https://doi.org/10.3311/PPci.37182

Periodica Polytechnica Civil Engineering, 68(4), pp. 1405–1417, 2024

Effect of Microwave Curing on the Performance of High-volume Fly Ash Concrete

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Received: 23 April 2024, Accepted: 10 July 2024, Published online: 05 August 2024

Abstract

Concrete curing significantly impacts mechanical properties and durability, yet traditional methods face efficiency challenges. Microwave curing (MC) offers a promising alternative, providing rapid and uniform concrete curing. However, fully understanding the impact of MC on concrete performance, particularly in high-volume fly ash concrete (HVFC), remains a research gap. This study addresses this gap by investigating the effect of MC on key properties of HVFC, including compressive strength, drying shrinkage, chloride ion penetration, and resistance to sulfate attack. Concrete specimens underwent MC at varied energies (200–1000 W) and durations (10–30 min) to evaluate their mechanical and durability characteristics. Results show that MC significantly boosts early-stage concrete strength, notably at high applied energy. The specimen cured at 1000 W for 30 min (MC1000-30) achieved the highest 1-day strength of 23.68 MPa. However, the normal curing specimen exhibited the highest strength of 32.07 MPa at 28 days while the strength value of the MC1000-30 specimen declined to 20.25 MPa, indicating a 36.85% decrease. Although declining strength was observed after 28 days, the MC1000-30 specimen demonstrated improved durability with significantly reduced drying shrinkage (by 83.12%) and chloride ion penetration (by 31.6%). The study underscores the feasibility of utilizing MC for HVFC as it demonstrated significant enhancements in both early-stage concrete strength and durability at a later stage. Careful parameter optimization can ensure sustained effectiveness over time, offering a viable alternative to traditional curing methods.

Keywords

microwave curing, high-volume fly ash concrete, compressive strength, drying shrinkage, durability

1 Introduction

Concrete, as a fundamental building material, underpins the infrastructure of modern society with its durability, versatility, and widespread utilization across construction projects worldwide. Yet, despite its ubiquity, the traditional curing process of concrete remains a bottleneck in construction timelines, often requiring prolonged periods for optimal strength development [1]. Conventional methods such as water curing and air drying, while effective, impose logistical challenges and project delays [2]. In response to these challenges, the exploration of alternative curing techniques has become paramount, with researchers actively investigating innovative approaches to accelerate the curing process while either maintaining or enhancing concrete performance [3].

Among these emerging methods, microwave curing (MC) stands out for its potential to revolutionize concrete curing practices by harnessing electromagnetic waves in the microwave frequency range to expedite the hydration process [4]. Efforts to expedite the curing process have spurred innovation in concrete technology, with researchers exploring alternative curing methods to reduce curing times while either maintaining or enhancing concrete performance [5–7]. By utilizing electromagnetic waves in the microwave frequency range, typically between 300 MHz and 300 GHz, MC offers the promise of rapid and uniform heating of concrete, leading to accelerated hydration reactions and faster strength development [8]. The application

Cite this article as: Lam, T.-K., Nguyen, D.-T., Le, T. H. M., Huynh, T.-P. "Effect of Microwave Curing on the Performance of High-volume Fly Ash Concrete", Periodica Polytechnica Civil Engineering, 68(4), pp. 1405–1417, 2024. https://doi.org/10.3311/PPci.37182

of MC in concrete technology represents a paradigm shift from conventional curing methods, offering several potential advantages [9]. Firstly, MC can significantly reduce curing times compared to traditional methods, thereby accelerating construction timelines and improving project efficiency [9]. In addition, MC can facilitate more uniform heat distribution within concrete, minimizing the risk of thermal differentials and associated issues such as cracking and internal stresses [10].

