparative data makes it difficult to judge whether natural waste fibers can

realistically act as sustainable alternatives rather than niche additions. The present work addresses this gap by systematically comparing polypropylene (PP) and pine needle (PN) fibers in cement mortar. The study focuses on:

- characterizing and preparing PP and PN fibers for use in mortar;
- establishing a standardized incorporation procedure at 1–5% by cement weight;
- evaluating fresh and hardened properties (workability, flexural and compressive strength, ultrasonic pulse velocity, density, and water absorption); and
- assessing the feasibility of PN fibers as a waste-derived alternative to PP in terms of performance and practical use.

Through this comparative framework, the study examines whether abundantly available natural waste, such as pine needles, can provide mechanically and physically acceptable reinforcement while contributing to more sustainable construction practices.

## 2 Experimental Methodology

### 2.1 Mix Proportioning

All mixes used a cement:sand ratio of 1:2 by weight with a constant water–cement ratio of 0.45. The control mix contained no fibers, while the fiber-reinforced mixes included polypropylene (PP) or pine needle (PN) fibers at 1–5% by cement weight. The detailed proportions are listed in Table 1.

Table 1: Mixture design proportion

+	Cement (g)	Sand (g)	Water (ml)	PP (%)	PN (%)
CM	600	1200	270	0	0
PP-1	600	1200	270	1	0
PP-2	600	1200	270	2	0
PP-3	600	1200	270	3	0
PP-4	600	1200	270	4	0
PP-5	600	1200	270	5	0
PN-1	600	1200	270	0	1
PN-2	600	1200	270	0	2
PN-3	600	1200	270	0	3
PN-4	600	1200	270	0	4
PN-5	600	1200	270	0	5

### 2.2 Cement and Fine Aggregate

Ordinary Portland cement was used in all mixes. Fine aggregate was characterized by standard sieve analysis. The gradation from 4.75 mm to 0.15 mm was used to compute the fineness modulus and to verify that the sand satisfied the limits for mortar applications.

### 2.3 Polypropylene (PP) Fibers

Commercial monofilament PP fibers were supplied with nominal length of 12 mm and diameter of 0.032 mm. The fibers had a tensile strength of about 350 MPa, an elastic modulus of 3.5 GPa, and a specific gravity of 0.91. Their high aspect



Figure 1: Standard sieve set used for fine aggregate gradation.



Figure 2: Commercial polypropylene monofilament fibers.

ratio ( $L/D \approx 375$ ) and hydrophobic, chemically inert surface make them suitable for crack-bridging and post-cracking ductility in cementitious matrices.

### 2.4 Pine Needle (PN) Fibers

Pine needles from mature *Pinus* trees were collected during the natural shedding period. They were washed with distilled water, air-dried for 48 h, and then cut manually to 12 mm length to match the PP fiber length. The needles have a tapered cross-section with an average diameter of 0.8–1.2 mm and a specific gravity of about 0.55, resulting in a much lower aspect ratio ( $L/D \approx 10-15$ ). The cellulosic composition

offers a lightweight, biodegradable reinforcement while maintaining sufficient stiffness during the service life of the mortar.

Using identical dosage levels (1–5% by cement weight) for PP and PN mixes allows direct comparison of the influence of fiber type while keeping the matrix composition unchanged.



Figure 3: Pine needle fibers: raw needles (left) and processed fibers (right).

## 2.5 Mixing, Casting, and Curing

### 2.5.1 Mixing Protocol

A laboratory mortar mixer was used to ensure consistent mixing across all batches. The sequence was kept identical for all mixes:

- Dry blend cement and sand for 60 s at 140 rpm.
- Add water gradually over 30 s while mixing continues.
- Introduce fibers incrementally over 45 s to minimize clumping.
- Continue mixing for a further 90 s until a visually uniform dispersion is obtained.

This sequence gave a total mixing time of 225 s and produced a uniform distribution of fibers without noticeable agglomeration or segregation.

### 2.5.2 Specimen Casting and Compaction

Fresh mortar was cast into lubricated 40×40×160 mm steel prism molds (Figure 4).

