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Research Article

Valorization of pinus and cedrus acicular leaves as bio-based fibers for reinforced cementitious composites: Extraction, microstructural characterization and mechanical performance

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ABSTRACT

In modern construction applications, various cement-based composite material systems are being developed using forest products and forest waste, such as bio-based fibers. These composites serve as sustainable building materials, including wood-cement composites, fiber-reinforced panels, lightweight building elements, and precast building components, especially in non-load-bearing architectural applications. In this study, the physical and mechanical properties of a composite produced in a similar manner, using acicular leaves of *Pinus nigra* and *Cedrus libani* as natural fibers, were examined. In this context, the fibers underwent a multi-stage pre-treatment, including hot water extraction, alkaline treatment, and $\text{Ca}(\text{OH})_2$ mineralization, followed by characterization; the treatments were verified by SEM, EDS, and FTIR analyses. Short *Cedrus* fibers are randomly distributed in the matrix to form an isotropic structure, while long *Pinus* fibers are oriented perpendicular to the load direction to obtain an orthotropic structure. Unit weight, ultrasonic pulse velocity, dynamic modulus of elasticity, and compressive, flexural, and splitting tensile strengths were determined. When compared, short, isotropic cedar fibers showed higher compressive strength, while long, oriented pine fibers exhibited superior bending and splitting tensile performance.

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1. Introduction

Research in building materials aims not only to meet high-strength requirements but also to satisfy multidimensional criteria such as lightness, material efficiency, workability, and architectural harmony. Extensive academic studies have examined fiber-reinforced cementitious composites, primarily because of their benefits in crack control, increased ductility, and modifications to the internal structure. Incorporating fibers into cementitious matrices alters mechanical behavior through fiber-matrix interaction, enabling the development of composite systems.

The primary purpose of reinforcing cementitious composites with fibers is to mitigate premature cracking and limited ductility arising from the brittle behavior and low tensile strength of conventional cementitious composites. Fibers added to the matrix delay the transformation of microcracks into macrocracks via the crack-bridging mechanism, thereby significantly increasing tensile and flexural strengths, toughness, and service life (Anas et al. 2022; Ünal and Canbaz 2025; Urtekin and Çelik 2025). Furthermore, fiber reinforcement substantially improves not only the mechanical strength of composites but also its post-damage deformation capacity and load-bearing behavior, making it an

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indispensable engineering approach in high-performance, long-lasting cementitious composites designs (Pham 2025). Natural fibers, while offering a sustainable reinforcement alternative with advantages such as renewability, low density, biodegradability, and low environmental impact, significantly increase mechanical strength, toughness, and deformation capacity by crack bridging and microcrack formation in the matrix. Literature studies indicate that the crack-bridging mechanism in natural fiber reinforced cementitious composites (NFRCC) is governed by fiber geometry, volume fraction, and fiber-matrix interfacial quality, and that this mechanism improves critical performance indicators, including post-peak bearing capacity, energy absorption, and residual strength in flexural and splitting tensile behavior (Lilargem Rocha et al. 2022). Additionally, natural fibers offer environmental advantages, as they are produced with a lower carbon footprint and lower energy consumption than synthetic fibers (Olanrewaju et al. 2025). However, achieving homogeneous distribution of natural fibers in matrix and improving the fiber-matrix interface pose significant design challenges for workability and durability; current studies aim to overcome these limitations through fiber surface modification, chemical pretreatments, and hybrid fiber systems. In the literature, natural fibers of vegetable (lignocellulosic) origin are mainly used. The classification of these fibers as bast fibers (hemp, jute, flax), leaf fibers (sisal, abaka), fruit fibers (coir), wood/cellulose origin fibers (wood fiber, kraft cellulose, micro/nano-cellulose), and agricultural residue fibers (rice husk, straw, bagasse) is widely adopted to explain how differences in fiber geometry, absorbency, surface roughness, and mechanical properties affect workability in fresh state and tensile behavior, toughness, and compressive strength in hardened state (Hamada et al. 2023). Vegetable fibers, from chemical and structural perspectives, have a lignocellulosic matrix consisting of cellulose, hemicellulose, and lignin. Cellulose content increases the fiber's tensile capacity and rigidity. In contrast, hemicellulose/pectin fractions enhance the fiber's hydrophilic behavior and interact with the high alkalinity of the cementitious medium, a critical mechanism in research on NFRCC (Camargo et al. 2020). Durability and fiber-matrix interface stability are the main topics of discussion in NFRCC, and since the high alkalinity of Portland cement can lead to degradation and mineralization of lignocellulose fibers over time, reducing the alkalinity of the cement matrix with pozzolanic admixtures and modifying the fibers by chemical or physical pretreatments stand out as the two main strategies in the literature to improve long-term performance (Camargo et al. 2020; Merta et al. 2017). A prominent trend in natural fiber research is the development of hybrid fiber systems by enhancing fiber surface roughness and fiber-matrix adhesion through pretreatments such as alkali treatment. It is emphasized that controlled removal of the hemicellulose/pectin fraction can increase interface strength. Nevertheless, excessive processing can reduce the fiber's tensile capacity, so optimization is a fundamental design parameter (Hamada et al. 2023; Camargo et al. 2020). Pretreatment can also improve fiber-matrix bond strength (Tarhan et al. 2025). Current literature reveals that the focus in NFRCC is no longer only

on strength increase, but also on microstructure-interface engineering, crack monitoring, durability and workability optimization, and that this holistic approach significantly improves the flexural and tensile behavior of this holistic approach, even if the compressive strength does not always increase, and changes the damage mode from brittle to controlled damage; It shows that the combination of fiber chemistry, geometry, pretreatment and matrix design has become a standard view in the field (Lilargem Rocha et al. 2022; Merta et al. 2017). In the NFRCC literature, regionally abundant biomass fibers such as bamboo, coconut, and palm fiber stand out; Studies with bamboo fibers reveal that fibers can improve mechanical strength and durability by limiting brittle cracking, but processability, water absorption behavior, and fiber-matrix interface design are critical parameters that determine performance (Dhakal et al. 2024; El Bourki et al. 2023). It has been reported that coconut/coir fibers significantly improve the tensile and flexural behavior of NFRCC. The optimal fiber ratio should be determined by considering workability and porosity. In the study of Abasi et al., it was stated that the 28-day flexural strength increased by 21%, 25% and 15.24%, the tensile strength increased by 29.66%, 38.66% and 22.81%, respectively, with the addition of 0.4–0.8–1.0% fiber by weight of cement, and the best performance was obtained with 0.8% fiber content (Kavitha and Kala 2017). In studies examining higher fiber volume ratios, an increase in tensile strength under compressive and splitting was observed when an appropriate mixture design was employed. The findings summarized by Lin et al. indicate that approximately 25% increases in compressive strength and 20.4% increases in splitting tensile strength can be achieved with 1.5% coconut fiber. These gains are closely related to matrix compaction, fiber-matrix adhesion, and the fiber-bridging mechanism (Lin et al. 2025). Studies on palm fibers reveal that the ductility and tensile ductility of NFRCC can increase significantly with increased fiber content. Nevertheless, adverse effects, such as loss of workability and reduced compressive strength, may occur if the optimal fiber ratio is exceeded (Ahmad et al. 2023; Althoey et al. 2022; Uzun 2024). Examples of fiber systems of natural origin and waste show that fibers behave not only as a reinforcing element but also as an active component that changes the fracture mode through friction and mechanical coupling on the crack surface, with Kilani et al. reporting an increase in tensile strength of about 52.5% in a system containing banana origin components, which quantitatively confirms this effect (Kilani et al. 2022).

The most critical design parameter for forest-derived fibers is fiber-matrix interface compatibility. In the study reported by Lin et al., fiber-matrix adhesion improved significantly after 2 hours of pretreatment of waste wood fiber with 2.5 M NaOH, and the flexural strength of the mortar increased by 34.7% relative to the control mixture (Althoey et al. 2022). In NFRCC containing sawdust, compressive strength generally decreases as the substitution rate increases because of higher porosity, but limited positive effects can be observed at low or optimum levels. In one study, an approximately 3% increase in compressive strength was reported with a 10% substitution of sawdust (El-Nadoury 2021). Studies on wood-cementitious composites reveal that density decreases as wood con-

tent increases (by up to ~11% over 28 days). In comparison, compressive strength can increase from early to later ages (~15%), indicating a balance between the "mitigation effect" and age-related strength gain (Dias et al. 2022). Similarly, in the literature on the use of lignocellulosic phases, such as wastepaper and cellulose fibers, in cementitious systems, it is commonly reported that these fibers provide crack control and increase toughness. However, at high dosages, they may adversely affect compressive strength due to increased porosity and water demand (Fernando et al. 2023).

