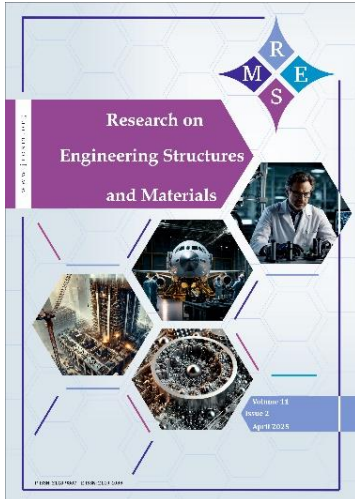




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Performance trade-offs and microstructural mechanisms of cement mortars modified with high-dosage hydroxypropyl methylcellulose (HPMC) for thermal insulation and high adhesion

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Abstract

Hydroxypropyl methylcellulose (HPMC) is typically restricted to low dosages ($\leq 0.3\%$) to maintain workability and bulk compressive strength. This study investigates the functional trade-offs and microstructural mechanisms of high HPMC dosages (0.5%, 0.75%, or 1.0% by weight of cement) to develop energy-efficient, high-adhesion mortar matrices. The cement mortar incorporates a 1:3 cement-to-sand ratio by weight and a water-to-cement ratio of 0.5. Experimental evaluations demonstrate that high HPMC dosages lower bulk density and compressive strength (reduction between 17% and 30%); however, the use of high HPMC dosages significantly enhances interfacial and thermal performance. Notably, incorporating 0.75% HPMC yields a 64% reduction in thermal conductivity to 0.79 W/m. $^{\circ}$ C versus 2.18 W/m. $^{\circ}$ C for control mortar, while 1.0% HPMC increases pull-off strength by 176% (2.15 MPa) and shear strength by 167% (0.4 MPa). Additionally, the use of HPMC caused an increase in the initial setting time and the formation of a thick layer on the surface; the absorption of cement mortar increased with an increasing dosage of HPMC, with a 71% increase in the absorption for cement mortar with 1% HPMC compared to the control mortar. Scanning Electron Microscopy (SEM) observations revealed progressive changes in the mortar matrix morphology with increasing HPMC dosage, including changes in the appearance and distribution of pores. These observations are qualitatively consistent with the measured changes in density, water absorption, mechanical properties, and thermal conductivity. These findings confirm that high-dosage HPMC mortars, especially with 0.75%, provide an optimal balance for energy-efficient exterior renders and high-adhesion repair coatings where thermal resistance and bonding performance take priority over bulk compressive capacity.

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1. Introduction

Buildings account for a major share of global energy consumption [1], largely due to thermal inefficiencies in the building envelope [2]. Issues such as substantial heat loss during winter, excessive heat gain in summer, and localized thermal bridging not only increase heating and cooling loads [3] but also compromise indoor thermal comfort and elevate operational carbon emissions [4]. Consequently, cement mortar is commonly used as an exterior render worldwide; however, modern building demands require thermal-insulating render materials to mitigate envelope heat losses and reduce energy consumption. Therefore, researchers continue to improve its properties. Using additives can play a significant role in improving the fresh and hardened properties of mortar and concrete. Hydroxypropyl methylcellulose (HPMC) is one of these additives that can be incorporated into cement mortar or concrete. In practical application, HPMC

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serves as a crucial functional additive in cementitious renders and tile adhesive mortars [5]. When incorporated into tile adhesives, HPMC acts as a rheology modifier and thickener, significantly improving slip resistance (anti-sagging) on vertical surfaces while extending open time, which enhances application workability and long-term adhesive bond strength [5].

The incorporation of HPMC in concrete mixtures provided an adequate air-void system and enhanced freeze-thaw durability; however, scaling resistance remains a challenge requiring further investigation and potential mitigation strategies [6]. Furthermore, the incorporation of HPMC improved crack resistance [7]. In addition, the use of HPMC decreases the migration of chloride [8]. Regarding the effects of HPMC on the hydration of cement, it was found that the use of HPMC usually retards the hydration of cement, lowers the heat release, and increases the setting time [8,9,10,11,12,13]. HPMC's viscosity has a significant impact on hydration delay and setting time [8]. The presence of HPMC caused a delay in cement hydration and an effective reduction in bleeding, segregation, and permeability [12,14]. Additionally, the effect of using HPMC alongside a polycarboxylate-based superplasticizer was investigated. It was revealed that the use of HPMC had a negative impact on the dispersion capacity of the superplasticizer by obstructing its adsorption on the surface of cement particles [15].

The incorporation of HPMC in the cement paste matrix caused an increase in the air voids, which caused a reduction in the compressive strength [10]. X-ray computed tomography (X-CT) and Mercury intrusion porosimeter (MIP) tests found that the increase in the HPMC dosage caused an increase in the total cumulative pore volume of the mortar [8]. A noticeable decrease in the mechanical properties of cement mortars incorporating low dosages of HPMC was observed; the presence of HPMC caused a reduction in compressive strength (29.09% to 57.79%), flexural tensile strength (20.81% to 49.48%), and dynamic modulus of elasticity (16.7% to 47.22%) depending on the percentage of HPMC [16]. A slight decrease in the compressive strength was also revealed in concrete mixtures incorporating iron tailings [7]. Exceptionally, the incorporation of HPMC into chloroaluminate cement for printable mortar caused an increase in the compressive strength of printed mortar [9]. Both flexural and shear bond strengths decreased with increasing the dosage of HPMC, especially for mortars with steel fibers, and extending the curing period from 7 to 28 days does not have a clear impact on the mechanical properties of mortars [11]. Lower dosages of HPMC (0.05%, 0.1%, or 0.15% by weight of cement) caused a reduction in both compressive and bond strength [17].

Increasing the dosage of HPMC caused an increase in the air voids and porosity [10,11]. Due to the increase in porosity, an 11.76% reduction in weight occurred in cement mortar with HPMC; this increase in porosity also led to higher water absorption and water loss [16]. The increase in porosity and change in the microstructure of cement mortar with HPMC caused an improvement in thermal resistance by 32.6% compared to the control mixture without HPMC [16]. The use of 0.1% HPMC by weight of cement caused a reduction in the thermal conductivity of cement mortar by 12% compared to cement mortar without HPMC [17]. In addition, it was revealed that both water retention and plastic viscosity increased proportionally with HPMC dosage [7,17,18].

Microstructural characterization via Scanning Electron Microscope-Backscattered Electron-Image Analysis (SEM-BSE-IA) showed that after hardening, the HPMC formed bridges, which prevent microcracks between aggregate interfaces [7]. The SEM analysis revealed that the use of HPMC in cement mortars forms a three-dimensional colloidal film that fundamentally changes the behavior of water migration within the mortar matrix. HPMC adsorbed onto the surfaces of both cement and sand, which created a grid similar to the structure of hydration products [18].