Compaction was performed on a mechanical jolting table (Figure 5) using 60 drops from a height of 12.5 mm to remove entrapped air and achieve uniform density while limiting fiber segregation.



Figure 4: Prismatic steel molds (40×40×160 mm) and fresh fiber-reinforced mortar.

### Curing Regime

After casting, molds were covered with a damp cloth and stored at 23±2°C for 24 h. Specimens were then demolded and placed in water at 23±2°C (saturated lime water) until the test age (28 days for mechanical and physical tests). This curing regime was applied consistently to all mixes.



Figure 5: Mechanical jolting machine used for specimen compaction.

## 2.5 Test Methods

All tests were performed under laboratory conditions on a minimum of three specimens per mix. Reported values are arithmetic means; the coefficient of variation for strength data was kept below 5%.

### 2.5.1 Fresh Properties: Workability

Workability was evaluated using the flow table test (ASTM C1437), see Figure 6. The test was carried out within 5 min after mixing. The spread of the mortar was measured in two perpendicular directions and the average diameter was used as the flow value for each mix.



Figure 6: Flow table used for workability measurements.

### 2.5.2 Compressive, and Flexural Strength

Compressive strength was measured on 40 mm cubes prepared from the prisms according to ASTM C109. Tests were performed at 28 days using a universal testing machine with a loading rate of 1.0 MPa/s.

Flexural strength was determined on 40×40×160 mm prisms in three-point bending following ASTM C348. A span of 100 mm and a loading rate of 0.05 MPa/s were used. Ultimate load and mid-span failure were recorded, and flexural strength was computed using the standard formula.

### 2.5.3 Physical Properties and Ultrasonic Pulse Velocity

Water absorption and apparent density were determined in accordance with ASTM C642. Specimens were oven-dried at 105°C to constant mass (72 h), cooled to room temperature, and then saturated in water to obtain the required mass measurements (oven-dry, saturated-surface-dry, and submerged).



Figure 7: Ultrasonic pulse velocity (UPV) test setup.

Ultrasonic pulse velocity (UPV) was measured using the direct transmission method (Figure 7). Matched 54 kHz transducers were placed on opposite faces of the specimen with coupling gel to ensure proper contact. Transit time was recorded with a resolution of  $\pm 0.1 \mu\text{s}$  and UPV was obtained by dividing the specimen length by the measured travel time,

providing a non-destructive indicator of internal quality and homogeneity.

## 3 Results and Discussion

This section first summarizes the material and mixture properties that form the basis for later performance comparisons between polypropylene (PP) and pine needle (PN) fiber-reinforced mortars. The focus is on verifying the suitability of the constituent materials and confirming that the mixture design consistently isolates the effect of fiber type and dosage.

### 3.1 Material Characterization

#### Portland Cement Properties

Cement testing confirmed that the binder satisfies ASTM C150 limits for all key parameters, indicating reliable setting behavior, adequate fineness, and stable volume change.

**Table 2:** Portland cement properties and compliance with ASTM C150

Property	Result	ASTM C150 limit
Standard consistency (%)	28	23–34
Initial setting time (min)	110	> 45
Final setting time (min)	180	≤ 375
Fineness by sieving (% retained)	7	< 10
Blaine fineness (cm <sup>2</sup> /g)	3007	≥ 2800
Specific gravity	3.09	≈ 3.15
Soundness expansion (mm)	6	≤ 10

The measured standard consistency (28%) lies near the mid-range of the specified band, supporting stable workability at the adopted water-cement ratio. Blaine fineness above 3000 cm<sup>2</sup>/g and low residue on the 90 μm sieve (7%) indicate adequate surface area for normal hydration kinetics. Soundness of 6 mm, well below the 10 mm limit, confirms acceptable volume stability. The specific gravity of 3.09 is close to typical values for Type I portland cement and does not introduce unusual density effects in the mixture design.

### 3.2 Fine Aggregate Characterization

Fine aggregate characterization showed that the sand is medium-fine and well graded, with properties suitable for mortar production.