In pine acicular leaf NFRCC, improvements in tensile behavior were reported to depend on fiber content. In one study, tensile strength increased by 23.5% at 0.5% fiber content and by 5.7% at 1.0% fiber content. It was emphasized that the bridging effect may be more effective at low dosages, whereas losses due to workability and porosity may predominate at high dosages (Khalid and Ali 2024). Studies examining how pine acicular-leaf fibers affect fracture mode and ductility, particularly in high-performance matrices such as self-compacting and ultra-high-performance concretes, indicate that this fiber type remains a limited area of research (Cogurcu 2022). Similarly, studies evaluating pine acicular-leaf fibers at the scale of cementitious mortar, considering viscosity, density, and mechanical properties together, are included in the literature (Zain-Ul-Abdin and Khitab 2020). Studies showing that *Cedrus libani* acicular-leaf is used in gypsum-based board products rather than concrete reveal that it can be used in mineral binder composites (Şahin and Çam 2022). The widespread investigation of cedrus-derived sawdust and similar wastes in cement boards and wood-cement board systems presents the compatibility and mechanical behavior of cedrus-derived lignocellulosic phases with cement (El Hamri et al. 2024). In summary, the literature findings show that the mechanical contribution of natural fibers is mainly realized through the crack control mechanism; It reveals that the strength and toughness are significantly improved, especially in flexural and splitting tensile behavior, thanks to the fact that the fibers reduce the stress accumulation at the crack end by bridging the microcracks and delaying the formation of macrocracks.

According to data from the General Directorate of Forestry for 2024, approximately 11 million hectares of *Pinus* and 580 thousand hectares of *Cedrus* are planted in Turkey. The acicular leaves of *Pinus* are long, whereas those of *Cedrus* are short. *Cedrus libani* A.Rich., a subspecies of *Cedrus*, has short acicular leaves ≈15–35 mm long, a rhomboidal cross-section, and a high specific surface area. It has a dense epicuticular wax layer typical of the Pinaceae family and a lignocellulosic chemical composition comprising cellulose, hemicellulose, lignin, resins, and hydrophobic extractives. In addition, the gradual deterioration of the wax layer due to natural aging increases surface roughness (Güney et al. 2016). *Pinus* species with acicular leaves, belonging to the subspecies *Pinus nigra*, are ≈75–175 mm long and 0.8–2.1 mm wide, and stand out for their fibrous morphology and high length/diameter ratio. These acicular leaves, characterized by anatomically dense sclerenchyma tissue, well-developed vascular bundles, and an epicuticular wax layer that may vary with environmental conditions, ex-

hibit important chemical properties that enhance the relative resistance of fibers to water, thanks to lignin and resinous extractive components, along with high cellulose and hemicellulose content (Öztürk Çoban and Seki 2025). *Cedrus libani* A.Rich., thanks to its short length, high specific surface area, and increasing surface roughness with age, has the potential to reduce density, control microcracking, and increase durability by forming an isotropic network of fibers in the cemented matrix; *Pinus nigra* acicular leaves, on the other hand, are a natural fiber that has the potential to enhance mechanical performance under loading conditions where tensile and flexural effects are dominant, thanks to their long, routable fiber geometry, high length/diameter ratios, and sufficient mechanical stiffness.

Today, various cement-based composite material systems are being developed using forest products and forest waste. These composites are emerging as alternatives, especially in non-load-bearing architectural applications. Forest products and forest waste are used as fibers or aggregates in composite systems, or in precast concrete composites containing fibers and in cement-based pressed board products. Mineral aggregates are rarely used in the design of these composites; instead, forest products and forest waste serve as reinforcement materials, such as fibers and chips, and the matrix consists of cement paste. Studies in the literature reveal that the mechanical properties of cement-based composites that do not contain aggregates and where wood waste is evaluated have been extensively investigated (Canbaz et al. 2021; Garcez et al. 2016; Mahzabin et al. 2013). These studies provide a clearer understanding of fiber-matrix interface interactions and charge transfer mechanisms. Similarly, in this study, only cement, fiber, and water were used in the production of the specimens, and no aggregate was used. No control specimens consisting of cement and water were produced.

In this study, dried, fallen acicular leaves of *Pinus nigra* Arnold and *Cedrus libani* A.Rich. were used as natural fibers, and the physical and mechanical properties of the resulting specimens were examined. SEM, EDS, and FTIR analyses were examined as qualitative and semi-quantitative evidence to verify the surface modification and mineralization of natural fibers before their incorporation into the cemented matrix. *Cedrus libani* A.Rich. short acicular leaves were incorporated into the mixture to form an isotropic fiber arrangement by being distributed randomly in all directions. By contrast, *Pinus nigra* Arnold's long acicular leaves were oriented perpendicular to the load direction and in one direction during specimen production, resulting in an orthotropic fiber structure. Thus, the effects of fiber length and fiber orientation on mechanical behavior were comparable. Aggregates and admixtures were omitted from the mixture to observe the physical and mechanical effects of the fibers fully. At the end of the 7 and 28 day curing periods, unit weight, ultrasonic pulse velocity, compressive and flexural strengths, and splitting tensile strength were measured for the produced specimens. Unit weight and ultrasonic pulse velocity measurements were used to reveal the effect of fiber addition and fiber orientation on matrix density and internal structure continuity; compressive, flexural, and splitting tensile tests were con-

ducted to evaluate how natural fiber-cement matrix interaction is reflected in mechanical performance. The role of fiber orientation in limiting crack progression and in load transfer mechanisms was examined in detail, particularly in flexural and tensile behavior.

2. Materials and Methods

2.1. Materials

In specimen production, CEM I 52.5 R cement from the Çimsa cement factory was used, and the cement properties are presented in Table 1. *Pinus nigra* Arnold and *Cedrus libani* A.Rich were used as natural fibers. The dried, fallen acicular leaves of the trees were used. The photograph and the technical specifications of the acicular leaves are presented in Table 2. In the experiments, tap water was used, and the laboratory chemical analysis report for the drinking water treatment plant is presented in Table 3.

2.2. Fiber pretreatment

Dry acicular leaves of *Pinus nigra* Arnold and *Cedrus libani* A.Rich, collected from the forest ecosystem, under-

went extensive multistage pretreatment before being incorporated into cement mixtures. Initially, the material was separated to remove biological contaminants, including soil, sand, ash, and fungal residues. The cleaned material was thoroughly rinsed with deionized water to remove surface contaminants, then dried in an oven at 60 °C for 24 hours. Subsequently, water-soluble organic compounds, including tannins and phenolics that may interfere with cement hydration, were extracted with hot water (80 °C) for 3 hours. This process was repeated twice with fresh deionized water. After extraction, the residues were filtered and dried for chemical treatment. Alkaline pretreatment was performed by soaking the materials in a 2% NaOH aqueous solution for four hours under continuous stirring, thereby removing hemicellulose components and partially increasing surface roughness. The processed residues were rinsed with deionized water until the pH approached neutrality, then dried in the oven. Mineralization was achieved by soaking the materials in a saturated $\text{Ca}(\text{OH})_2$ solution at 25 °C for 24 h, with a solid-to-liquid ratio of 1:10 (g mL^{-1}). The process was repeated twice with a fresh $\text{Ca}(\text{OH})_2$ solution to ensure uniform surface coverage. Finally, the mineralized residues were carefully rinsed to remove excess surface scale and then dried at 60 °C before being prepared for use in cementitious composite mixtures.

Table 1. Cement properties.

Chemical Content (%)				Physical Properties		
CaO	64.70	MgO	1.35	Density (g/cm^3)	3.06	
SiO ₂	21.20	Na ₂ O	0.38	Blain (m^2/g)	4300	
Al ₂ O ₃	4.60	SO ₃	3.50	Setting time (min)	Initial 95	Final 125
Fe ₂ O ₃	0.28	K ₂ O	0.20	Compressive strength (MPa)	7 th day 50	28 th day 60
LOI	3.5	Cl	0.01			

Table 2. *Pinus nigra* Arnold and *Cedrus libani* A.Rich. Acicular leaves characteristics.

	<i>Pinus nigra</i> Arnold Leaves type : Acicular (Needle) Length : 75-175 mm Width : 0.8-2.1 mm Unit weight : 0.14 g/cm^3 Density* : 0.35-0.59 g/cm^3 Water absorption: 35.4 % (untreated) 26.9 % (treated)		<i>Cedrus libani</i> A.Rich. Leaves type : Acicular (Needle) Length : 15-35mm Width : 0.8-2.1 mm Unit weight : 0.13 g/cm^3 Density** : 0.48-0.51 g/cm^3 Water absorption: 50.1 % (untreated) 41.5 % (treated)
	* Ross (2010)		**Efe (2021)

Table 3. Properties of tap water.

