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Experimental Investigation of the Mechanical, Physical, and Microstructural Performance of Cement Boards Reinforced with Hybrid and PVA Fibers

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Abstract

This study explores the combined influence of hybrid fibers (HF) and polyvinyl alcohol (PVA) fibers on the structural and physical performance of fumed-silica cement boards. Scanning electron microscopy (SEM) was employed to analyze mortar mixtures containing different fiber proportions and to assess improvements in their microstructure. The experimental program included tests for compressive strength, stiffness, density, ultrasonic pulse velocity, and setting time. Findings show that incorporating 1% hybrid fibers yields the best mechanical performance, achieving a compressive strength of 46.89 MPa and a stiffness of 99.34, along with a 2.16% reduction in density compared to the reference mix. A mixture with 2% PVA fibers also enhances compressive strength (43.4 MPa) and stiffness, while higher fiber content generally leads to longer setting times. SEM observations revealed effective crack-bridging and thickening of the base matrix. Overall, the results indicate that the combination of 1% HF fibers and 2% PVA fibers represents the optimal formulation in terms of strength, durability, and rigidity, supporting the development of more advanced and high-performance cement boards.

Keywords: Hybrid; Poly vinyl fiber; SEM; Density; Setting Time.

1. Introduction

The construction industry has come a long way over the past few decades, driven by customers' desire for materials that last longer and perform better in hot weather. Cement boards are one of the most popular building materials for buildings and structures. However, they are not widely used due to their problems, including surface cracking, increased moisture absorption, and poor load-bearing capacity over time.[1, 2]

To address these problems, more cementitious additives have been used, including silica fume. Silica fume makes materials stronger, less porous, and denser at the microscopic level. It is often said that replacing 10% of silica fume is the ideal amount for optimal performance and lower cost. Adding fiber to cement composites has also proven to be a smart way to make them stronger and better able to withstand heat. Basalt fibers make materials stiffer and more rigid, while polyvinyl alcohol (PVA) fibers make materials more flexible and help prevent cracks from widening.[3]

The incorporation of these fibers into a hybrid system with a fixed 10% silica fume concentration is expected to have a synergistic effect, enhancing the strength and durability of the material. This study aims to evaluate the effect of hybrid fiber reinforcement (basalt + PVA) on the mechanical and thermal properties of cement boards, with a focus on determining appropriate fiber ratios to optimize performance. [4, 5]

2. Experimental Work and Material

2.1. Material

The test specimens were made with a number of different materials. These were cement, fine aggregate, water, silica fume, PVA , and basalt fibres

2.1.1. Cement

This study used Ordinary Portland Cement (Type I), which was made in Iraq and sold under the name Tasluja. It met the requirements of ASTM C150-04 [6] for its physical and chemical properties.

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Table 1. The chemical composition of ordinary Portland cement OPC type (I).

Oxides Composition	Oxide content%	Limits of Iraqi Specification No.5/1984
SiO_2	20.2**6**	-
Al_2O_3	5.50	-
Fe_2O_3	2.**19**	-
CaO	61.**39**	-
MgO	2.29	< 5.00
SO_3	2.5	< 2.8
Free CaO	1.12	-
Loss on Ignition	3.4	< 4.00
Insoluble Residue	0.71	< 1.50
Lime Saturation Factor	0.92	0.66-1.02

2.1.2. Fine Aggregate

This study utilised natural sand that passed through a 1.18 mm filter as fine aggregate. The chosen sand was Ottawa sand, which met ASTM C778 standards.[7] Table 2 shows how the fine aggregate's particles are spread out by size. The fine aggregate meets ASTM C778 grading standards because it is easy to work with, has the right packing density, and spreads evenly throughout the cementitious matrix.