**Table 3:** Sand gradation and derived fineness modulus

Sieve size (mm)	Retained (%)	Cumulative retained (%)	Passing (%)
4.75	0.0	0.0	100.0
2.36	12.4	12.4	87.6
1.18	21.0	33.4	66.6
0.60	23.0	56.4	43.6
0.30	10.0	66.4	33.6
0.15	19.0	85.4	14.6
Pan	14.6	100.0	0.0

The fineness modulus of 2.94 classifies the aggregate as medium-fine sand with a continuous gradation, which promotes dense packing and limits internal voids. A specific gravity of 2.65 and low water absorption (0.4%) imply that the aggregate contributes minimally to additional water demand, allowing the designed water-cement ratio to govern workability and strength development. The gradation curve (Figure 9) lies within typical limits for mortar sand, confirming that no corrective blending was required.

### 3.2 Mixture Proportions

All mixtures were designed to keep the binder and aggregate contents constant while varying only the fiber type and dosage. Table 4 summarizes the mixture compositions used for the experimental program.

**Table 4:** Mixture compositions with systematic fiber dosage variation

Component	CM	Fiber content (% by cement weight)				
		1	2	3	4	5
Cement (g)	600	600	600	600	600	600
Sand (g)	1200	1200	1200	1200	1200	1200
Water (ml)	270	270	270	270	270	270
w/c ratio	0.45	0.45	0.45	0.45	0.45	0.45
PP fibers (g)	0	6	12	18	24	30
PN fibers (g)	0	6	12	18	24	30

The control mix (CM) establishes the reference response without fibers. Fiber-reinforced mixes maintain identical binder, aggregate, and water contents, while the fiber mass increases linearly from 1% to 5% of cement weight. This design ensures that observed changes in fresh and hardened properties can be attributed primarily to fiber type and dosage, rather than to changes in the underlying matrix composition.

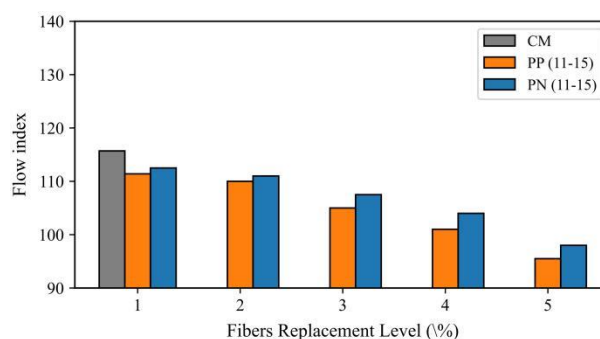
### 3.3 Fresh Property Assessment

#### 3.3.1 Workability from Flow Table Test

Flow table tests were used to quantify the consistency of the control and fiber-reinforced mortars. Table 5 summarizes the measured flow spread and corresponding flow index for each mix.

**Table 5:** Flow table results for control and fiber-reinforced mortars

Mix ID	Flow spread (mm)	Flow index (%)
CM	231	115.7
PP-1	223	111.4
PP-2	220	110.0
PP-3	210	105.0
PP-4	202	101.0
PP-5	191	95.5
PN-1	225	112.5
PN-2	222	111.0
PN-3	215	107.5
PN-4	208	104.0
PN-5	196	98.0



**Figure 8:** Effect of fiber content on mortar workability.

Both PP and PN fibers cause a clear, approximately linear reduction in flow with increasing dosage. At 5% fiber content, the flow index decreases by about 17% for PP mixes and 15% for PN mixes relative to the control. The stronger reduction in PP mixes is consistent with their higher aspect ratio and finer diameter, which increase internal friction and restrict mortar flow more than the coarser PN fibers.

From a practical standpoint, the results indicate that mixtures with higher fiber contents will require either

additional workability control (e.g., plasticizers) or modified placement procedures, especially when PP fibers are used.