Chemical Analysis Result (mg/L)						
SO ₄	NO ₃	Cl	NH ₄	Mn	Al	Fe
70	7.5	43	<0.05	<0.0007	<0.012	<0.0075
pH	Conductivity ($\mu\text{S/cm}$)		Hardness (Fr°)		Turbidity (NTU)	
7.28	664		32		0.10	

2.3. Preparation of specimens

In this study, dry *Pinus nigra* Arnold and *Cedrus libani* A.Rich were used as natural fibers derived from acicular leaves. The physical and mechanical properties of cementitious composites at different proportions were investigated. The cementitious composites mixture is given in Table 4, and no admixtures or aggregates other than cement, water, and natural fiber were used to isolate the fiber's effect. The natural fibers of *Pinus nigra* and *Cedrus libani* origin used in this study are not homogeneous materials produced by standard processes, but lignocellulosic structures collected as forest waste and then subjected to multi-stage processes such as pre-cleaning, screening, washing, extraction, characterization, and mineralization. As a result of these processes, the physical properties of the fibers vary, and significant differences are observed between fibers. Therefore, determining the volumetric ratios of the fibers precisely and repeatability is difficult. In this study, fiber amounts were expressed by weight to ensure the controllability and reproducibility of the experimental design, and the fiber/cement ratio was defined on this basis. Although volumetric ratios are more appropriate when standard, homogeneous, and industrially produced fibers are used, mass ratios were used in this study due to the natural and heterogeneous fiber structure.

The water/cement ratio and the amount of natural fiber were kept constant, while the cement content was increased. In this study, cement contents of 600–900 g were used to create a gradual binder content series with a constant fiber content (140 g) and a constant water/cement ratio (0.40). Thus, the fiber/cement ratio was reduced from 0.23 to 0.16, and the effect of this change on the physical and mechanical behavior of composites was examined.

Cedrus libani A.Rich. acicular leaves mixture C is symbolized by *Pinus nigra* Arnold acicular leaves mixture P. Standard specimens of 4x4x16 cm were produced. The curing of the specimens was carried out in accordance with the TS EN 196-1 standard. In this context, all specimens subjected to compressive strength, flexural strength, and splitting tensile strength tests were cured for 7 and 28 days at a temperature of 20 ± 2 °C. After curing, unit weights and ultrasonic pulse velocities were measured. Flexural, compressive, and splitting tensile tests were then performed, and the dynamic elastic modulus was calculated. A three-point flexural test was performed, and the compressive strengths of cube specimens were determined. Photographs of C and P type specimens, along with flexural, compressive, and splitting tensile test setups, are shown in Fig. 1.

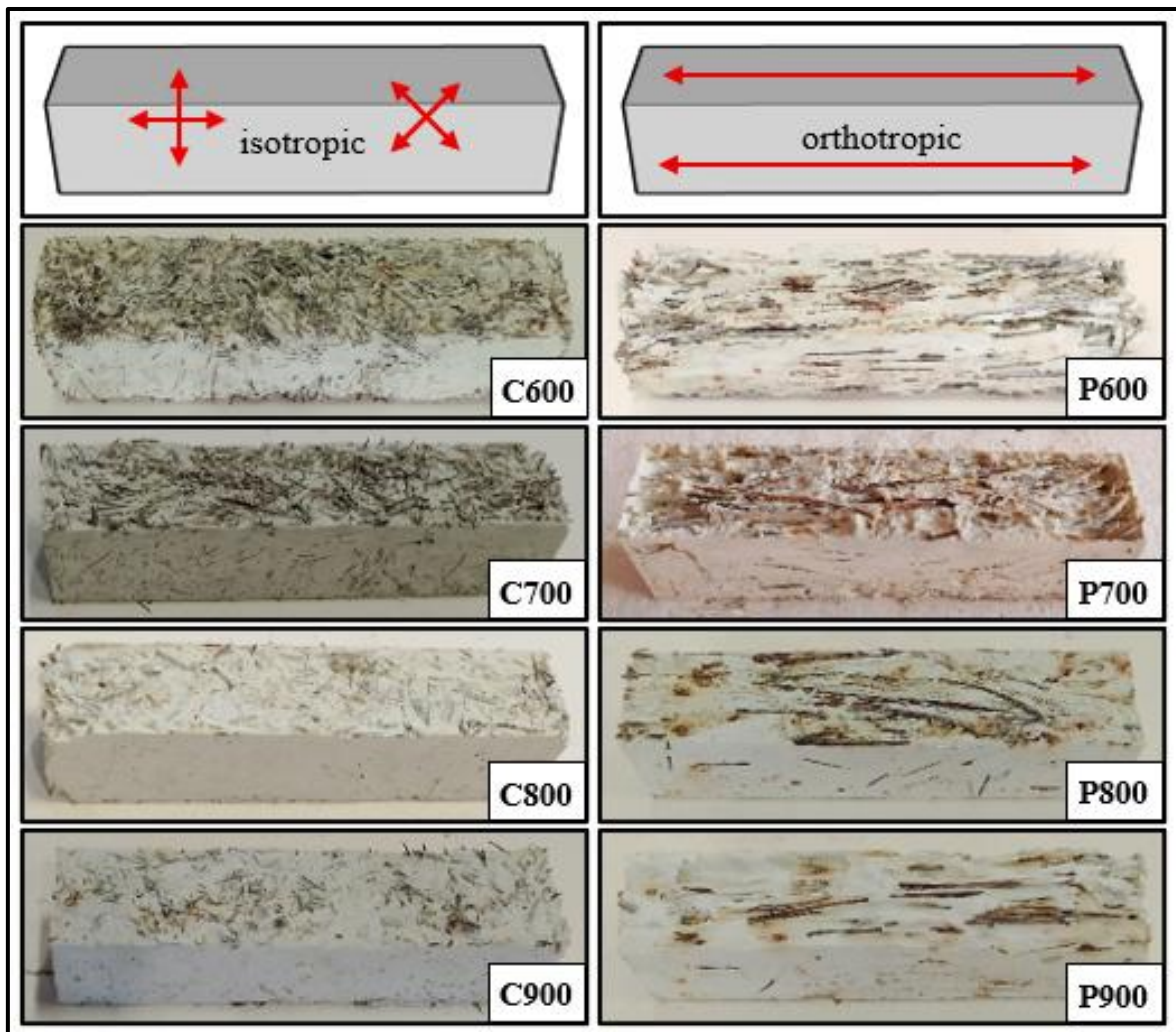


Fig. 1. Type C and P specimens.

The specimens were prepared in accordance with the mixing and production principles defined in the TS EN 196-1 standard for blends containing C-type fibers. The primary purpose of the production process is to ensure that the fibers are uniformly distributed within the cement matrix and to prevent the formation of agglomerations. This allows the fibers to be oriented in different directions within the composite structure, contributing to more uniform and isotropic mechanical properties. In specimens with P-type fibers, the fibers were mixed with the matrix in a specific direction and placed in the formwork. Manual orientation of long fibers perpendicular to the load direction was carried out under controlled, idealized laboratory conditions to examine the effect of fiber orientation on mechanical behavior in isolation. This method does not represent a production technique applicable at construction sites. Furthermore, once the

mixture was placed in the mold, pressure was applied, similar to wood–cement-based pressed board manufacturing techniques, resulting in a denser, more compact, and tidier internal structure.

The geometric properties of the natural fibers used in this study limit the determination of fresh mixture consistency by standard methods. C-type fibers from *Cedrus libani* have lengths of approximately 15–35 mm in nature and in the experimental study, while P-type fibers from *Pinus nigra* are longer, ranging from 75–160 mm. In particular, the high length/diameter ratio of P-type fibers makes one-way application a suitable measure of mixture workability. Therefore, standard fresh consistency tests, such as slump or the spreading table, do not yield feasible or representative results for this material system. Accordingly, fresh mixture properties were not evaluated using standard consistency tests in the study.

Table 4. Mix proportions.

Fiber type	Code	Cement (g)	Fiber (g)	Fiber/Cement	Water (g)	W/C
C type <i>Cedrus libani</i> A.Rich acicular leaves	C600	600	140	0.23	240	0.40
	C700	700	140	0.20	280	0.40
	C800	800	140	0.18	320	0.40
	C900	900	140	0.16	360	0.40
P type <i>Pinus nigra</i> Arnold acicular leaves	P600	600	140	0.23	240	0.40
	P700	700	140	0.20	280	0.40
	P800	800	140	0.18	320	0.40
	P900	900	140	0.16	360	0.40

2.4. Flexural strength test

Prismatic specimens measuring 40×40×160 mm, produced in accordance with the TS EN 196-1 (2016) standard, were subjected to a three-point flexural test at the end of 7 and 28 day curing periods. During the experiments, loading was performed using the span and loading speed specified in the standard. In specimens produced with natural fibers of varying compositions and geometries, the mechanical behavior was evaluated as a function of fiber distribution and orientation within the matrix. In this context, the flexural behavior of isotropic specimens, in which short fibers are randomly distributed in multiple directions, and orthotropic specimens, in which long fibers are aligned in one direction perpendicular to the load direction, was compared. In the experimental study, a total of 24 specimens were tested, with each of the two specimen groups, type C and type P, consisting of three replicates, to examine the flexural strength of the specimens.