After reviewing the previous studies, which focused on using HPMC in cement mortar, it can be seen that key parameters remain inconsistent across the literature, particularly regarding bonding and mechanical behavior. For example, while some studies report that HPMC improves long-term adhesive bond strength through increased water retention [5], others observe that higher HPMC dosages decrease shear and flexural bond strength due to elevated air-void formation [11,17]. Moreover, the reported compressive strength reduction varies considerably in the literature—ranging from marked drops of 29% to 58% [16] to minor decreases [7] or even strength increases in specialized cements [9]. However, the effect of relatively high HPMC dosages on the combined

physical, mechanical, thermal, interfacial, and microstructural properties of cement mortar is still not fully understood. Especially, an understanding of the simultaneous/cross mechanisms between the reduction in thermal conductivity and interfacial bond strengths (pull-off and shear strength) at high dosages (0.5%–1.0%), as well as matrix porosity, remains lacking in the literature. Therefore, the current study investigates the effect of relatively high HPMC dosages of 0.5%, 0.75%, and 1% by weight of cement. A comprehensive analysis of fresh-state properties, physical/mechanical performance, thermal insulation, and microstructural mechanisms was performed to investigate the comprehensive behavior of cement mortar with HPMC.

The main contribution of the current study is to provide a comprehensive evaluation of relatively high HPMC dosages in cement mortar by considering physical, mechanical, thermal, interfacial, and microstructural properties together. In particular, the study evaluates the relationship between the reduction in thermal conductivity and the improvement in shear and pull-off strengths, specialty rendering and repair mortars where adhesion and thermal resistance take priority over compressive strength.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC) Type I, manufactured at the Badosh plant complying with ASTM C150 [19], was used in this study. Chemical compositions and physical properties of cement were presented in Tables 1 and 2, respectively. The fine aggregate (sand) used in this study was obtained from the Kanhash River.

Table 1. Chemical composition (percentage) and specific gravity of ordinary Portland cement

Component	Portland cement	ASTM C150 Limits [19]
SiO ₂	19.8	-----
Al ₂ O ₃	4.13	6.0
Fe ₂ O ₃	3.85	6.0
CaO	61.87	-----
MgO	3.52	6.0
SO ₃	1.79	3.0
Cl ⁻	0.01	-----
LOI	2.35	3.5
Specific Gravity	3.15	
C ₃ S	63.04	-----
C ₂ S	9.21	-----
C ₃ A	4.43	8.0
C ₄ AF	11.72	-----

Table 2. Physical properties of ordinary Portland cement

Properties	Value	ASTM C150 Limit [19]
Initial setting time (Minutes)	125	Not less than 45
Final setting time (Minutes)	300	Not more than 375
Blaine (m ² /kg)	300	Not less than 260
Expansion (%)	0.04	Not more than 0.8
3 days compressive strength (MPa)	11	Not less than 7.0
7 days compressive strength (MPa)	18	Not less than 12.0
28 days compressive strength (MPa)	29	-----

The fine aggregate had an absorption of 1.51%, a specific gravity (saturated-surface dry, SSD) of 2.61 in accordance with ASTM C128 [20], and a fineness modulus of 3.1. Figure 1 illustrates the gradation of fine aggregates. The HPMC powder used in this study is an industrial-grade product, manufactured by Shijiazhuang Bairuisite Cellulose Company; the HPMC has a nominal viscosity of

200,000 mPa·s; methoxy content: 18%–32%; hydroxypropyl content: 8%–16%; fineness: 80–100 mesh; gel temp: 54–75°C; moisture: $\leq 5\%$; ash content: $\leq 2\%$; pH 7–8. Table 3 shows the mixture proportions per unit of kg/m³. For simplicity, the cement-to-sand ratio (oven-dry) is 1:3 by weight, and the water-to-cement ratio is 0.5, where tap water was used. The HPMC dosages are 0.5%, 0.75%, or 1% by weight of cement.

Table 3. Mixture proportions (kg/m³)

Mixtures*	w/c	Cement kg/m ³	Water kg/m ³	Fine Aggregate kg/m ³ (oven dry)	HPMC kg/m ³
M-0	0.5	509	254	1525	0
M-0.5	0.5	509	254	1525	2.54
M-0.75	0.5	509	254	1525	3.82
M-1	0.5	509	254	1525	5.09

* Mixture designation: M-X; X = Dosage of HPMC by weight of cement; Note: 1 kg/m³ = 0.06243 lb/yd³

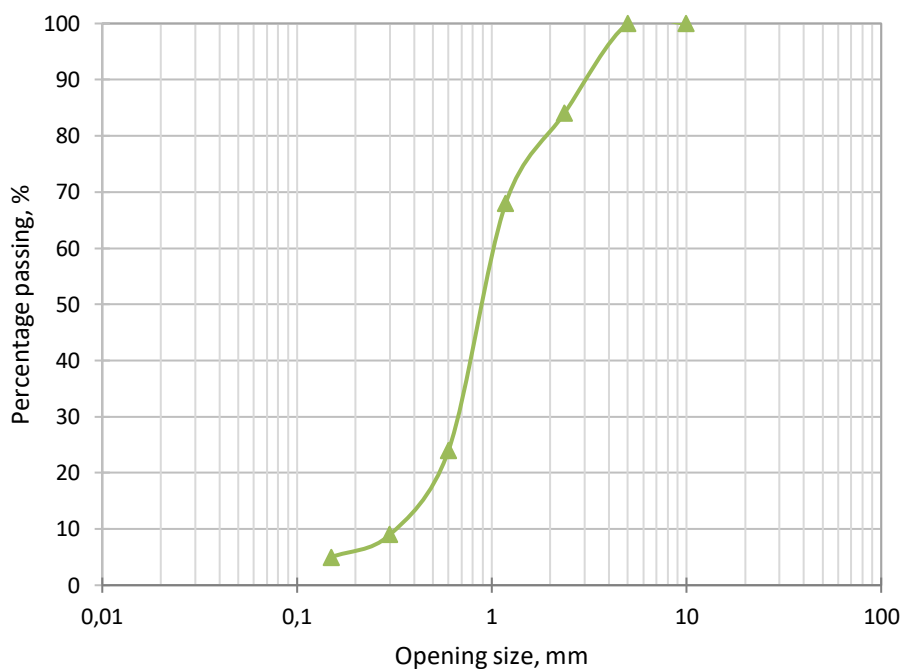


Figure 1. Grading curve for fine aggregate

2.2 Methods

The mixing procedure and the preparation of cement mortar were executed in accordance with BS EN 196-1 [21]. The HPMC powder was mixed with the whole amount of water for 2 minutes with manual stirring to prepare the HPMC solution; cement and sand (oven-dry at 105°C) were mixed together for 1 minute, then the HPMC solution was added gradually and evenly to the mixture of cement and dry sand. The whole mixture was mixed manually for 4 minutes. The testing of the flowability of cement mortar was conducted in accordance with BS EN 1015-3 [22]. The scanning electron microscope (SEM) (Zeiss EVO-10) was used to investigate the microstructural characterization of cement mortars; the tested specimens were at an age of 28 days without stopping the hydration process; also, the surface of the tested specimens was not coated. The SEM was operated at an accelerating voltage of 10 kV with working distances ranging from 14 to 20 mm, using the secondary electron (SE1) detector. The tests of initial and final setting time of cement paste with or without HPMC were conducted in accordance with ASTM C-191 [23]. The bleeding test was utilized in accordance with ASTM C940-22 [24]. The testing of compressive and flexural strengths was conducted in accordance with BS EN 1015-11 [25]. For each mixture, 3 prisms

(40×40×160 mm) were cast, demolded after 24 hours, and cured for 28 days in a lime-saturated water tank. The average compressive strength was obtained from 3 specimens.