Table 2. The size of the particles in the fine aggregate

Sieve size	Percent passing (%)	Specification limits (%)
10	100	100
4.75	92.7	90_100
2.36	79.65	75_100
1.18mm	68.6	55_90
600 µm	52.6	35_59
300 µm	27.4	8_30
150	2.65	0-10

2.1.3. Silica fume

Silica fume is a kind of silicon dioxide (SiO_2) that does not have a crystal structure. The particles are very small, with an average size that is almost 1/100th that of regular cement grains. Silica fume is a very reactive pozzolanic material when added to cementitious systems because it is very fine, has a large specific surface area, and has a lot of SiO_2.[8]

Table 3. Information on silica fume

Compound	Wt %
SiO_2	95.10
Fe_2O_3	0.10
CaO	0.24
MgO	0.43
Na_2O	0.23
K_2O	0.93
SO_3	0.11
L.O. I	2.0
	Σ= 99.99

*Chemical tests were conducted by Iraq geological survey, central laboratories department.

Table (3) shows that silica fume has more than 90% SiO_2, which makes it more reactive as a pozzolan and helps make a denser cementitious matrix.[9]

2.1.4. Basalt Fibre

To make basalt fibre, real basalt rock is melted at about 1500 °C and then extruded into long, thin strands. The technique of making it is similar to making glass fibres, however it is thought to use less energy [10]. The Iraqi Sika Company provided basalt fibres for this investigation, which were utilised to strengthen cement mortar. strength more than 3000 MPa, which shows that they are good in making cementitious composites stronger and less likely to break.

Table 4. The basalt fiber properties

Properties	Continuous Basalt fiber
Breaking Strength (Mpa)	3,000 – 4,840
Modulus of Elasticity (Gpa)	3,100– 3,800
Breaking Extension (%)	3.1
Fiber Diameter (µm)	6 - 21
Linear Density (tex)	60-4,200
Temperature Withstand (℃)	-260….+700

2.1.5. Superplasticizer

Polycarboxylate (VISCO CRETE-180 GS) is a high-performance additive that meets ASTM C494 standards . It works as a water-reducing, set-retarding, shrinkage-controlling, and superplasticizing agent for both concrete and mortars.[11]

Table 5. the specifications of Polycarboxylate super plasticizer

Composition	Aqueous solution of modified polycarboxylates
Packaging	Bulk Deliveries 1000 LTRs IBC 20 kg Pail
Appearance / Colour	Light brownish liquid
Storage conditions	In dry conditions at temperatures between +5°C and +35°C. Protect from direct sunlight. It requires recirculation when held in storage for extended periods.
Specific gravity	1.070 ± (0.005) g/cm^3
pH-Value	4 - 6
Total chloride ion content	Nil

The use of a polycarboxylate-based superplasticizer (Table 5) makes sure that the mix is easy to work with and that the fibres are evenly spread out, while also cutting down on the need for more water .

2.1.6. polyvinyl alcohol

Polyvinyl alcohol (PVA) fibers, obtained from Lakhani Fabrics Company, India, are high-performance reinforcing materials for mortar and concrete. They are characterized by excellent crack-control ability, high tensile strength, and significant modulus of elasticity. [12] Unlike many synthetic fibers, PVA fibers form strong molecular bonds with the cementitious matrix—up to three times higher than conventional alternatives—resulting in improved crack resistance and durability. Their technical properties are summarized in Table (6).[13]

Table 6. The polyvinyl alcohol fiber Technical Parameter

Technical Parameter	100% PVA
Fibre Type	Bunchy Monofilaments
Density	1.29
Formula	（CH2CHOH)n
Titer	1.80-2.40 Dtex
Dry breaking tenacity	≥11.50 cN/dtex ≥
Dry breaking elongation	4.0-9.0 %（L/L）
Initial modulus	280 cN/dtex ≥
Specification	6MM, 12MM
Hot water resistance	2.0 % ≤
Oli agent content	0.2 % ≤