2.5. Compressive strength test

A compressive test was conducted on cubic specimens (40×40×40 mm) prepared from C-type and P-type materials at various cement ratios, in accordance with TS EN 196-1 (2016). The experiments were performed on a universal testing press, and loading was continued

until the specimens failed under the specified standard conditions. During the compressive test, the effects of different cement ratios and specimen types on mechanical behavior were evaluated. In this experimental study, measurements were performed on a total of 24 specimens, with three replicates for each of the C and P type specimen groups, to evaluate compressive strength.

2.6. Splitting tensile strength test

The splitting tensile strength of the specimens was determined using the Brazilian test method. In this experiment, a compressive load was applied to prismatic specimens, inducing tensile stresses across the specimen's cross-section. As the applied load increased, the specimen fractured into two parts under tensile stress. To determine the splitting tensile strength of type C and type P specimens, experiments were conducted on a total of 24 specimens, with three replicates per group.

3. Results and Discussion

3.1. Characterization of C and P type acicular leaves

The microstructural characteristics of untreated and chemically treated C type and P type acicular leaves were investigated by scanning electron microscopy (SEM) to

clarify how fiber length and surface modification influence surface morphology prior to incorporation into cementitious composites.

SEM observations provide qualitative evidence regarding removal by extraction, surface roughening, and mineral deposition, all of which are known to affect fiber-matrix compatibility. Scanning electron microscopy (SEM) images of untreated C type leaves (Fig. 2) reveal a relatively smooth and compact surface characterized by longitudinal grooves and an intact epicuticular wax layer. At higher magnifications ($\times 500$ – $\times 1000$), subtle surface asperities and closed voids become apparent. These morphologies are representative of untreated lignocellulosic fibers, which are rich in waxy extractives

and hemi cellulosic components, potentially impeding interfacial interactions with cementitious matrices (De Aguiar et al. 2023; Melichar et al. 2024). Following the mineralization of $\text{Ca}(\text{OH})_2$, the surface of the fiber shows significant roughness due to the emergence of granular and platelet-like deposits. At higher magnifications ($\times 1000$ – $\times 4000$), these characteristics reveal the precipitation of calcium-based minerals on the fiber surface. The combined effects of alkaline pretreatment and mineralization diminish the impact of hydrophobic extractives and encourage a more varied surface topology. This change in surface properties indicates that surface modification following alkali pretreatment and mineralization was successful (Zhu et al. 2023; Maier et al. 2024).

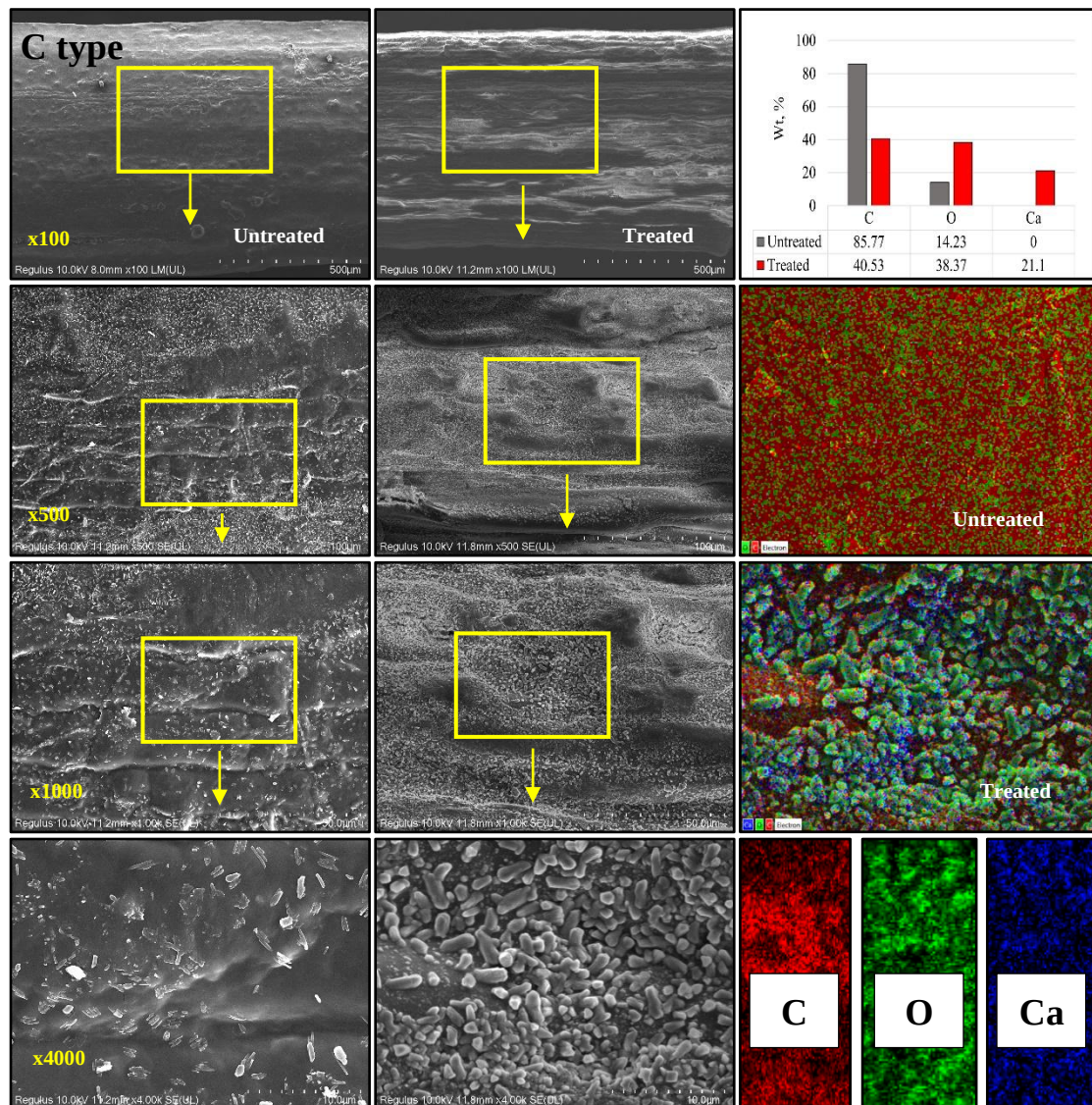


Fig. 2. SEM and EDS analysis of C type acicular leaves.

Fig. 2 shows the EDS analysis results and elemental mapping images of C-type fibers before and after $\text{Ca}(\text{OH})_2$ mineralization, illustrating the evolution of surface chemistry and the spatial distribution of C, O, and Ca. C-type fibers contain 85.77% wt% C and 14.23% wt% O. This result is characteristic of lignocellulosic biomass. It also shows a relatively homogeneous spatial

distribution of carbon and oxygen throughout the analyzed area, suggesting a chemically homogeneous surface before processing (Xia et al. 2023; Gharieb et al. 2024). After treatment with $\text{Ca}(\text{OH})_2$, a significant compositional change occurred in type C sheets. EDS results show a significant addition of calcium (21.10 wt%), a decrease in carbon content (40.53 wt%), and an increase in

oxygen content (38.37 wt.). This change clearly demonstrates that calcium-based phases effectively precipitate onto the fiber surface. Elemental mapping confirms that calcium is not homogeneously distributed, but rather concentrated in localized regions, forming mineral-rich areas that partially cover the organic substrate. This type of heterogeneous Ca enrichment has been commonly associated with surface deposition mechanisms where calcium hydroxide reacts with exposed hydroxyl groups in cellulose chains, promoting interfacial bonding rather than forming a continuous mineral shell (Feng et al. 2025).

In Fig. 3 untreated P type leaves exhibit a distinct longitudinal morphology characterized by a high length-to-diameter ratio. Scanning Electron Microscope (SEM) images captured at $\times 100$ and $\times 500$ magnifications reveal aligned grooves on a relatively smooth surface, whereas higher magnifications reveal only minor surface irregularities. This observed morphology indicates limited po-

tential for mechanical interlocking in the untreated condition, consistent with previous findings on pine-derived fibers (El Hamri et al. 2024; Albadrani 2023). Following the mineralization with $\text{Ca}(\text{OH})_2$, as shown in Fig. 3, the fiber surface experiences a notable change in morphology, characterized by the development of plate-like and clustered mineral formations. Under higher magnification, these formations appear as a thick yet uneven layer that partially fills surface grooves and microvoids (De Michele et al. 2025; Ajibola et al. 2024). Comparative SEM analysis reveals that chemical treatment and mineralization alter the surface morphology of both C type and P type fibers; however, the implications of these changes vary based on fiber geometry and loading mode. C-type fibers generally exhibit more homogeneous surface modifications, while P-type fibers display more localized mineralized regions (Kirker et al. 2024; El-Feky et al. 2024).