Figure 2. Shear strength test (Triplet test)



Figure 3. Pull-off strength test



Figure 4. Thermal conductivity test



The wet and dry densities were measured in accordance with BS EN 1015-6 [26] and BS EN 1015-10 [27], respectively. The absorption of cement mortar was measured in accordance with BS EN 1015-18 [28]. The shear strength of cement mortars (triplet test) was utilized in accordance with BS EN 1052-3 [29], clay bricks were used in the test, as shown in Figure 2. The pull-off strength of cement mortars was determined in accordance with BS EN 1015-12 [30]; the cement mortar was placed on the back side surface of terrazzo tiles, where the back side surface is rough and made of cement mortar, as illustrated in Figure 3. For the thermal conductivity test, cement mortar was cast in a plastic mold with a diameter of 100 mm and a thickness of 10 mm. After 24 hours, the specimens were demolded and cured for 28 days in a lime-saturated water tank. Then, the specimens were dried in an oven at 60°C until reaching a constant weight. The thermal conductivity test was performed using a custom steady-state thermal conductivity apparatus, as shown in Figure 4. More details about the apparatus can be explained in the previous study [31]. The developed device operates in accordance with ASTM C177 [32]/ASTM C518 [33].

3. Experimental Results and Discussion

Four cement mortar mixtures and a series of experimental tests were utilized to investigate the physical and mechanical properties of cement mortars incorporating HPMC. The one-way analysis of variance (ANOVA) was utilized in the current study to test the differences between results. In the ANOVA test, if the p -value is less than 0.05, Tukey's HSD test was followed to identify which groups differed from each other. In Tukey's HSD test, if the p -value is ≤ 0.05 , this means that the difference is statistically significant.

3.1 Flowability of Cement Mortar

Table 4 and Figure 5 show the results of the flow test for the cement mortars. It was found that the presence of HPMC caused a significant decrease in the flowability of cement mortar. Specifically, relative to the control mixture (160.7 mm), increasing the HPMC dosage reduced the fresh mortar flow values to 150.3 mm, 135.0 mm, and 120.0 mm, representing percentage decreases of 6.5%, 16.0%, and 25.3%, respectively.

Table 4. Mortar properties

Mixtures*	Flow (mm)*	Temp., °C†	Wet density (g/cm ³)*	Dry density (g/cm ³)*	Bleeding %*	Initial setting (min)*	Surface skinning time (min)*	Absorption %*
M-0	160.7	23.0	2.17	2.16	2.37	90	380	2.11
M-0.5	150.3	22.5	1.95	1.90	0.00	95	350	3.17
M-0.75	135.0	24.0	1.90	1.86	0.00	110	280	3.31
M-1	120.0	23.0	1.86	1.84	0.00	120	240	3.60

* Mixture designation: See Table 3; * Each value is an average of three tested specimens; † Temperature for fresh mortar during mixing; Note: 1 in. = 25.40 mm

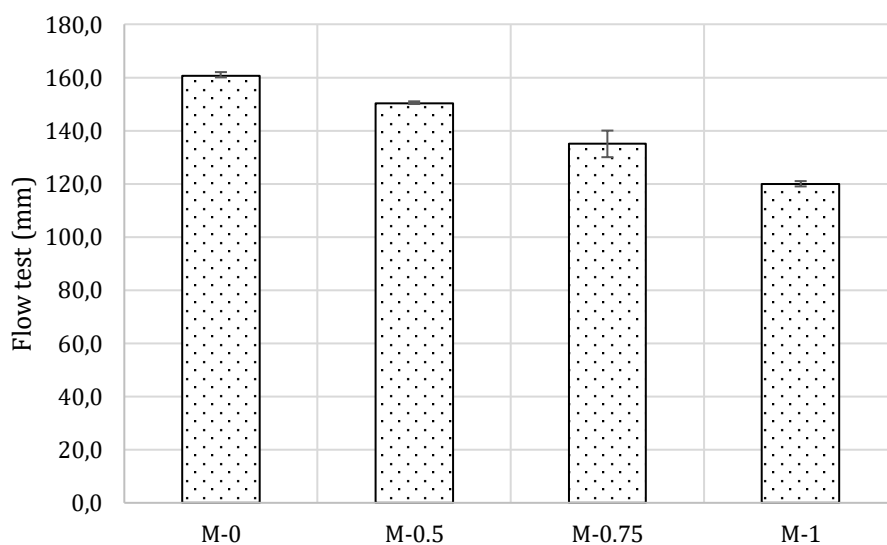


Figure 5. Flow vs. mortar mixtures

The reduction in the flowability of cement mortar by increasing the dosage of HPMC means that the plastic viscosity is increased. This decrease in flowability is primarily governed by HPMC's high water retention capacity, its ability to bind free water, and the formation of a polymeric network among cement particles [7]. Although HPMC also entrains micro-air bubbles, which can reduce inter-particle friction, the governing mechanism reducing flow value is the immobilization of free water within the polymeric network. Additionally, Table 4 reports fresh mortar temperatures ranging from 22.5 °C to 24.0 °C; however, these minor temperature variations exert a negligible influence on viscosity or setting kinetics, confirming that workability changes are governed by HPMC dosage rather than thermal effects. Also, it is important to mention that the fixed water-to-cement ratio of 0.5 used for all cement mortars had a direct relationship to the reduction in

flowability by increasing the dosage of HPMC. In the current study, the ANOVA and Tukey's HSD test showed that the reduction in flowability is statistically significant, with p -values ranging from 0.0010 to 0.0058. This finding is in line with the studies [9,18].

3.2 Microstructural Characterization / SEM Analysis

The SEM analysis, as shown in Figure 6, illustrates that the incorporation of HPMC induced progressive microstructural changes. The control cement mortar (0% HPMC, Figure 6a) exhibited a relatively heterogeneous morphology with irregular hydration-product features and visible voids.