2.2. Mixture design

In this investigation, six mortar mixes were formulated with a consistent cement-to-sand ratio of 1:2.75 by weight and a predetermined water-to-binder ratio (W/B) of 0.42. Table (7) shows the total amount of binder in all the combinations. To get a flow value of (100 ± 5)% at the low W/B ratio of 0.42, a reference mix (Ref.) was made by adding 1.5% superplasticizer by weight of cement. We made three modified mixes (PVA1, PVA2, and PVA3) from this reference mix by substituting 10% of the cement with silica fume (SF). Also, hybrid mixes (A) were made by mixing basalt fibres and PVA fibres in equal amounts, with a predetermined amount of silica fume at 10%. The addition of SF makes new mortar much less workable and needs more superplasticizer, therefore a replacement level of 10% was chosen as the best ratio . By changing the amount of superplasticizer used, the flow of all mixtures stayed within the intended range of (100 ± 5)%. All samples were put in a normal curing tank with water for 7, 14, and 28 days. Table (3) shows the exact amounts of each item required to make the mixtures.

Table 7. The chemical composition of ordinary Portland cement OPC type (I).

Mixture Name	Cement (g)	Sand (g)	Water (g)	SF (g)	BF%	PVA%
Ref	1000	2750	420	0	0	0
H 1	900	2750	420	100	0.5	0.5
H 2	900	2750	420	100	1	1
H 3	900	2750	420	100	1.5	1.5
P 1	900	2750	420	100	0	1
P 2	900	2750	420	100	0	2
P 3	900	2750	420	100	0	3

The experimental program tested the physical and mechanical characteristics of samples of cement mortar. We used standard tests to find the compressive strength (ASTM C109/C109M) [14] , splitting tensile strength (ASTM C496/C496M) [15] , flexural strength (ASTM C348) [16] , water absorption (ASTM C642)[17], ultrasonic pulse velocity (ASTM C597-22)[18] , and thermal conductivity (ASTM C1113/C1113M)[19] . Samples of various shapes and sizes were made according to each technique, cured under uniform circumstances, and examined at 7, 14, and 28 days to provide precise comparisons across mix patterns.

3. Results and Discussion

3.1. Compressive Strength Results

Comparing the compressive strength results at 7, 14, and 28 days to the reference mix, it is evident that the addition of basalt (BF), PVA, and hybrid fibers improves the results.The reference panels had the lowest strength (22.58, 28.47, and 40.88 MPa) across all age groups. Hybrid mixes (H1–H3) fared the best overall. H1 achieved the highest long-term strength (46.89 MPa at 28 days), indicating that BF and PVA work in concert. Basalt fibers added stiffness and strength,[19, 20] while PVA fibers enhanced toughness and crack-bridging. Conversely, higher dosages (H2, H3) showed reduced early strength, most likely due to increased fiber clustering and porosity. PVA mixes also improved strength when compared to the reference. The optimal dosage of 2% (PVA2) was 43.43 MPa at 28 days. Increasing the PVA content to 3% resulted in a slight decrease in strength (41.42 MPa), indicating that an excessive number of fibers negatively impacts matrix densification. [21] Overall, hybrid reinforcement—especially H1—provided the best balance of strength development across curing ages.[22]