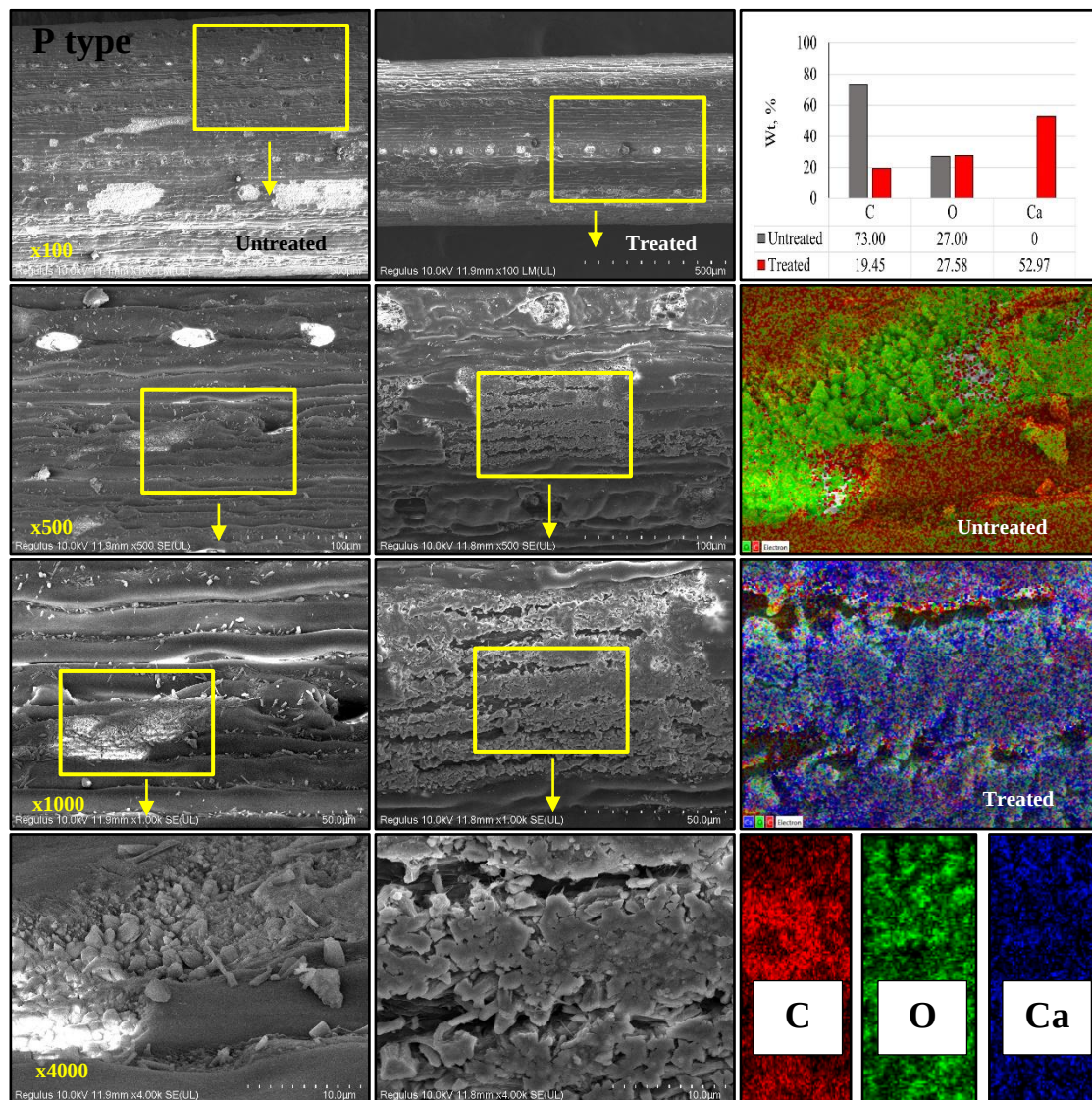


Fig. 3. SEM and EDS analysis of P type acicular leaves.

Fig. 3 shows the EDS results of the P-type fibers. The EDS results show a composition dominated by carbon (73.00 wt.) and oxygen (27.00 wt.) As a result of $\text{Ca}(\text{OH})_2$

mineralization, the fibers have a calcium-dominant surface composition; Ca is present at 52.97 wt., along with oxygen (27.58 wt.) and a significantly reduced carbon

fraction (19.45 wt). Elemental mapping reveals a dense and continuous distribution of calcium-rich phases throughout the analyzed area, indicating the formation of a robust inorganic layer that partially masks the underlying organic structure (Xu et al. 2025; Li et al. 2025; Zhang et al. 2025).

Fig. 4 illustrates the FTIR spectra of untreated and $\text{Ca}(\text{OH})_2$ -treated C type and P fibers, highlighting the chemical modifications induced by alkaline treatment and subsequent mineralization. In both untreated C type and P type fibers, broad absorption bands observed in

the 3600–3200 cm^{-1} region are attributed to O–H stretching vibrations associated with hydroxyl groups in cellulose, hemicellulose, and adsorbed moisture. These features are characteristic of lignocellulosic biomass and have been widely reported for untreated wood-based fibers (El Hamri et al. 2024; Maier et al. 2024). Following $\text{Ca}(\text{OH})_2$ treatment, a noticeable reduction in band breadth and intensity is observed, suggesting partial removal of hemicellulosic components and a decrease in free hydroxyl groups due to chemical interaction with calcium species.

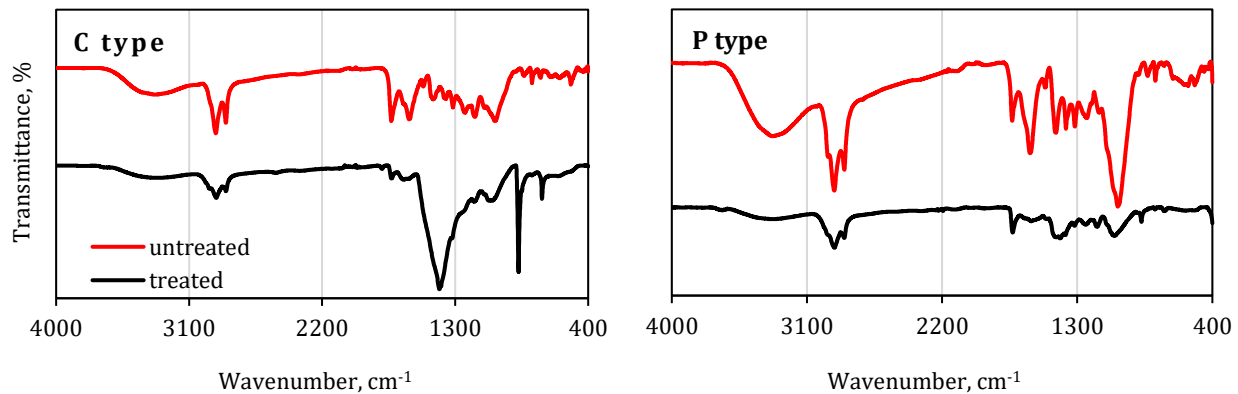


Fig. 4. FTIR analysis of C and P type acicular leaves.

The absorption bands located at approximately 2916 and 2849 cm^{-1} correspond to asymmetric and symmetric C–H stretching vibrations of aliphatic $-\text{CH}_2$ and $-\text{CH}_3$ groups originating from cellulose and lignin structures. In treated fibers, these bands exhibit reduced intensity, indicating partial degradation or extraction of amorphous organic constituents during alkaline treatment. Similar trends have been reported for alkali-treated lignocellulosic fibers intended for cementitious composites (Melichar et al. 2024; Zhu et al. 2023). In the carbonyl region, the band around 1720–1730 cm^{-1} , which is associated with C=O stretching of acetyl and ester groups in hemicellulose, is clearly visible in untreated fibers but becomes significantly weakened or nearly disappears after $\text{Ca}(\text{OH})_2$ treatment. This result indicates that the acetyl and ester groups associated with hemicellulose are reduced after $\text{Ca}(\text{OH})_2$ treatment (Kirker et al. 2024; Bufalino et al. 2023). The fingerprint region (1200–1000 cm^{-1}) exhibits notable bands at approximately 1170 and 1040 cm^{-1} , which are associated with C–O–C and C–O stretching vibrations of polysaccharide structures. These bands are observed after treatment with $\text{Ca}(\text{OH})_2$, suggesting that the fundamental cellulose framework remains unchanged (Zhao et al. 2025; Lin et al. 2026). Distinct differences between untreated and treated fibers are most evident in the emergence and intensification of bands around ~1400–1420 cm^{-1} , ~871 cm^{-1} , and ~712 cm^{-1} in $\text{Ca}(\text{OH})_2$ -treated specimens. These bands are characteristic of carbonate (CO_3^{2-}) vibrational modes and indicate the formation of calcium carbonate phases through carbonation of $\text{Ca}(\text{OH})_2$ (Zhao et al. 2025; Lin et al. 2026).