### 3.4 Aggregate Gradation Analysis

The particle size distribution of the fine aggregate, summarized in Table 3 and illustrated in Figure 9, corresponds to a fineness modulus of 2.94 and a fines content of 14.6%. This medium-fine, continuously graded sand promotes dense packing and a relatively cohesive mortar matrix. Because the aggregate skeleton is already well-graded, the observed changes in workability can be attributed primarily to fiber geometry and content rather than to variations in aggregate

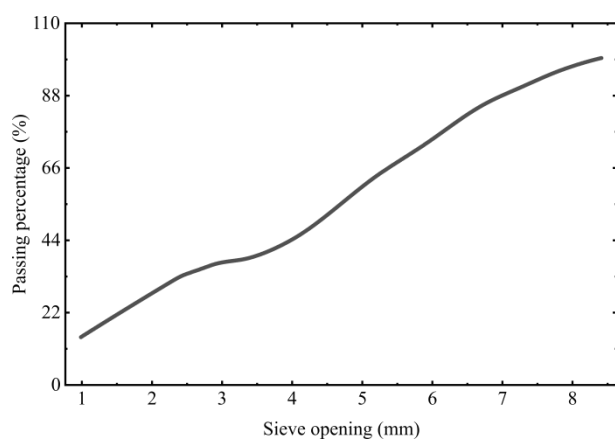


Figure 9: Particle size distribution curve for fine aggregate.

structure. In other words, the gradation provides a stable background against which the influence of PP and PN fibers on fresh behavior can be clearly distinguished.

### 3.5 Mechanical Property Development

Mechanical properties at 28 days were evaluated in terms of compressive strength, flexural strength, and ultrasonic pulse velocity (UPV), following the test methods described in the Experimental Methodology. For each mix, at least three specimens were tested and the mean values were used for comparison. These results are discussed alongside the durability indicators to highlight the combined effect of fiber type and dosage on overall mortar performance.

### 3.6 Durability Characteristics

Durability was assessed through water absorption and saturated surface-dry (SSD) density, both obtained in accordance with ASTM C642. These parameters provide insight into porosity, permeability, and the effect of low-density fibers on the composite.

#### 3.6.1 Water Absorption

Water absorption increases monotonically with fiber content for both PP and PN systems. At 5% dosage, absorption is approximately doubled relative to the control, reaching 17.7% for PP-5 and 21.1% for PN-5, compared to 8.1% for CM. PN mixes consistently show higher absorption than PP mixes at the same dosage, reflecting the hydrophilic, porous nature of the cellulosic PN fibers and their rougher surface, which create additional pathways for water transport.

#### 3.6.2 SSD Density

The corresponding SSD densities are reported in Table 7. SSD density decreases nearly linearly as fiber content increases, with PN mixes showing larger reductions than PP mixes. At 5% dosage, PP-5 exhibits a 3.7% reduction in density, while PN-5 shows a 5.7% reduction relative to the Table 6: Water absorption results for control and fiber reinforced mortars control. This trend is consistent with the lower specific gravity of PP (0.91 g/cm<sup>3</sup>) and especially PN (0.55 g/cm<sup>3</sup>) compared to the cementitious matrix (about 3.09 g/cm<sup>3</sup>). Fibers effectively replace a fraction of the dense matrix with lighter inclusions and introduce additional voids at the fiber-matrix interface.

Table 6: Water absorption results for control and fiber reinforced mortars

Mix ID	Dry mass (g)	Saturated mass (g)	Water absorption (%)	Increase vs. CM (%)
CM	165.2	178.5	8.07	—
PP-1	162.8	178.2	9.46	17.2
PP-2	160.4	178.8	11.47	42.1
PP-3	158.1	179.5	13.53	67.7
PP-4	155.9	180.1	15.52	92.3
PP-5	153.6	180.8	17.73	119.8
PN-1	161.5	179.1	10.90	35.1
PN-2	159.2	180.4	13.32	65.1
PN-3	156.8	181.7	15.87	96.6
PN-4	154.5	182.9	18.37	127.6
PN-5	152.1	184.2	21.11	161.6