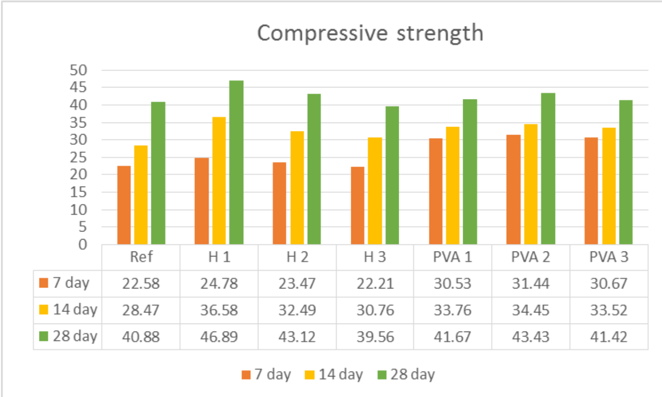

Figure 1. The compressive strength behavior of different mixing ratio

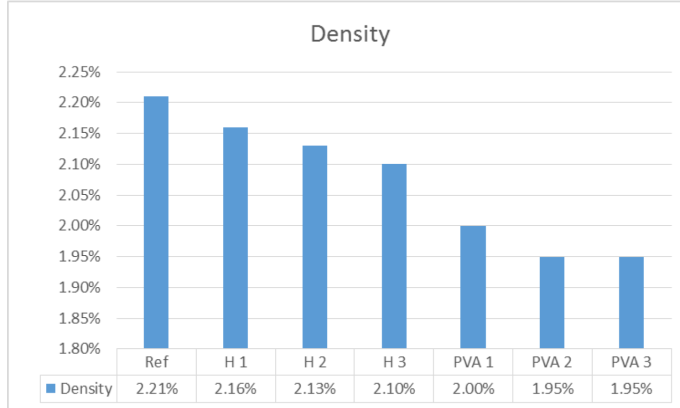

Figure 2. Density of different mixing ratio

3.2. Density

The density test is one of the basic tests in studying the physical properties of concrete and cement mortar. It is considered an important indicator of the mixing quality and homogeneity of the internal structure of the sample. A high density indicates a decrease in internal pores and defects, while a low density indicates an increase in pores and gaps, which indicates a decline in mechanical properties. The results of this test are also used to evaluate the effect of additives, whether mineral or fiber, on improving or reducing the cohesion of the microstructure The density test is one of the basic tests in studying the physical properties of concrete and cement mortar. It is considered an important indicator of the mixing quality and homogeneity of the internal structure of the sample. A high density indicates a decrease in internal pores and defects, while a low density indicates an increase in pores and gaps, which indicates a decline in mechanical properties. The results of this test are also used to evaluate the effect of additives, whether mineral or fiber, on improving or reducing the cohesion of the microstructure..

As for the diagram (2), adding PVA fibers to the reference mix leads to a decrease in density, and as the percentage of fibers increases, the density decreases due to the interlocking of fibers within the structure and the generation of gaps between them. At 1%, it recorded 2, and at 2% and 3%, it recorded 1.95 , and When adding hybrid fibers, the highest density is achieved at 1% compared to the rest of the added percentages of basalt and PVA fibers. This indicates that the mixture of both basalt fibers and PVA fibers will provide a high density, as each of them performs a specific function and increases the interlocking between them and the homogeneity between the matrix and the fibers. Because their density is different, it will reduce the gaps between them and give a structure with good density and good mechanical and physical properties[23].

3.3. Ultrasonic Pulse velocity

This test demonstrates the density of a material by passing waves through it and measuring the wave speed. As the speed increases, the internal density of the material increases[24]. While we note that UPV gradually decreases with increasing PVA content,as showing in the figure (3) the highest UPV value (4521 m^3/s) was found at 1% PVA, while it decreased slightly at 2% PVA (4432 m^3/s) and the decrease increases to (4265 m^3/s) at 3% PVA compared to 1% PVA. [25, 26] These results indicate a decrease in UPV with increasing fiber content compared to lower fiber contents, due to lower workability leading to increased fiber clumping and difficulty in homogeneous distribution.

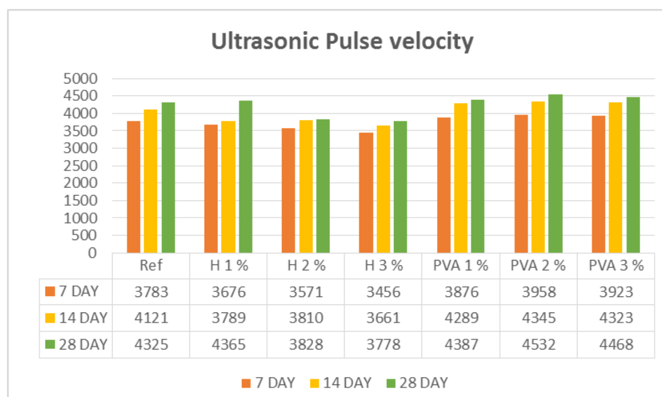

Figure 3. Water Absorption behavior of different mixing ratio

However, it has the ability to resist the bridge stress transmitted through the PVAF, BF crack, leading to high compressive strength up to a certain fiber content [27]. For hybrid fibers, the UPV value increases with the curing period from 7 to 28 days. This is due to the continued hydration process and the increased thickness of the microstructure resulting from the reaction of calcium hydroxide in the cement with silica fume during cement hydration. This reaction forms a C-S-H gel that fills the voids and enhances the bonding between the cement paste components. It was observed that the mixture containing 1%