3.2. Compressive strength test

The cement-based composites developed in this study are similar to wood-cement composites and wood-based cement binder products in their applications. These materials are widely used in the construction industry, especially in the production of precast composite elements containing wood fibers or particles and in wood-cement-based pressed boards. Because such composite systems are generally not designed as load-bearing structural elements, high compressive strength is not considered a basic performance criterion. In fact, the literature frequently reports that the compressive strength of similar composite materials is relatively low (Canbaz et al. 2021; Garcez et al. 2016; Mahzabin et al. 2013). The main reason for this is the limited bonding capacity of wood-based phases with the cement matrix, which results in higher void ratios within the composite structure (Canbaz et al. 2021).

Fig. 5 shows the compressive strength results obtained at the end of 7 and 28 day curing periods for cementitious composites reinforced with P and C type natural fibers at different cement ratios; these values are key mechanical indicators reflecting changes in matrix development, fiber-matrix adhesion, and internal structural continuity. Across all specimen series, the curing process produced significant increases in compressive strength, associated with the formation of hydration products and a more compact matrix structure. In C type specimens, compressive strength ranged from 5.41 to 6.30 MPa during the 7 day curing period and increased to 7.15–9.09 MPa at the end of the 28 day curing period. With increasing cement content, compressive strength

rose by approximately 16.4% at 7 days and by approximately 27.2% at 28 days. This trend can be explained by the isotropic fiber arrangement formed by the random, multidirectional distribution of type C fibers, which allows the matrix to develop more homogeneously and transfer load more evenly during curing. In P type specimens, compressive strength was lower than in C type specimens. During the 7 day curing period, it ranged from 2.93 to 5.70 MPa, and at the end of the 28 day curing period, it increased to 4.02–7.98 MPa. When C and P type specimens are compared at the same cement ratios, C type specimens exhibit higher compressive strength at both curing times. During the 28 day curing period, the compressive strength of the C900 specimens was approximately 14.0% higher than that of the P900 specimens. This difference can be attributed to the isotropic arrangement of short fibers, which provides a more balanced stress distribution under compressive loads and increases the load-bearing capacity of the fibrous and porous structure, while effective stress redistribution is

also recognized as an important contribution of fiber-reinforced composite systems (Alshabrawi and Uysal 2025). The C type isotropic short fiber arrangement provided higher absolute compressive strength values than the P type orthotropic long fiber arrangement. These findings make it clear that fiber length and orientation are key design parameters that govern the compressive behavior of cementitious composites. In general, the 7- and 28-day compressive strength values for both C-type and P-type specimens are considerably lower than the compressive strength of concrete used in conventionally produced load-bearing systems. The main reason for this is the design approach and target application area of the developed composite system. The targeted application area is non-structural elements such as partition boards, lightweight panels, and rehabilitation layers. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) values are shown in Table 5.

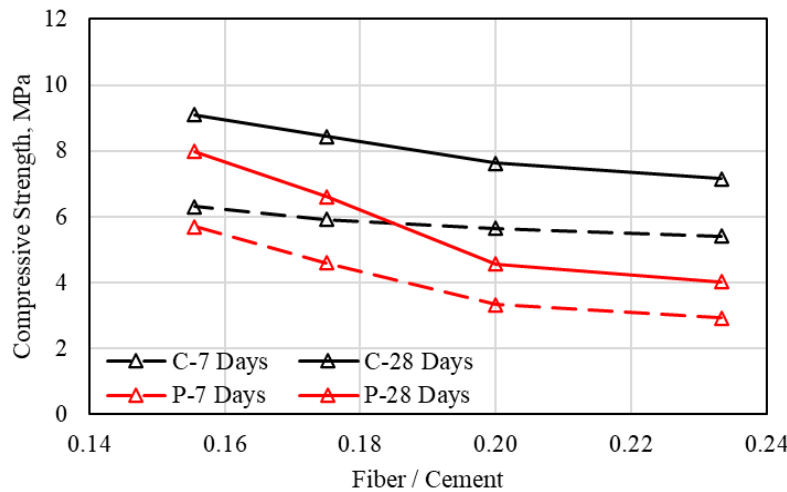


Fig. 5. Compressive strength at different fiber/cement ratios.

3.3. Flexural strength test

In Fig. 6, the flexural strength values obtained at the end of 7 and 28 day curing periods for different fiber/cement ratios in reinforced cementitious composites with P and C type natural fibers are presented. Flexural strength is a mechanical parameter directly related to the crack bridging capacity of the fibers, fiber orientation, and fiber-matrix interaction in fiber-cement composites. In C type specimens, flexural strength ranged from 0.91 to 2.32 MPa during the 7 day curing period and increased to 1.27–3.45 MPa at the end of the 28 day curing period. In P type specimens, flexural strength was significantly higher than in C type specimens. During the 7 day curing period, flexural strength ranged from 4.83 to 6.38 MPa, and at the end of the 28 day curing period, it ranged from 6.59 to 9.33 MPa. When C and P type specimens are compared at the same curing time and fiber/cement ratios, the flexural strength of P type specimens is much higher. For example, in the mixture with the highest cement content, the flexural strength of P type specimens was approxi-

mately 170% higher than that of C type specimens during the 28 day curing period. Similarly, even with a 7 day curing period, the flexural strength of P type specimens was approximately 2.5-5 times that of C type specimens. This higher-than-expected flexural strength is directly related to the fact that the long fibers in P type specimens are oriented in one direction perpendicular to the flexural plane. The tensile stresses that occur during the flexural test are concentrated on the lower surface of the specimen; long fibers placed in this direction cut off the direction of crack advancement, creating an effective crack bridging mechanism. The orientation of the fibers perpendicular to the load direction enabled them to experience the tensile stresses directly. It was found that isotropic fiber orientation made a minor contribution to flexural behavior compared to orthotropic orientation; the effect of fiber orientation on flexural behavior is much more pronounced than on compressive behavior. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) are shown in Table 5.

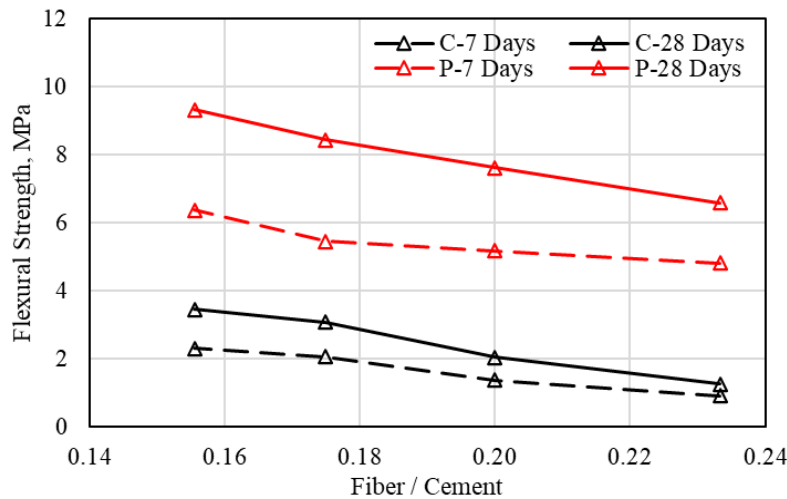


Fig. 6. Flexural strength at different fiber/cement ratios.

3.4. Splitting tensile strength test

In Fig. 7, the tensile strength values of composites reinforced with P and C type natural fibers, obtained at the end of 7 and 28 day curing periods for different fiber/cement ratios, are presented. Tensile strength at fracture is a mechanical parameter that is highly sensitive to fiber-matrix interactions and directly reflects resistance to crack initiation and propagation in cementitious composites. For C type specimens, tensile strength at splitting was measured at 1.10–1.55 MPa during the 7 day curing period, and these values increased to 1.37–2.12 MPa at the end of the 28 day curing period. With a decrease in the fiber/cement ratio (higher cement content), the strength increased by approximately 40.7% after 7 days and by approximately 55.5% after 28 days. This increase can be attributed to the matrix becoming more continuous as curing progresses, with cracks becoming multifaceted and demarcated due to the isotropic distribution of short C type fibers. In P type speci-

mens, tensile strength at splitting was higher in both absolute terms and in terms of increase rates. During the 7 day curing period, the strength of P type specimens ranged from 1.53 to 2.97 MPa, and at the end of the 28 day curing period, it reached 2.24–2.97 MPa. With a decrease in the fiber/cement ratio, the strength increased by approximately 34.8% after 7 days of curing and by approximately 32.7% after 28 days of curing. When C type and P type specimens are compared at the same curing time and fiber/cement ratios, the tensile strength of P type specimens at splitting is significantly higher. For example, in the mixture with the highest cement content, the tensile strength of the P type specimen at splitting during the 28 day curing period was measured to be approximately 40% higher than that of the C type specimen. A similar trend is observed during the 7 day curing period. This higher-than-expected tensile strength at splitting is directly related to the fact that the long fibers in P type specimens are oriented in one direction and perpendicular to the flexural and tensile planes.