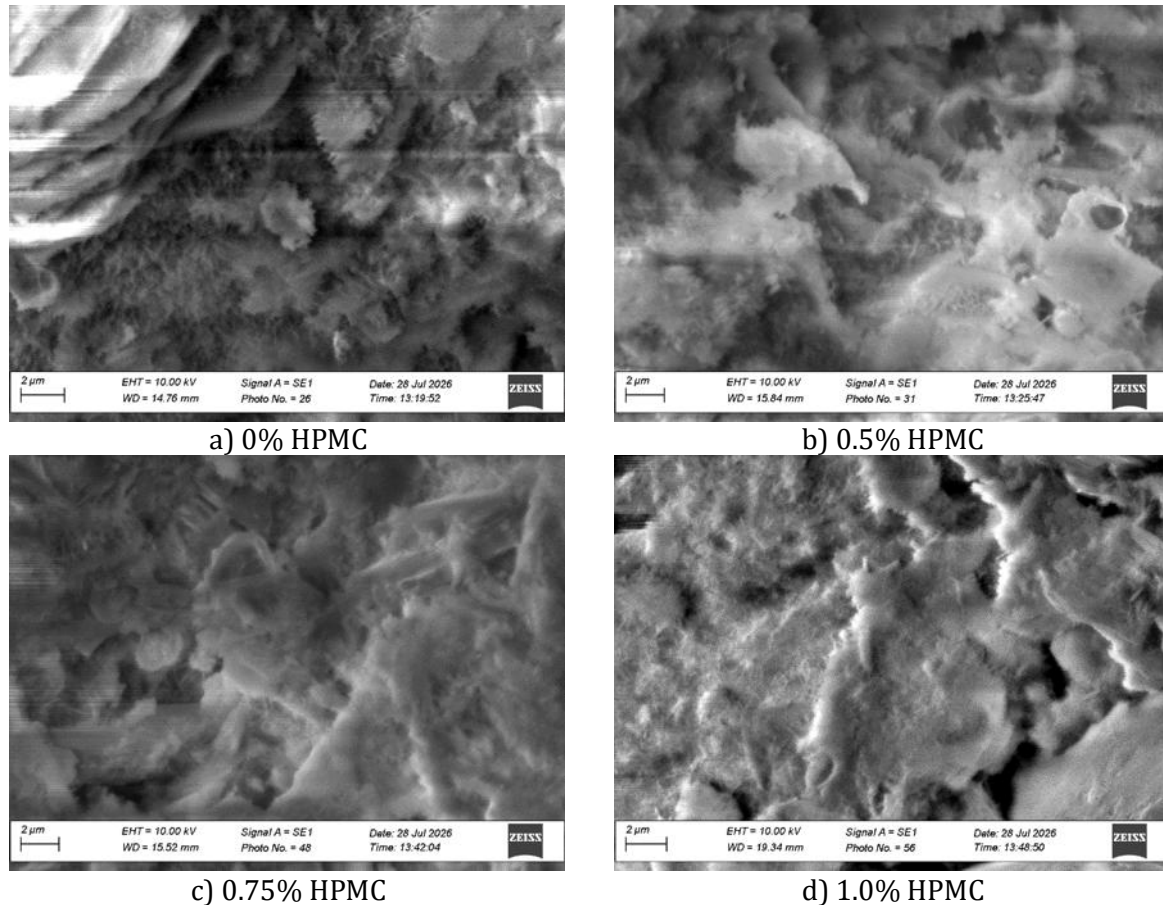


Figure 6. Qualitative SEM micrographs illustrating the surface morphology and microstructural evolution of cement mortars with varying dosages of HPMC (2 μ m scale)

On the other hand, the incorporation of 0.5% HPMC caused a change in the matrix, as shown in Figure 6b compared to Figure 6a. Since early hydration is bound to use up the available water, the dissolved cellulose ether creates fine film networks that may bridge the micro-voids, connecting C-S-H aggregates. The observed morphology may be influenced by the film-forming and water-retention behavior of HPMC. Increasing the HPMC dosage to 0.75%, the SEM analysis (Figure 6c) shows a visually denser and more continuous matrix compared with the control and 0.5% HPMC mixtures. Some hydration-product features appeared less distinct, while fewer large visible voids were observed in the examined regions. These observations suggest modification of the matrix morphology with increasing HPMC dosage. Finally, at an HPMC dosage of 1.0% (Figure 6d), the examined SEM region appeared more continuous and compact; however, this localized morphology should not be interpreted as an overall reduction in porosity, particularly because the measured density decreased with increasing HPMC dosage. The addition of HPMC to the mixture led to a decrease in wet and dry densities and an increase in absorption, but thermal conductivity decreased.

The changes in matrix structure, including the presence of pores, may provide a rationale for these results. At the same time, the modification of the matrix with the help of HPMC may have

contributed to the growth of shear and pull-off strengths. However, as a methodological limitation, because SEM observations are primarily morphological and obtained from selected microscopic regions, they may not fully represent the pore structure of the bulk mortar, confirm the precise spatial distribution of HPMC, or conclusively establish the presence of continuous polymer films or polymer–C–S–H bonding. Therefore, the SEM results are interpreted qualitatively and in conjunction with the macroscopic test results as supporting evidence rather than direct proof of the mechanisms responsible for these macroscopic changes.

3.3 Density of Cement Mortar

The results of wet and dry density of cement mortar, as presented in Table 4 and Figure 7, revealed that both wet and dry densities decreased with increasing the dosage of HPMC. The reduction in wet and dry densities were 14.3% and 14.8%, respectively, for cement mortar with 1% HPMC (M-1) compared to the control mortar (M-0). In the case of the wet density, the reduction compared to the control cement mortar (M-0) and between M-1 and M-0.5 were statistically significant, with a p -value of 0.0010, while the differences among other cement mortars (M-0.5 versus M-0.75, and M-0.75 versus M-1) were not statistically significant.

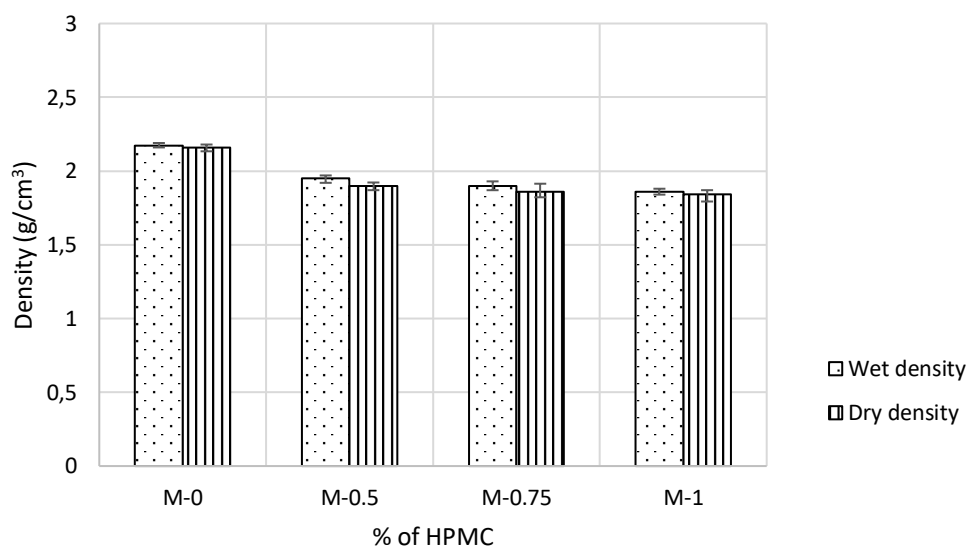


Figure 7. Density vs. mortar mixtures

In addition, the reduction in the dry density compared to the control cement mortar (M-0) was statistically significant, with a p -value of 0.0010, while the differences among other cement mortars (M-0.5, M-0.75, and M-1) were not statistically significant. The SEM observations provide morphological evidence that is consistent with the reduction in density. HPMC works as a surfactant in fresh mortar, leading to the trapping of air bubbles and micro-cavities during mixing. For cement mortar incorporating 1% of HPMC (M-1, Figure 3d), the SEM micrograph shows a modified matrix structure that reflects these entrained air features. Although the specific gravity of HPMC is lower than that of hydrated cement, the addition of 0.5% or 1% of HPMC by weight of cement cannot explain the noticeable reduction in density. Instead, trapped air bubbles and the resulting increase in porosity are the main causes of the reduced bulk density. This finding is consistent with previous studies [7]. A distinct pattern also appears in the wet-to-dry density gap. While M-0 changes by only 0.01 g/cm³ upon drying (2.17 to 2.16 g/cm³), HPMC mortars show a 0.04–0.05 g/cm³ difference. This expanded delta reflects HPMC's moisture retention: ether functional groups lock in pore water via hydrogen bonding, and developing polymer membranes block capillary channels. Retaining this extra bound water retards internal drying and reduces capillary tension associated with drying shrinkage.