fibers achieved the highest UPV value (4467) at 28 days compared to the control mixture. This indicates that adding 1% fibers improves density and the bonding between the fibers and the cement matrix. This is attributed to PVA fibers improving internal bonding and reducing internal cracking due to their high adhesion to the matrix, while basalt fibers prevent crack propagation and improve durability. Conversely, the UPV value decreases when the fiber percentage increases to 2% and 3%. This is due to fiber clumping and heterogeneous dispersion, leading to increased voids around them. Despite the presence of silica dust, the fibers act as a barrier, preventing the uniform dispersion of silica dust particles within the substrate. They fill the voids around the fibers, causing them to clump together in certain areas. Overall, the results indicate that a 1% hybrid mixture (polyvinyl alcohol + basalt) with silica dust achieves the best balance between density, internal bonding, and ultrasonic velocity, while larger increases in fiber content lead to a slight deterioration in the homogeneity of the concrete structure.

3.4 Setting time

Figure (4) shows the development of setting time when PVA is added at a rate of 1-3% by weight to a mortar (cement containing 10% by weight of SF). We note that setting time increases with the addition of PVA fibers due to the reduction in workability and increased viscosity, making water distribution within the mortar less efficient. This slows the movement of water into the cement particles, thus slowing down the hydration reaction and apparent setting [28]. As the percentage of added fibers increases, setting time increases due to the formation of a fiber network within the matrix. This network may prolong the time required for the particles to bond together to initiate the primary reaction. and the Figure shows the development of the setting time when HF is added at a rate of 1-3% wt in mortar (cement containing 10% wt of SF). The diagram indicates an increase in setting time when HF fibers are added because the presence of basalt fibers increases viscosity and water content, while PVA fibers reduce workability and also increase viscosity. Therefore, the mixture of these two types delays the setting time. However, the presence of SF may reduce the setting time, but only slightly, because it accelerates the pozzolanic reaction, and when the percentage of fibers increases, its effect is very small [29, 30].

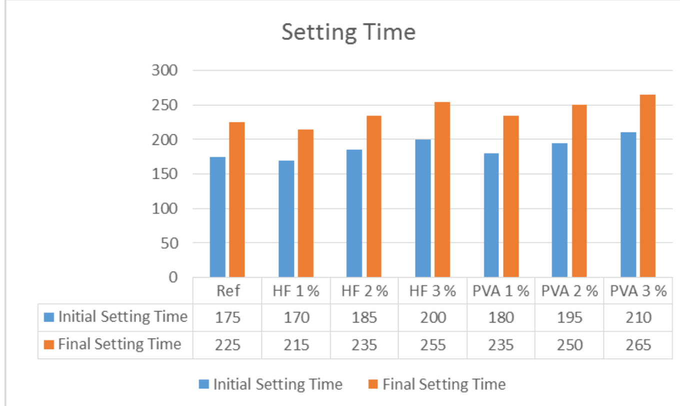

Figure 4. Influence of HF wt% and PVA on the Initial and Final Setting Time (IST, FST) of Mortar While Keeping SF Percent Fixed (10 wt%)

3.5 Hardness Test

Shore D hardness is a measure of the hardness resistance of a material. This test is affected by several factors such as the particle size involved in the mixture, the degree of moisture, and the age of the sample.