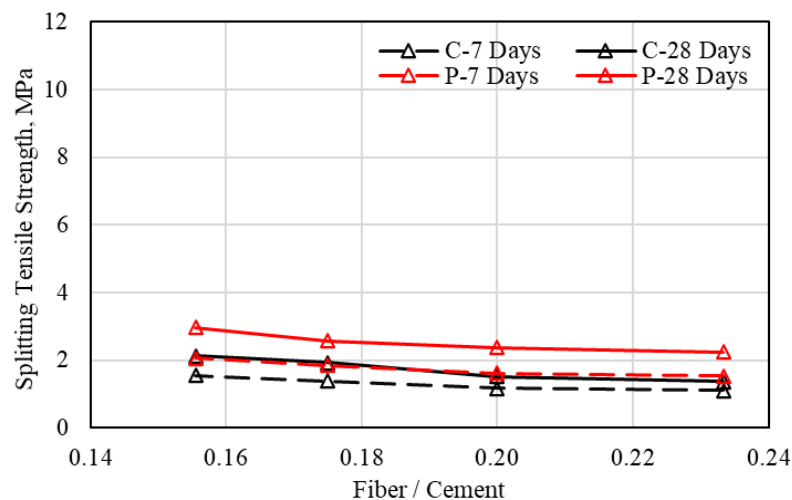


Fig. 7. Splitting tensile strength at different fiber/cement ratios.

In the split tensile test, tensile stresses along the specimen are concentrated in a central plane; long fibers placed perpendicular to this plane impede crack propa-

gation, creating an effective crack-bridging and tensile load carrying mechanism, consistent with the tensile-strength contribution of fiber reinforcement reported by

Youssef et al. (2026). The length and orientation of the fibers increase tensile strength to levels higher than expected. The increase in tensile strength at splitting in C type specimens was more balanced but more limited compared to orthotropically oriented P type specimens. When tensile strength results from the split are evaluated alongside the compressive and flexural strength results, it is evident that the role of fiber orientation in mechanical behavior varies with the type of loading. While the C type isotropic short fiber arrangement provided more balanced and high strengths in compressive behavior, the P type orthotropic long fiber arrangement showed significant superiority in loading situations where tensile stresses, such as flexure and splitting tensile, were dominant. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) are shown in Table 5.

3.5. Unit weight

Fig. 8 presents the unit weight values for composites reinforced with P and C type natural fibers at different

cement ratios. The results clearly show that fiber type, fiber length, and fiber orientation have a pronounced effect on composite density. Across all specimen series, unit weight increased with higher cement content. This trend can be attributed to increased cement content, greater matrix volume, and more efficient filling of fiber-induced voids. In particular, in mixtures containing 800 g and 900 g of cement, a denser matrix structure develops, and the internal void ratio decreases markedly. In type C specimens, the unit weight increased from 1.394 kg/dm³ to 1.596 kg/dm³ with increasing cement content, and in type P specimens, it increased from 1.273 kg/dm³ to 1.675 kg/dm³. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) values are shown in Table 5. In addition, the decrease in unit weight may not be solely due to the low density of the fibers. It is also associated with increased porosity and an increase in the void ratio in the matrix with the addition of fiber. In particular, the fibers partially disrupt the matrix continuity and reduce the compactness of the mixture in the composite structure.

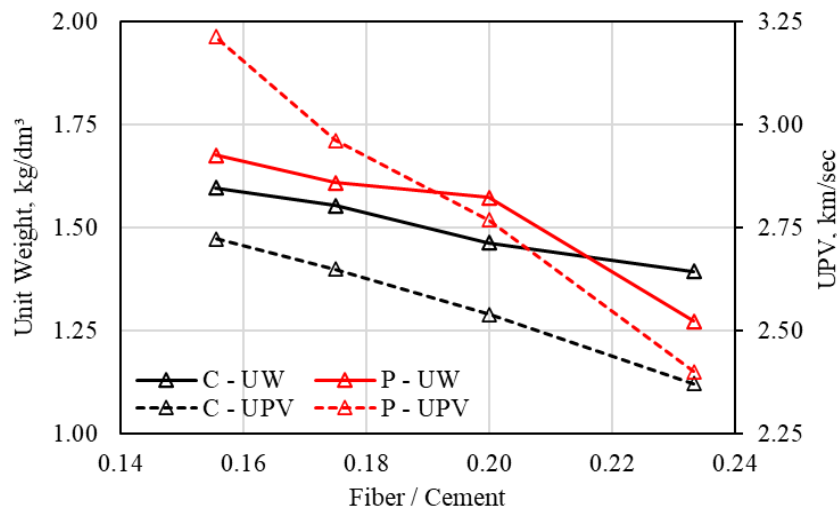


Fig. 8. Unit weight and UPV at different fiber/cement ratios.

3.6. Ultrasonic pulse velocity test

In Fig. 8, the measured ultrasonic pulse velocity (UPV) values of composites reinforced with natural fibers of types P and C at different cement ratios are presented. UPV results provide information on the continuity of the internal structure, the distribution of gaps, and fiber-matrix interactions in composites. Similar sensitivity of UPV to internal structural continuity was reported by Ünal et al. (2025). Across all specimen series, a significant upward trend in UPV values was observed with increasing cement content. This can be attributed to a denser matrix, a lower void ratio, and more continuous ultrasonic wave propagation through the material. In type C specimens, UPV was measured at 2.371 km/s in the C600 specimen and 2.723 km/s in the C900 specimen, representing an increase of approximately 14.9%. The isotropic fiber arrangement, formed by the random, multi-

directional distribution of short type C fibers, provides a more homogeneous structure within the matrix, allowing more uniform propagation of ultrasonic waves. This behavior is consistent with the increase in homogeneous density observed in the unit-weight results. In P type specimens, the increase in UPV was more pronounced. UPV, measured at 2.400 km/s in the P600 specimen, increased to 3.214 km/s in the P900 specimen, representing approximately a 34.0% increase. The orthotropic fiber arrangement, created by orienting long P type fibers perpendicular to the load direction and in a single direction, produced discontinuities around the fibers at low cement ratios; however, with increasing cement content, these discontinuities were largely eliminated, resulting in a significant improvement in ultrasonic wave transmission. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) values are shown in Table 5.

In addition, water absorption tests were conducted to determine the water absorption behavior of the specimens at the end of the 28-day curing period. According to the results, the water absorption rates of C600–C900 type specimens were 17.5%, 17.20%, 16.70%, and 16.10%, respectively. In addition, the water absorption values of the fibers are given in Table 2, and the fibers in the mixture are also likely to absorb some of the mixing water. On the other hand, these rates were measured as 19.10%, 18.60%, 18.30%, and 17.90% in P600–P900 type specimens. The findings show that the void ratio decreases as the matrix gains a denser, more continuous structure with increasing cement content, and water absorption capacity decreases accordingly. They also show that an increase in fiber content leads to higher water absorption values, indicating increased pore volume and connectivity within the composite structure. This increase in porosity is thought to negatively impact the propagation of ultrasonic waves, resulting in lower UPV values.

3.7. Dynamic modulus of elasticity

Fig. 9 shows the dynamic modulus of elasticity for composites reinforced with P- and C-type natural fibers, calculated at different cement contents. The dynamic modulus of elasticity is an important parameter that

reflects the rigidity and continuity of the internal structure of composites. When evaluated alongside the unit weight and UPV results, it enables a holistic interpretation of material behavior. Across all specimen series, a significant upward trend in the dynamic modulus of elasticity was observed with increasing cement content. This may be attributed to the matrix developing a denser, more continuous structure, increased fiber-matrix contact area, and a reduced void ratio. Increases in unit weight and UPV values support the results for the dynamic modulus of elasticity. In type C specimens, the dynamic modulus of elasticity ranged from 7.99 to 12.06 GPa, and the modulus increased by approximately 50.9% with higher cement content. The isotropic fiber arrangement, formed by the random, multidirectional distribution of C-type short fibers, yields a more homogeneous internal structure, thereby increasing rigidity. In P-type specimens, the dynamic modulus of elasticity increased from 7.48 GPa to 17.65 GPa, a rise of approximately 136.1%. This is because the UPV value used in the calculation was measured in the orthotropic plane. For this reason, the rigidity appears relatively high in this direction. Mean results were calculated for each variable's experimental outcome, and the standard deviation (SD) and coefficient of variation (CV) values are shown in Table 5.