3.4 Initial Setting Time and Surface Skinning Time

Table 4 and Figure 8 show the results of the initial setting time and surface skinning time of cement pastes with or without HPMC. For the initial setting time, it was found that increasing the dosage

of HPMC caused an increase in the setting time. The increase in the initial setting time for M-0.5, M-0.75, and M-1 was approximately 6%, 22%, and 33%, respectively, compared to M-0. The statistical analysis reveals that the increase in the initial setting time was statistically significant between the following: M-0 versus M-0.75 (p -value is 0.0012), M-0 versus M-1 (p -value is 0.0010), M-0.5 versus M-0.75 (p -value is 0.0073), and M-0.5 versus M-1 (p -value is 0.0010). However, it was not statistically significant between the following: M-0 versus M-0.5 and M-0.75 versus M-1, where the p -value was higher than 0.05. This finding was also revealed by another study [12]. The increase in initial setting time may be associated with the interaction of HPMC with cement particles and the modification of water mobility and cement hydration kinetics. The increased viscosity and water-retention capacity of HPMC may additionally influence the transport of dissolved species and the development of early hydration products. For the surface skinning time, it was found that by increasing the dosage of HPMC, the surface skinning time was decreased. However, this result does not represent the actual situation of the bulk mortar. It was found that there is a thick layer on the top of the Vicat mold. The formation of this thick superficial layer can be attributed to localized water retention, air entrainment, and rapid polymer film formation at the air–mortar interface [7]. After breaking that superficial layer, plastic and unhydrated mortar was still present beneath it. Therefore, the reported surface skinning time does not represent the final setting time.

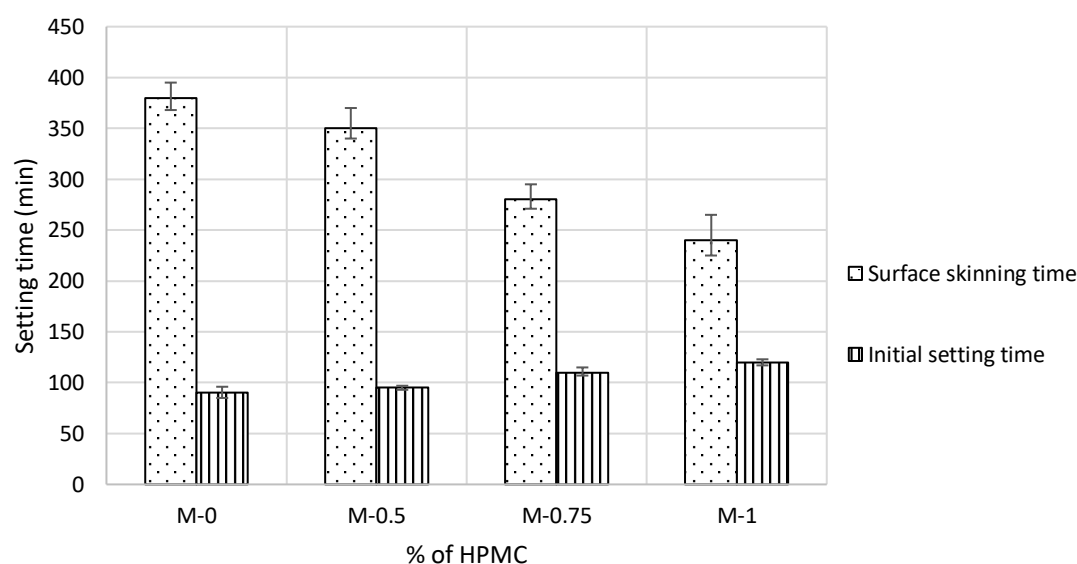


Figure 8. Initial setting and surface skinning times vs. mortar mixtures

3.5 Absorption of Cement Mortar

The results of water absorption capacity in percentage of hardened cement mortars, as illustrated in Table 4 and Figure 9, revealed that increasing the dosage of HPMC caused an increase in absorption; the absorption increased by approximately 50%, 57%, and 71% for cement mortars M-0.5, M-0.75, and M-1, respectively, compared to the control cement mortar. The presence of HPMC in the fresh cement mortar caused changes in the pore structure and may have promoted the formation and retention of air voids and microcavities, as suggested by the SEM observations in Figure 6. This polymer matrix has the hydrophilic nature of HPMC, which increased the absorption capacity of the cement mortar. In the current study, the increase in absorption is statistically significant compared to the control cement mortar (M-0), where the p -value was 0.0010; also, the increase in absorption between M-0.5 and M-1 was statistically significant, where the p -value was 0.0472. Whereas, the increase in absorption was not statistically significant between M-0.5 and M-0.75, or between M-0.75 and M-1. This finding is supported by a previous study [16].

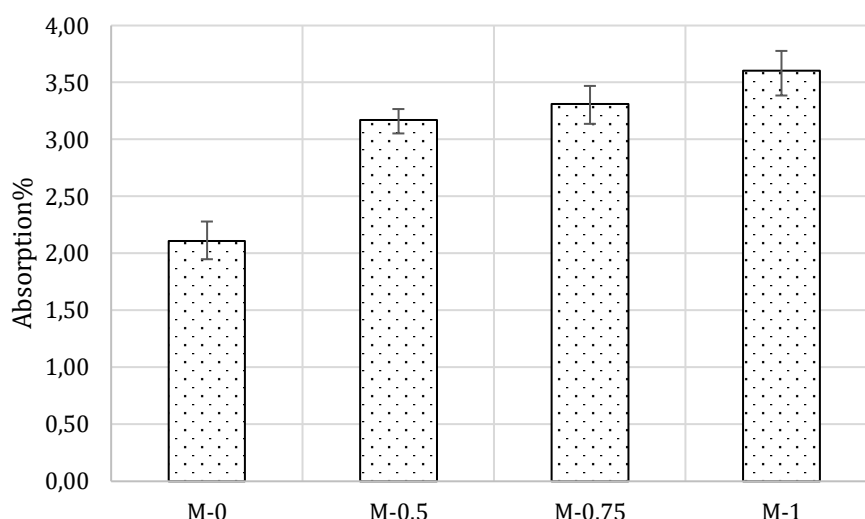


Figure 9. Absorption vs. mortar mixtures

3.6 Bleeding of Cement Mortar

The bleeding of cement mortars was observed for cement mortar mixtures, as shown in Table 4. Based on the results, it is obvious that the use of HPMC, regardless of its dosage, prevented bleeding. This finding is also found in a previous study [12]. The reason behind this could be the adsorption of HPMC to cement and sand particles, which caused a reduction in the migration of water [12]. In addition, the use of HPMC caused an increase in water retention, which led to keeping water and reducing its migration [18]. In job-site applications like exterior renders and plasters, this complete lack of bleeding brings clear practical advantages. Halting internal water movement stops heavy sand grains from settling out, which prevents aggregate segregation during pumping and troweling. The higher paste viscosity also boosts matrix cohesion, giving the wet render enough sag resistance so workers can apply thicker coats to vertical walls without slumping.