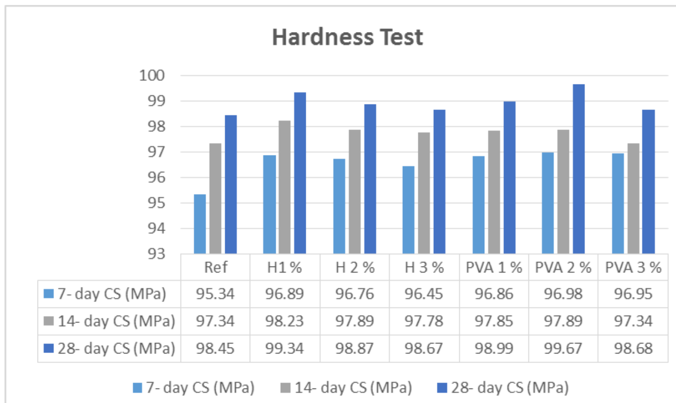

Figure 5. Hardness test of PVA and hybrid fiber at different mixing ratio with SF (10 wt%) Percent Fixed in mortar

While the (5) chart shows the addition of PVA fibers at different doses and also with a fixed silica fume replacement ratio, we notice a gradual increase in hardness, and the highest hardness was achieved at a certain ratio, after which it decreased slightly. This indicates that at this ratio, a homogeneous distribution of fibers was obtained[31] .While H1% yields a stiffness percentage higher than the reference value, this can be explained by the addition of 10% silica fibers, as well as the combined effect of adding both basalt and PVA fibers. Silica fills the pores in the concrete structure, basalt fibers provide surface resistance to deformation, and PVA reduces premature surface cracking, thus giving the surface high stiffness.

Therefore, H1 achieves a balance between distribution and density. [32]

Characterization Measurement

Scanning electron microscope (SEM) imaging was used to characterize the microstructure around the fiber-cement matrix interface.[33]

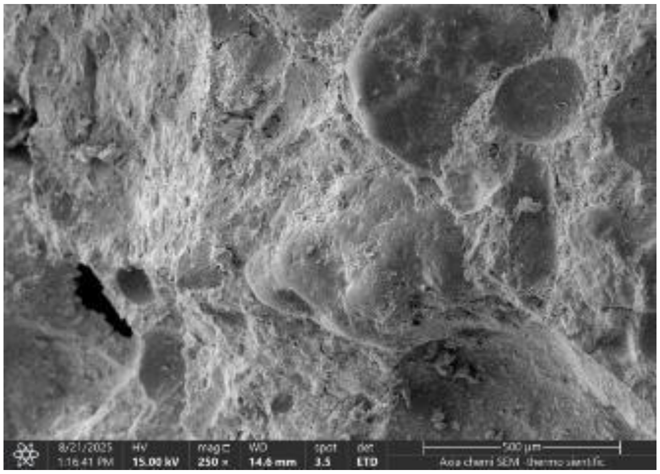

Figure 6. The SEM of microstructure surface of control sample

The scanning electron microscope image shows a relatively heterogeneous and porous microstructure, with clear gaps and microcracks in the reference mix. This indicates the presence of weak interfacial zones and large pores in the cementitious matrix. [34]This explains the poor mechanical performance of the reference mix compared to the fiber-reinforced samples, resulting in reduced tensile and flexural strengths due to poor crack-bridge mechanisms.

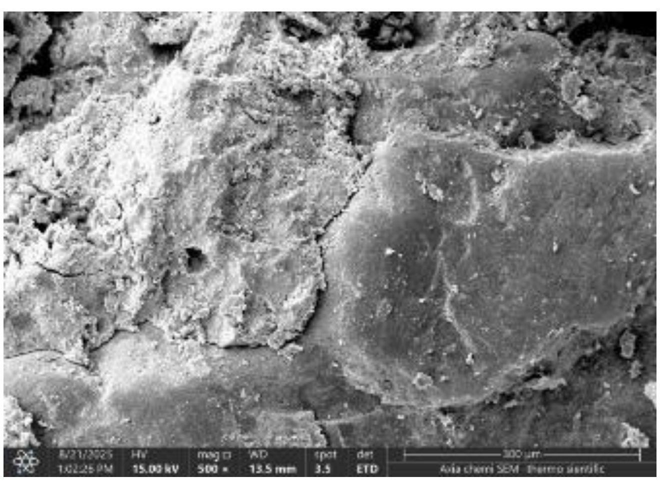

Figure 7. The SEM of microstructure surface of 2% addition of PVA sample

Figures (7) show poor interfacial bonding, with visible microcracks, due to the weak bond between the fibers and cement and the lack of additional hydration products to fill the interface gap. [33]