Previous studies have investigated the performance and properties of concrete cured using microwave energy. For instance, Shen et al. [11] studied the effects of microwave power and time on ultra-high performance geopolymer concrete, demonstrating enhanced compressive strength of 125.4 MPa and flexural strength of 6.0 MPa at 3 days with optimal microwave power and time settings. Zhang et al. [5] explored the impact of microwave radiation on recycled concrete powder in cement-based materials, resulting in an increase in the activity index from 53% to 75% at 7 days with 800 W microwave energy. Leung and Pheeraphan [8, 9] reported experimental results on the early and later strength of mortar and concrete specimens cured with microwave energy, highlighting the potential of MC for practical construction applications. They achieved a 40% increase in early-age strength compared to conventional curing methods. Zhou et al. [12] investigated the influence of secondary water curing on the performance of microwave-cured concrete, revealing that while MC improves early-age compressive strength, secondary water curing enhances later-age strength and durability, with a 15% increase in compressive strength observed at 28 days. Han et al. [4] systematically investigated the impact of MC on ternary blended concrete properties using the simplex centroid method, demonstrating significant improvements in both mechanical properties and durability, with a 20% increase in flexural strength observed. Pan et al. [13] explored the effects of isothermal MC on steel fiber-reinforced reactive powder concrete, showing accelerated mechanical strength development and enhanced microstructure properties, with a 30% increase in compressive strength observed.

High-volume fly ash concrete (HVFC) is a specialized concrete mixture that incorporates a large proportion of fly ash, a byproduct of coal combustion, as a partial replacement for Portland cement [14]. HVFC offers several benefits, including improved workability, reduced hydration heat, and enhanced long-term durability [15]. Current research on HVFC is focused on exploring its potential as a sustainable alternative to traditional concrete [16]. HVFC incorporates a higher volume of fly ash, reducing the environmental impact of concrete production by limiting the use of cement. Studies in this field aim to optimize HVFC mix designs to enhance the mechanical properties, durability, and sustainability of concrete. Researchers are investigating various factors such as fly ash composition, water-to-binder ratio, curing methods, and supplementary additives to improve HVFC's performance [14, 15, 17, 18]. Additionally, there is growing interest in understanding the long-term behavior of HVFC in real-world applications and its compatibility with different construction practices and environments [17]. Overall, current research efforts underscore the potential of HVFC to contribute to more eco-friendly and resilient infrastructure systems [19]. However, the unique composition of HVFC presents distinct challenges in terms of curing and strength development, making it an ideal candidate for investigation into the efficacy of MC.

Previous research in the field of HVFC has encountered certain limitations, primarily in the scope of investigation and experimental design. Many studies have focused on conventional curing methods, overlooking the potential benefits of alternative techniques such as MC. Moreover, the exploration of MC in HVFC has been relatively sparse, with limited attention to the influence of MC parameters on concrete properties. This research addresses these gaps by conducting a comprehensive investigation into the effects of MC on HVFC performance. By systematically varying MC parameters such as curing energy (200, 600, and 1000 W) and duration (10, 20, and 30 min), a nuanced understanding of MC impact on mechanical and durability characteristics is provided. Furthermore, this study employs a multidimensional approach, evaluating compressive strength, drying shrinkage, chloride ion penetration (RCPT), and sulfate attack resistance at different specimens' ages. These comprehensive approaches facilitated a detailed examination of the influence of MC parameters on the properties of HVFC. Overall, this research contributes to the ongoing efforts to advance HVFC technology and enhance the sustainability and efficiency of construction practices. By elucidating the role of MC in HVFC, this research provides valuable insights that can inform future developments in HVFC curing methodologies and support the continued evolution of construction practices toward more sustainable and resilient infrastructure solutions.

2 Materials and experimental methods

2.1 Materials

The experimental investigation in this study meticulously selected materials to seamlessly align with HVFC production practices and meet the precise objectives of the inquiry. In detail, grade-40 blended Portland cement as per TCVN 6260:2020 [20] (a density of 3.07 g/cm^3 and a mean particle size (*d*50) of 21.42 µm) was chosen for its widespread application in construction projects. In addition, type-F fly ash conforming to the TCVN 10302:2014 standard [21] (a density of 2.23 g/cm^3 and a *d*50 of 23.08 µm) was used as a partial cement substitution. Further, commercial industrial hydrated lime (HL) with a density of 2.21 g/cm^3 and *d*50 of 19.89 µm was integrated, meeting the criteria essential for achieving the study's objectives. The primary chemical compositions of all powders are shown in Table 1.