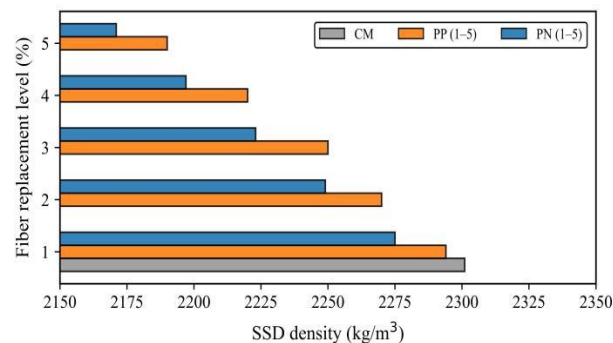
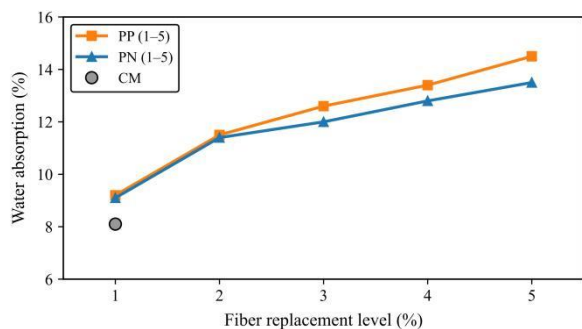


Figure 10: Variation of water absorption with fiber content.

Figure 11: Density reduction with increasing fiber content.

Table 7: SSD density of control and fiber-reinforced mortars

Mix ID	SSD density (kg/m <sup>3</sup> )	Density reduction (% vs. CM)	Fiber type
CM	2301	—	None
PP-1	2284	0.74	PP
PP-2	2267	1.48	PP
PP-3	2250	2.22	PP
PP-4	2233	2.96	PP
PP-5	2216	3.69	PP
PN-1	2275	1.13	PN
PN-2	2249	2.26	PN
PN-3	2223	3.39	PN
PN-4	2197	4.52	PN
PN-5	2171	5.65	PN

From a durability perspective, higher absorption implies greater susceptibility to freeze-thaw damage and chemical ingress, while reduced density can be advantageous where weight reduction is required. A practical compromise emerges at moderate fiber dosages (about 2–3%), where mechanical benefits can be obtained without pushing water absorption to the highest levels observed in the 4–5% mixes. For applications where durability is critical, PP fibers are more favorable than untreated PN fibers, due to their lower impact on absorption and better moisture resistance. Improving PN performance would likely require surface treatments or modifications aimed at reducing water uptake and refining the fiber-matrix interface.

### 3.7 Mechanical Properties and Internal Quality

Mechanical performance at 28 days was assessed through flexural strength, compressive strength, and ultrasonic pulse velocity (UPV). The results in Table 8 provide a compact overview of the response of all mixes.

#### 3.7.1 Summary of Mechanical Test Results

Table 8: Mechanical properties and ultrasonic pulse velocity at 28 days

Mix ID	Flexural strength (MPa)	Compressive strength (MPa)	UPV (km/s)	Fiber content (%)
CM	11.80	67.08	4.36	0
PP-1	12.62	59.68	4.22	1
PP-2	12.65	52.19	4.18	2
PP-3	10.41	48.17	3.98	3
PP-4	10.46	46.46	3.96	4
PP-5	10.29	39.70	3.93	5
PN-1	9.57	51.76	3.87	1
PN-2	10.13	43.71	3.85	2
PN-3	9.95	33.35	3.83	3
PN-4	9.59	32.75	3.76	4
PN-5	9.51	31.84	3.75	5

### 3.6.3 Combined Interpretation and Durability Implications

The strong correlation between increasing water absorption and decreasing density (with R<sup>2</sup> > 0.95) indicates that fiber incorporation primarily acts by increasing overall porosity and modifying the microstructure around the fibers. These effects are more pronounced in PN-reinforced mortars, where hydrophilic fibers and a more irregular geometry lead to higher permeability and lower density than in the PP mixes at the same dosage.