3.7 Mechanical Properties of Cement Mortar

3.7.1 Compressive Strength

The results of compressive strength of cement mortar specimens after 28 days of curing are illustrated in Table 5 and Figure 10. The results showed that the incorporation of HPMC caused a reduction in the compressive strength. This finding is in the same line with the findings of prior studies [7,16]. Specimens of mixture M-0.75 experienced a 17% reduction in compressive strength compared to the control mixture M-0, and had the lowest reduction compared to other mixtures. This reduction in compressive strength can be attributed to the surfactant behavior of HPMC, which entrains air bubbles and promotes micro-cavity formation within the paste matrix, leading to lower bulk density, as explained earlier. The statistical analysis showed that the reduction in the compressive strength for mixtures M-0.5 and M-1 compared to the control mixture (M-0) is statistically significant, with p -values of 0.0269 and 0.0443, respectively.

Whereas the reduction among other mixtures (M-0.75 versus M-0, M-0.75 versus M-0.5, M-0.5 versus M-1, and M-0.75 versus M-1) is not statistically significant, with p -values greater than 0.05. The reason behind the lower strength reduction in mixture M-0.75 compared to M-0.5 and M-1 could be related to the formation of polymer films. In mixture M-0.5, the HPMC dosage is low, which causes trapping of air bubbles, while the polymer film is not sufficient to support the matrix. In mixture M-0.75, increasing the dosage allows HPMC to form continuous polymer films that fill the micro-cavities and bridge small cracks, which leads to reducing the negative impact of air bubbles and improving the matrix structure. However, at a higher dosage in mixture M-1, the excessive use of HPMC could entrain more air bubbles and coat the unhydrated cement particles, which delays the hydration process and causes a further reduction in compressive strength.

Table 5. Results of mechanical strengths and thermal conductivity

Mixtures*	Compressive strength (MPa)*	Flexural strength (MPa)*	Shear strength (MPa)*	Pull-off strength (MPa)*	Thermal Conductivity (W/m. °C)*
M-0	22.7	5.77	0.15	0.78	2.18
M-0.5	15.93	5.10	0.23	1.43	1.33
M-0.75	18.80	5.00	0.23	1.95	0.79
M-1	16.60	4.73	0.40	2.15	0.88

* Mixture designation: See Table 3

* Each value is an average of three tested specimens (at age of 28 days)

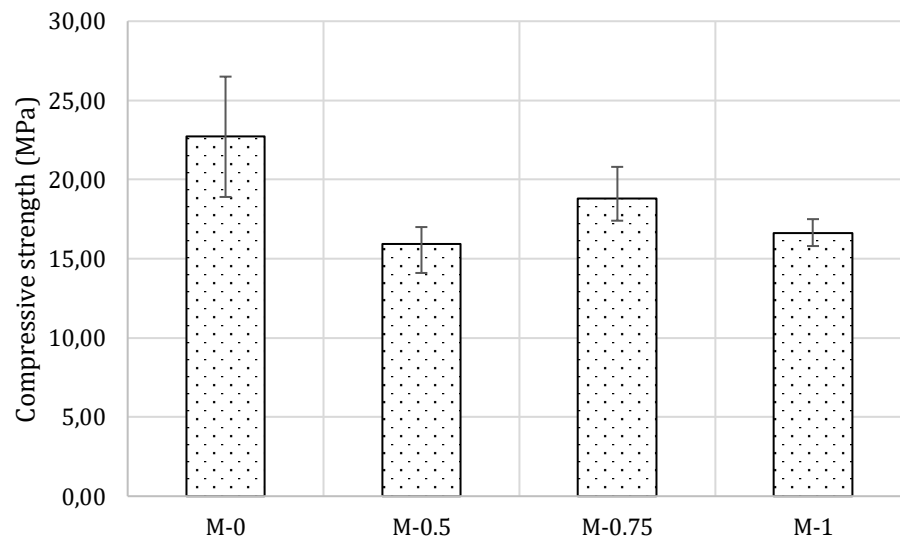


Figure 10. Compressive strength vs. mortar mixtures

3.7.2 Flexural Strength

The results for the flexural strength of cement mortar prisms, as shown in Table 5 and Figure 11, illustrate that the use of HPMC caused a moderate reduction in the flexural strength. This finding is in line with prior studies [11,16]. The reduction values range from 12% to 18% compared to the control cement mortar (M-0). This decrease is linked to the increased porosity caused by the air-entraining effect of HPMC. However, the flexural strength loss was smaller than expected relative to the density loss, as the polymer film formation helps transfer tensile stresses across micro-voids. The statistical analysis showed that the reduction in flexural strength is not statistically significant, except that the reduction for mixture (M-1) compared to the control mixture (M-0) is statistically significant, with a p -value of 0.0262.

Figure 12 illustrates the relationship between the flexural-to-compressive strength ratio (F/C) versus mixtures; the main finding is that the ratio (F/C) is increased for all mixtures compared to the control one. That increase in the ratio (F/C) confirms an enhancement in matrix ductility and toughness under stress. This finding is supported by another prior study [18]. Although complete load-deflection curves were not measured to calculate total energy absorption, the higher F/C ratio indicates an improvement in relative flexibility and ductility, which leads to a less brittle matrix. The SEM analysis, as shown in Figure 6, revealed morphological differences between the control mortar and mortars including different dosages of HPMC. These changes, as illustrated in the SEM analysis, may be associated with the water-retention and rheological effects of HPMC and may contribute to the observed changes in mechanical and interfacial properties. However, the SEM images alone cannot confirm the formation of continuous polymer films or polymer bridges within the cementitious matrix.