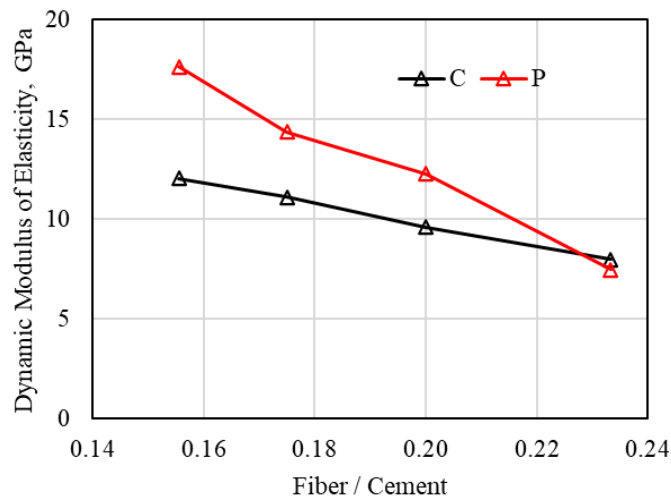


Fig. 9. Dynamic modulus of elasticity at different fiber/cement ratio.

3.8. Fracture analysis

In Fig. 10, the observed fracture forms after flexural, compressive, and splitting tensile tests on P and C type natural fiber-reinforced cementitious composites produced at different cement ratios were evaluated, and the damage patterns qualitatively confirm the mechanical performance results.

Spread crushing behavior is dominant in both C type and P type specimens under compressive loading, and the compressive behavior is mainly controlled by matrix continuity. On the other hand, under tensile stress conditions such as flexural and splitting tensile loading, fiber length and orientation become decisive; the long, orthotropically oriented P-type fibers delay fracture through crack bridging, resulting in more ductile and

controlled damage development. Type C specimens with an isotropic short-fiber arrangement exhibit more homogeneous crack control but limited crack control and complete fracture, with a more classical separation mechanism.

4. Conclusions

In this study, Cedrus libani A. Rich. and Pinus nigra Arnold were evaluated for their effects on the physical and mechanical behavior of cementitious composites as a function of fiber length and orientation. The results clearly demonstrated that fiber geometry and orientation govern distinct mechanical responses under different loading conditions. It was determined that isotropic

composites produced with short, randomly distributed *Cedrus libani* acicular leaves exhibited a more homogeneous internal structure, which positively affected compressive strength, unit weight, and ultrasonic pulse velocity. The isotropic fiber arrangement supported matrix continuity, providing a more balanced stress distribution under compressive loads and promoting stiffness development. On the other hand, in orthotropic composites in which long *Pinus nigra* acicular leaves are oriented perpendicular to the load direction, tensile strength in flexural and splitting tests was observed to increase significantly. This increase has been attributed to the fact that long fibers provide an effective crack-

bridging mechanism under loading conditions dominated by tensile stresses. The results for ultrasonic pulse velocity and dynamic modulus of elasticity indicated differences in internal structural continuity and rigidity with respect to fiber orientation. It has been determined that ultrasonic wave transmission increases with stronger fiber-matrix interaction, particularly at high cement ratios, and that a more continuous structure form. Fracture observations indicate that matrix-controlled failure behavior predominates under compressive loads; in tensile loading in flexural and splitting tests, fiber orientation significantly affects the fracture mode and limits crack propagation.

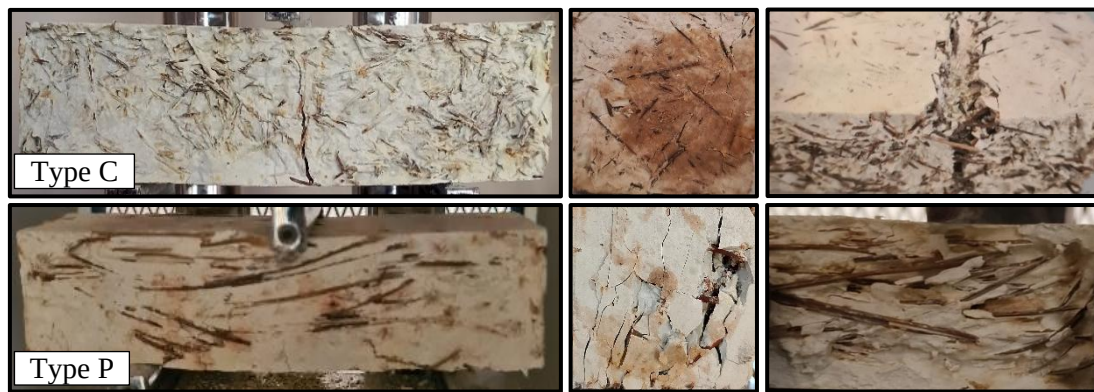


Fig. 10. Fracture analysis of type C and P specimen (flexural, compressive, and splitting tensile tests).

Table 5. Statistical analysis of data.

Code	Cure	Compressive Strength (MPa)			Flexural Strength (MPa)			Splitting Tensile Strength (MPa)		
		Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)
C600	7 days	5.41	0.22	4.1	0.91	0.07	7.7	1.10	0.07	6.4
C700		5.64	0.32	5.7	1.38	0.11	8.0	1.17	0.05	4.3
C800		5.93	0.30	5.1	2.06	0.14	6.8	1.39	0.11	7.9
C900		6.30	0.44	7.0	2.32	0.10	4.3	1.55	0.10	6.5
C600	28 days	7.15	0.37	5.2	1.27	0.08	6.3	1.37	0.06	4.4
C700		7.63	0.53	7.0	2.05	0.11	5.4	1.51	0.07	4.6
C800		8.44	0.62	7.3	3.09	0.16	5.2	1.93	0.11	5.7
C900		9.09	0.45	5.0	3.45	0.20	5.8	2.13	0.17	8.0
P600	7 days	2.93	0.22	7.5	4.83	0.29	6.0	1.53	0.10	6.5
P700		3.33	0.16	4.8	5.18	0.32	6.2	1.62	0.09	5.6
P800		4.59	0.23	5.0	5.46	0.22	4.0	1.86	0.09	4.8
P900		5.70	0.30	5.3	6.38	0.43	6.7	2.07	0.15	7.2
P600	28 days	4.02	0.23	5.7	6.58	0.27	4.1	2.24	0.11	4.9
P700		4.57	0.33	7.2	7.63	0.31	4.1	2.37	0.17	7.2
P800		6.62	0.33	5.0	8.44	0.62	7.3	2.57	0.20	7.8
P900		7.97	0.59	7.4	9.33	0.51	5.5	2.97	0.14	4.7
Code		Unit Weight (kg/dm ³)			UPV (km/s)			$E_{dynamic}$ (GPa)		
		Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)
C600	28 days	1.39	0.10	7.2	2.37	0.10	4.2	7.99	0.61	7.6
C700		1.46	0.11	7.5	2.54	0.20	7.9	9.61	0.46	4.8
C800		1.55	0.12	7.7	2.65	0.21	7.9	11.12	0.74	6.7
C900		1.60	0.11	6.9	2.72	0.12	4.4	12.06	0.73	6.1
P600	28 days	1.27	0.08	6.3	2.40	0.14	5.8	7.48	0.56	7.5
P700		1.57	0.09	5.7	2.77	0.22	7.9	12.29	0.54	4.4
P800		1.61	0.09	5.6	2.96	0.19	6.4	14.38	0.96	6.7
P900		1.68	0.12	7.1	3.22	0.22	6.8	17.65	0.88	5.0

SEM analyses showed that $\text{Ca}(\text{OH})_2$ treatment produced partial surface mineralization and increased surface roughness, while EDS and elemental mapping confirmed progressive calcium enrichment and a corresponding decrease in surface carbon content. FTIR results further indicated the removal of hemicellulosic components and the formation of carbonate-related bands without altering the cellulose backbone. These findings confirm the surface modification and mineralization of the fibers.

In general, the short, isotropic fiber arrangement offers advantages in terms of compressive behavior and internal structural continuity. In contrast, the long, oriented fiber arrangement makes a greater contribution to mechanical behavior when tensile effects predominate. These findings reveal that fiber length and fiber orientation are key parameters that should be evaluated together in the design of natural fiber cementitious composites, depending on the targeted mechanical performance. Cedrus libani A. Rich. and Pinus nigra Arnold species as natural fibers, showing that it is a suitable approach to improve the mechanical behavior of cementitious composites. Based on the twenty-eight-day cure results, the inclusion of these fibers in the matrix limited crack initiation and propagation, thereby making charge transfer more controlled. The isotropic distribution of short Cedrus libani acicular leaves has a positive effect on compressive strength and internal structural homogeneity by supporting matrix continuity; the directed use of long Pinus nigra acicular leaves provided significant increases in tensile strength in flexural and splitting, where tensile stresses are dominant. It has been shown that as fiber-matrix interaction strengthens, fracture behavior tends toward a more controlled mode of damage, and fibers play an active role in improving mechanical performance.

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Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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