### 3.7.2 Flexural Response

PP-reinforced mortars show a clear flexural benefit at low dosage. The maximum flexural strength is obtained for PP-2

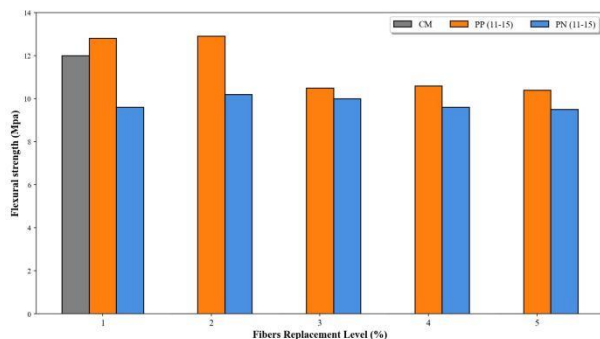


Figure 12: Flexural strength as a function of fiber content.

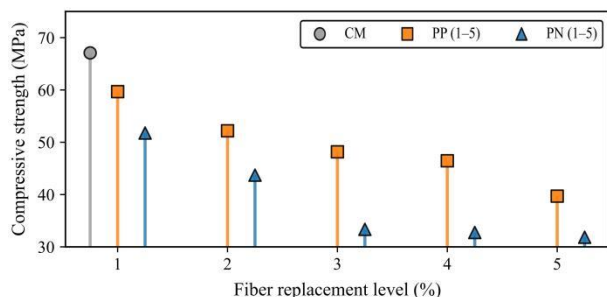


Figure 13: Compressive strength trends for fiber-reinforced mortars.

(12.65 MPa), corresponding to an increase of about 7 % relative to the control. This behaviour is consistent with effective crack bridging at moderate fiber contents; once the dosage exceeds 2 %, the loss of matrix continuity and increased likelihood of fiber clumping outweigh the reinforcement benefit, and flexural strength drops back towards or below the reference value.

PN mixes, in contrast, remain below the control across the entire dosage range (9.5–10.1 MPa). The limited improvement suggests weaker fiber–matrix interaction, likely driven by the hydrophilic cellulosic nature of the needles and less favourable surface characteristics, which promote interfacial defects rather than efficient stress transfer.

### 3.7.3 Compressive Strength Behaviour

Both fiber systems reduce compressive strength, but the severity of the reduction depends on fiber type and content. For PP mixes, compressive strength decreases from 67.1 MPa (CM) to 59.7 MPa at 1 % (PP-1, roughly 11 % reduction) and

to 39.7 MPa at 5 % (PP-5, about 41 % reduction). PN mixes show a stronger penalty, with PN-5 dropping to 31.8 MPa (around 53 % lower than the control). The main factors behind the strength loss are:

- increased void content and disruption of dense pastepacking,
- weaker interfacial transition zones around fibers,

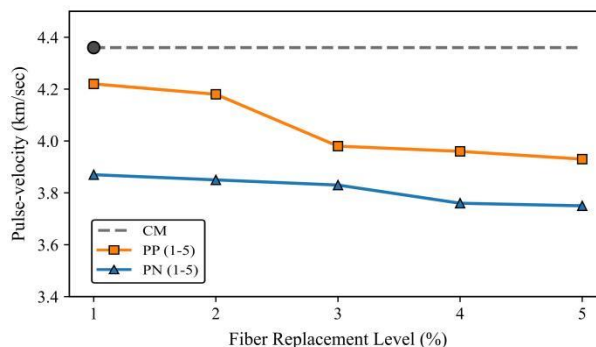


Figure 14: Correlation between ultrasonic pulse velocity and compressive strength.

- microcrack initiation at fiber–matrix interfaces under compressive loading.

PP fibers retain higher compressive strength at all dosages than PN fibers, indicating better compatibility with the cement matrix and more uniform dispersion.

### 3.7.4 Ultrasonic Pulse Velocity and Internal Quality

UPV values follow the same trend as compressive strength. The control mix shows the highest pulse velocity (4.36 km/s), consistent with a dense and relatively defect-free microstructure. As fiber content increases, UPV gradually decreases: PP mixes remain in the 3.93–4.22 km/s range, whereas PN mixes fall to 3.75–3.87 km/s.