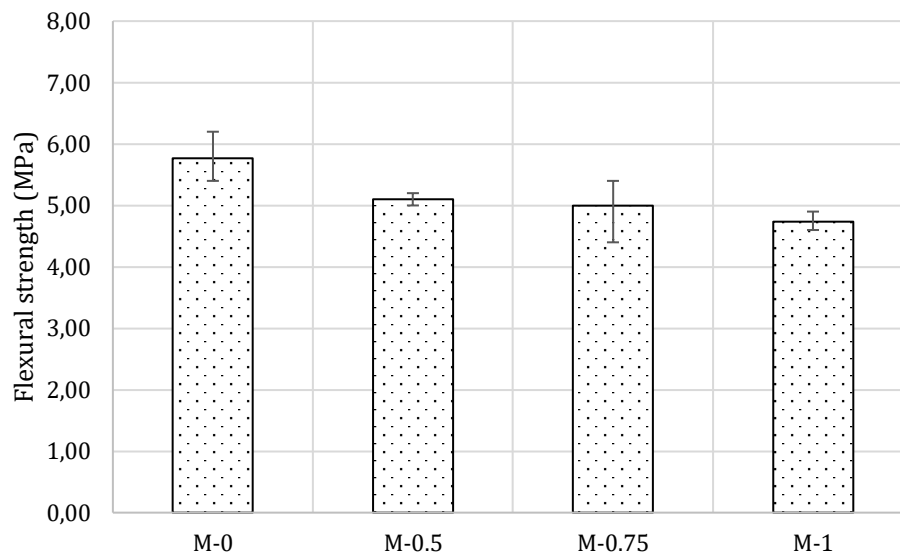


Figure 11. Flexural strength vs. mortar mixtures

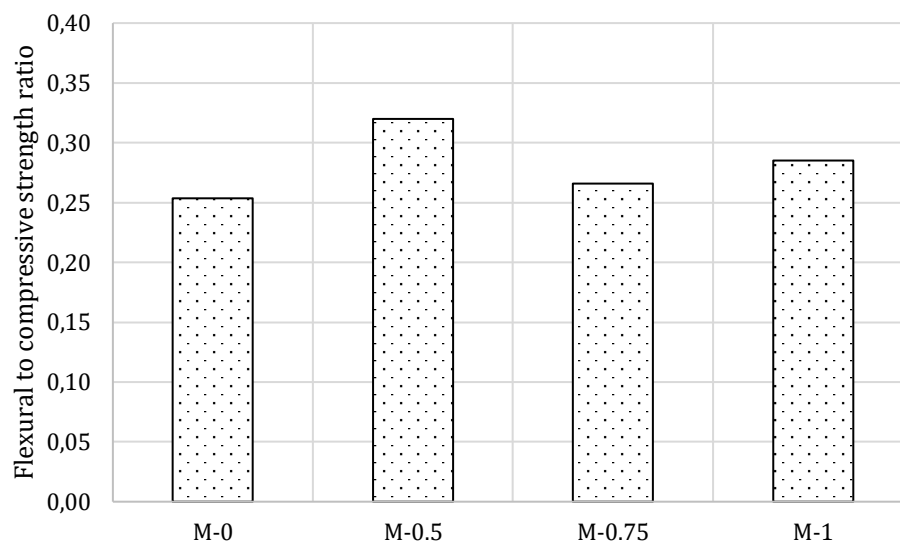


Figure 12. Flexural to compressive strength ratio vs. mortar mixtures

3.7.3 Shear Strength

Table 5 and Figure 13 illustrate the shear strength of cement mortars. The results show that mixtures M-0.5 and M-0.75 had an identical increase in shear strength of 53%, while mixture M-1 had a noticeable increase of 167% compared to the control mixture M-0. That increase in shear strength was statistically significant when comparing the results for (M-1 versus M-0, M-1 versus M-0.5, and M-1 versus M-0.75), where p -values are 0.0010, 0.0022, and 0.0022, respectively. whereas, the increase was not significant for (M-0.5 versus M-0, M-0.75 versus M-0, and M-0.75 versus M-0.5). The observed morphological changes, as shown in Figure 3, may be associated with the increase in shear strength; however, SEM observations alone cannot confirm the underlying mechanism. This increase could be attributed to an improvement in interfacial adherence and friction coefficient. The presence of HPMC helps retain water near the brick interface. This allows full C-S-H gel hydration and the formation of polymer films. Also, HPMC increases the cohesion and packing density of the mortar, which increases the frictional resistance along the joint. All tested specimens exhibited shear failure exclusively within the mortar layer, corresponding to the “*shear failure only in the mortar*” failure mode defined in BS EN 1052-3.

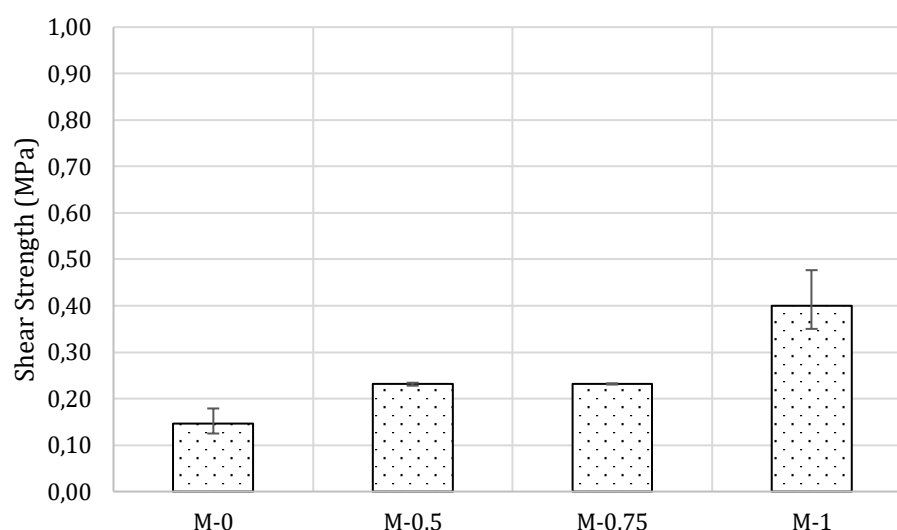


Figure 13. Shear strength vs. mortar mixtures

3.7.4 Pull-off Strength

Table 5 and Figure 14 show the pull-off strength of cement mortars. The results show that mixtures M-0.5, M-0.75, and M-1, compared to the control mixture M-0, had an increase of 83%, 150%, and 176%, respectively. The statistical analysis showed that the increase in the pull-off strength was statistically significant, with p -values ranging from 0.0010 to 0.0205, except for the comparison of M-1 versus M-0, where the statistical analysis was not significant. As illustrated in Figure 6, adding HPMC was associated with morphological changes in the examined matrix regions.

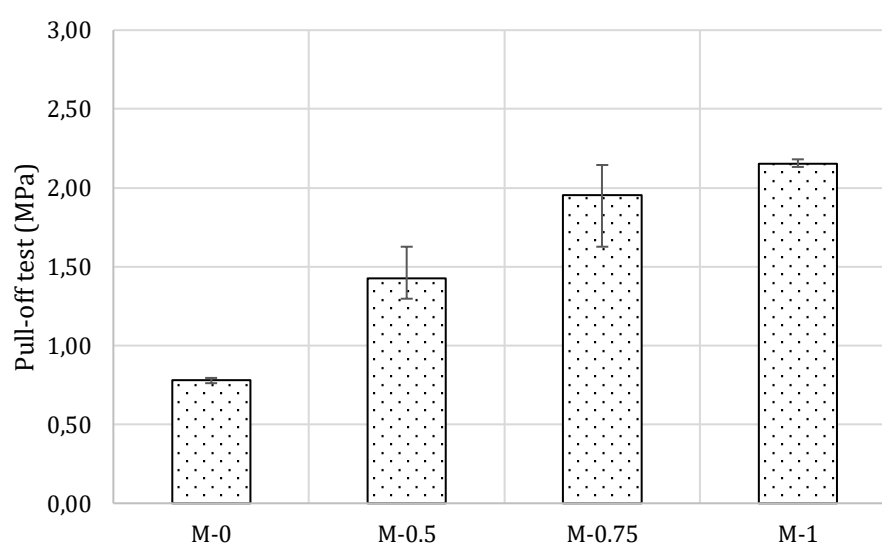


Figure 14. Pull-off strength vs. mortar mixtures

The failure mode in all tested specimens was a cohesion fracture within the mortar, similar to type B, as indicated in BS EN 1015-12. These changes, together with the measured increase in pull-off strength, may indicate modification of the matrix and crack-bridging behavior; however, the formation of flexible polymer bridges cannot be confirmed from SEM morphology alone. The improved pull-off strength may therefore be associated with changes in matrix cohesion, water retention, and the interaction of HPMC with the cementitious constituents.