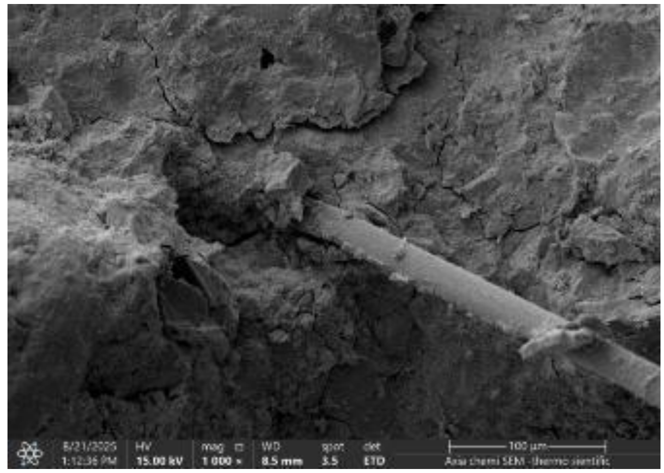

Figure 8. The SEM of microstructure surface of 3% addition of Hybrid sample

Figures (8) show better interfacial bonding as a result of basalt fibers. The addition of basalt fibers to the PVA fibers to form a hybrid enhanced the bonding between the fibers and the cement matrix, thus delaying crack propagation. [35,36] Therefore, SEM imaging demonstrated that the addition of basalt fibers significantly improved the bonding between the fibers and the cement matrix. This in turn contributed to bridging cracks and producing a more cohesive and robust microstructure.[37]

4. Conclusions

This research paper highlights several key findings regarding the effect of hybrid (H) fibers and polyvinyl alcohol (PVA) fibers on the mechanical and physical performance of cement boards, based on experimental and analytical data. The following is a summary of the main findings:

- The use of hybrid (H) fibers and polyvinyl alcohol (PVA) fibers improved the mechanical and physical properties of cement boards.

- A 1% hybrid fiber composition showed significant improvement, achieving exceptional compressive strength (46.89 MPa), stiffness (99.34), and density (2.16%). Ultrasonic pulse velocity: 4365 m^3/s

- PVA fibers performed best at a 2% hybrid fiber composition, achieving a compressive strength of 43.43 MPa, stiffness of 99.67, and an ultrasonic pulse velocity of 4532 m^3/s .

- We observe that the setting time increases with the percentage of added fibers, due to the formation of a fiber network within the base material. This network may extend the time required for the molecules to bond together and initiate the initial reaction.

- Both fiber types enhanced water absorption compared to the control mix, indicating a balance between mechanical reinforcement and strength. Scanning electron microscopy (SEM) images showed that the addition of basalt fibers significantly improved the bond between the fibers and the cement matrix, facilitating crack filling and resulting in a more cohesive and flexible microstructure.

- The simultaneous use of fibers with 10% silica fume also demonstrated synergistic effects, enhancing durability and structural integrity.

The study recommends an optimal reinforcement ratio of 1% of the hybrid material (H) and 2% of polyvinyl acetate (PVA) for producing high-performance cementitious boards with good stiffness. The findings of this research are expected to be further developed and utilized in future studies (based on the results and discussions).

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Conflict of interest
The author declares that there is no conflict of interest regarding the publication of this paper.

Author Contribution Statement
The author confirms sole responsibility for all aspects of the study, including conceptualization, methodology, data collection, analysis, and manuscript preparation.

Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Declaration Statement
The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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