A strong correlation ( $R^2 \approx 0.94$ ) is observed between UPV and compressive strength (Figure 14), confirming that UPV can be used as a reliable non-destructive indicator of internal quality for these mortars. Lower velocities are associated with higher porosity and more pronounced microstructural discontinuities, especially in PN-reinforced mixes.

### 3.7.5 Optimal Fiber Content and Comparative Assessment

For PP-reinforced mortars, 2 % fiber content emerges as a practical optimum. At this dosage, the mix combines:

- increased flexural strength (12.65 MPa, about +7 % vs.CM),

- acceptable compressive strength (52.19 MPa, roughly 22 % below CM),
- only a modest reduction in UPV (4.18 km/s).

This balance indicates that moderate PP dosages can enhance toughness and post-cracking behaviour without excessively compromising compressive capacity or internal quality.

PN reinforcement, in its current untreated form, does not exhibit a similar optimum: all dosages result in lower flexural strength, significantly reduced compressive strength, and lower UPV compared to the control. While PN fibers offer clear environmental and density advantages, their mechanical efficiency is limited by poor interfacial bond and higher induced porosity. To become competitive with PP in structural or semi-structural applications, PN fibers would require additional treatments (e.g. surface modification, coupling agents, or hybridization with synthetic fibers) to improve bonding and reduce the associated microstructural damage.

#### 4 Conclusion

This study investigated the use of polypropylene (PP) and pine needle (PN) fibers in cement–sand mortar for potential strengthening and retrofitting applications. By keeping the matrix composition constant and varying only fiber type and content, the workability, mechanical properties, density, water absorption, and internal quality were systematically assessed.

PP fibers showed a clear beneficial effect on flexural behaviour at low dosages. An optimum around 2% (by cement weight) emerged, where flexural strength increased by about 7% compared with the control, while compressive strength and UPV remained at acceptable levels. Beyond this dosage, the loss of matrix continuity and increased porosity led to a reduction in both strength and internal quality.

PN fibers, in their untreated form, did not provide comparable mechanical improvements. Across the tested range, PN mixes generally exhibited lower flexural and compressive strengths than the control, together with higher water absorption and a more pronounced decrease in density and UPV. These trends are consistent with the hydrophilic, porous nature of the natural fibers and less favourable fiber–matrix bonding, which promote interfacial defects rather than efficient stress transfer.

Durability-related indicators confirmed the trade-off introduced by fiber addition. Both PP and PN fibers increased

water absorption and reduced SSD density in a dose-dependent manner, with PN having the stronger effect. While the resulting reduction in density is attractive for lightweight applications, the higher absorption implies increased permeability and potentially lower resistance to freeze–thaw and chemical attack, especially at high fiber contents.

Overall, PP-reinforced mortar at moderate fiber content can be considered a technically viable option where enhanced toughness and limited weight reduction are desirable, provided that the associated increase in porosity is managed. PN fibers, although attractive from a sustainability and density perspective, require further modification before they can match or exceed the performance of PP in structural or semistructural uses.

#### Recommendations for Future Work

Based on the experimental findings, the following directions are recommended:

- Surface modification of pine needles: Apply chemical or physical treatments to remove waxy layers, reduce water uptake, and improve bonding at the fiber–matrix interface.
- Influence of fiber geometry: Investigate longer PN fibers (e.g. up to 50 mm) and alternative aspect ratios for both PP and PN to clarify their role in crack bridging and post-cracking behaviour.
- Extension to concrete: Study the performance of PP and modified PN fibers in concrete mixes and in fullscale structural elements to assess their effectiveness beyond mortar-level testing.
- Fiber orientation and placement: Explore methods to control fiber orientation (e.g. preferential alignment along the prism length) and to minimise surface exposure, with the aim of improving mechanical efficiency and surface finish.
- Workability control: Evaluate the use of plasticizers or superplasticizers to maintain target workability at constant water–cement ratio when using higher fiber dosages, particularly for PP-reinforced mortars.

These steps would help refine fiber-reinforced mortar systems and bring natural fiber solutions closer to practical, durable, and sustainable strengthening applications.

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