3.8 Thermal Conductivity of Cement Mortar

Table 5 and Figure 15 illustrate the positive impact of using HPMC on the thermal conductivity of cement mortars. The results reveal that the incorporation of HPMC caused a clear reduction in the thermal conductivity of cement mortars. Specifically, thermal conductivity dropped from 2.18

W/m·°C in M-0 to 1.33 W/m·°C in M-0.5, 0.79 W/m·°C in M-0.75, and 0.88 W/m·°C in M-1, representing reductions of 39%, 64%, and 60%, respectively. Among these mixtures, the mixture with 0.75% HPMC (M-0.75) had the highest reduction in thermal conductivity, 64% compared to the control mixture with 0% HPMC (M-0). The statistical analysis showed that the reduction in thermal conductivity was statistically significant, with *p*-values ranging from 0.0010 to 0.0229, except for the comparison between M-0.75 and M-1.0, where the statistical analysis was not significant. This finding is in the same line with the findings of other studies [16,17]. The reduction in thermal conductivity may be associated with the reduction in density and changes in the pore structure caused by HPMC. However, mixture M-1 showed a slightly higher thermal conductivity than M-0.75, despite having a dry density of 1.84 g/cm³ and water absorption (3.60%) compared to 1.86 g/cm³ and water absorption (3.31%). The possible explanation could be attributed to pore coalescence at 1.0% HPMC dosage, where isolated micro-voids merge into connected capillary channels. Also, higher HPMC content increases moisture retention within the pore structure, and water conducts heat more effectively than trapped air. In future work, the micro-pore characterization tests, like Mercury Intrusion Porosimetry (MIP), are essential to explain the obtained results. The SEM images provide qualitative evidence of morphological changes in the examined regions, including differences in the appearance and distribution of voids. However, SEM alone cannot quantify the total pore volume or establish the specific mechanism responsible for the reduction in thermal conductivity. HPMC acts as a surfactant that entrains closed micro-cavities within the paste matrix, which act as thermal insulating air barriers. Furthermore, HPMC may modify the connectivity and distribution of capillary pores through its water-retention and film-forming behavior. Together with the increased presence of entrained air voids, these changes may contribute to the observed reduction in thermal conductivity. Based on the experimental findings and limitations in the current study, the following future research areas are suggested. First, studying the air content in either plastic or hardened cement mortar, the volume of air bubbles, and their distribution.

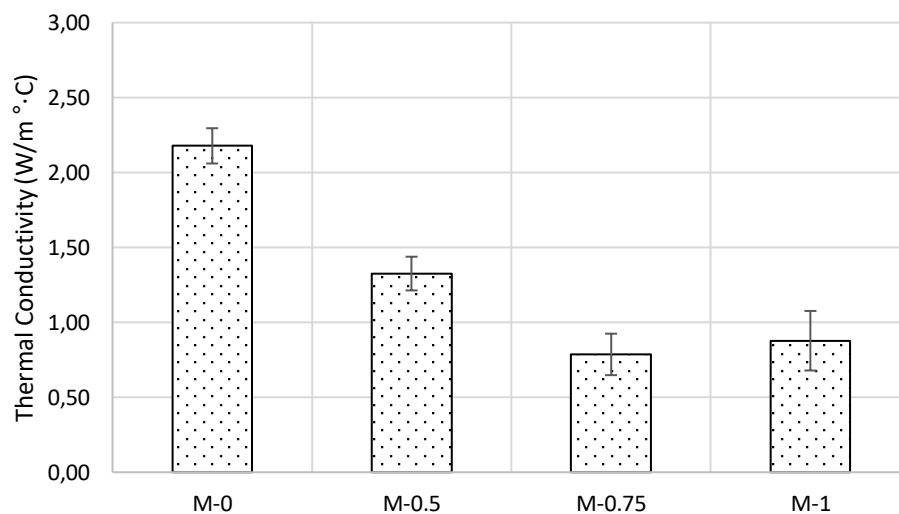


Figure 15. Thermal conductivity vs. mortar mixtures

Micro-pore characterization tests such as Mercury Intrusion Porosimeter (MIP) are highly recommended for future work. Second, performing durability tests, such as freezing and thawing and wetting and drying, should be performed before using the HPMC cement mortar as an exterior render material.

4. Conclusions

Four cement mortar mixtures were cast, and a series of experimental tests were utilized to investigate comprehensively the physical and mechanical properties of cement mortar incorporating HPMC. Based on statistical evaluations using ANOVA and Tukey's HSD test and experimental findings, it can be concluded:

- The use of HPMC caused a reduction in the flowability of cement mortars compared to the control mixture, and the flowability is reduced by increasing the dosage of HPMC, decreasing by 25.3% from 160.7 mm in M-0 to 120.0 mm in M-1.
- The use of HPMC caused a reduction in both wet and dry densities compared to the control cement mortar mixture, where dry density decreased from 2.16 g/cm³ in M-0 to 1.84 g/cm³ in M-1.
- The use of HPMC caused a delay in the setting process, where the initial setting time increased with an increasing dosage of HPMC, rising from 90 min in M-0 to 120 min in M-1. However, regarding the apparent reduction in final setting time, it was found that there is a thick layer on the top of the Vicat mold, and that layer gives an indication of the surface skinning time rather than reflecting the true bulk matrix setting.
- The use of HPMC caused an increase in absorption, where absorption increased with an increasing dosage of HPMC. The absorption increased by 71% for cement mortar with 1% HPMC compared to the control cement mortar, rising from 2.11% in M-0 to 3.60% in M-1.
- The use of HPMC, regardless of its dosage, prevented bleeding of cement mortars, dropping the bleeding percentage from 2.37% in M-0 to 0.00% across all HPMC mixtures.
- The use of HPMC caused a reduction in compressive strength. The M-0.75 experienced a 17% reduction in compressive strength compared to the control mixture M-0, and had the lowest reduction compared to other mixtures.
- The use of HPMC caused a reduction in flexural strength; the reduction values range from 12% to 18% compared to the control cement mortar (M-0).
- The use of HPMC caused an increase in shear strength and pull-off strength, showing maximum increases of up to 167% (0.40 MPa) and 176% (2.15 MPa) at 1.0% HPMC dosage, respectively.
- The use of HPMC caused a reduction in thermal conductivity, where the 0.75% HPMC dosage achieved a maximum reduction of 64% (0.79 W/m·°C compared to 2.18 W/m·°C for M-0).
- The SEM observations revealed progressive changes in the mortar matrix morphology with increasing HPMC dosage, including changes in the appearance and distribution of pores. These observations are qualitatively consistent with the measured changes in density, water absorption, mechanical properties, and thermal conductivity; however, SEM alone cannot confirm the chemical distribution of HPMC or the formation of continuous polymer films.
- The results revealed that HPMC-modified mortars exhibited enhanced thermal resistance and interfacial bond strength, making them highly suitable for energy-efficient exterior renders and high-adhesion repair mortars, where a 0.75% HPMC dosage is optimal for thermal insulation renders, while a 1.0% HPMC dosage is recommended for high-adhesion repair coatings.

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