Aggregates utilized in the study included crushed stone (particle size in the range of 5.0 to 9.5 mm, a density of 2746 kg/m^3, and a water absorption rate of 1.36%) and crushed sand (fineness modulus of 2.96, a density of 2770 kg/m^3, and a water absorption rate of 1.37%). The grain size distribution of crushed sand is plotted in Fig. 1.

Tap water, complying with the specifications of TCVN 4506:2012 [22], was utilized as the mixing water, ensuring consistency and reliability throughout the experimental process. Type-G superplasticizer (SP) in compliance with TCVN 8826:2011 [23] was also used to ensure the desired workability of the fresh concrete mixtures.

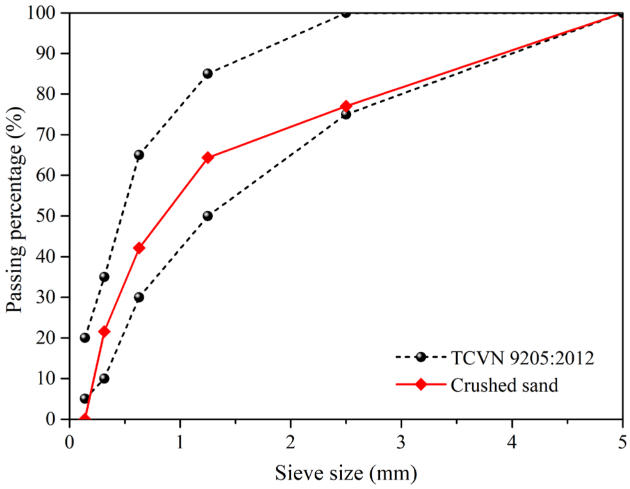


Fig. 1 Grain size distribution of crushed sand

2.2 Mixture proportions

In this study, the mixture proportions for preparing HVFC specimens were meticulously designed following the guidelines of TCVN 10306:2014 [24]. Based on the prior trials in the laboratory, the water-to-binder ratio was maintained at 0.3, ensuring an optimal balance between workability and strength. Fly ash was used to substitute 50 wt.% of cement and 5% of HL was added to the mixture. The incorporation of fly ash and hydrated lime contributes to the reduction of cement content while enhancing the performance of the HVFC. Furthermore, the use of an SP with a dosage of 0.47% total weight of powder aided in achieving the desired consistency and flowability of the HVFC mixture. The quantity of each concrete ingredient was calculated for 1 m^3 as shown in Table 2. These meticulously selected proportions were aimed at achieving the desired performance characteristics of the HVFC specimens while adhering to established standards.

Table 1 Chemical compositions of cement, fly ash, and hydrated lime

Chemical compositions	Cement	Fly ash	Hydrated lime
CaO (wt.%)	63.5	2.34	95.4
SiO_2 (wt.%)	20.5	62.0	0.69
Fe_2O_3 (wt.%)	4.88	9.14	0.19
Al_2O_3 (wt.%)	4.34	20.8	0.04
MgO (wt.%)	1.43	0.01	2.74
K_2O (wt.%)	0.47	2.75	0.13
Na_2O (wt.%)	1.17	0.47	0.41
SO_3 (wt.%)	2.89	0.50	-
P_2O_5 (wt.%)	-	0.29	-
TiO_2 (wt.%)	0.31	0.88	-
Others (wt.%)	0.51	0.82	0.40

2.3 Specimen preparation and test methods

The mixing process for preparing the HVFC specimens involved several sequential steps as described in Fig. 2 to ensure thorough blending of the materials and uniform distribution of additives. Upon completion of the mixing process, the HVFC specimens were cast into molds and allowed to be set for 24 hours then demolding.

Subsequently, various curing conditions were applied to the specimens, with some subjected to normal water curing (NC) and others undergoing MC using microwave equipment as shown in Fig. 3. Following the designated curing conditions as outlined in Table 3, the concrete specimens were then stored in the laboratory at an ambient condition. Later on, the cured specimens were subjected to

Table 2 Mixture proportions of concrete specimens (kg/m^3)

Cement	Fly ash	HL	Sand	Stone	Water	SP
352	352	35	210	1156	211	3.5

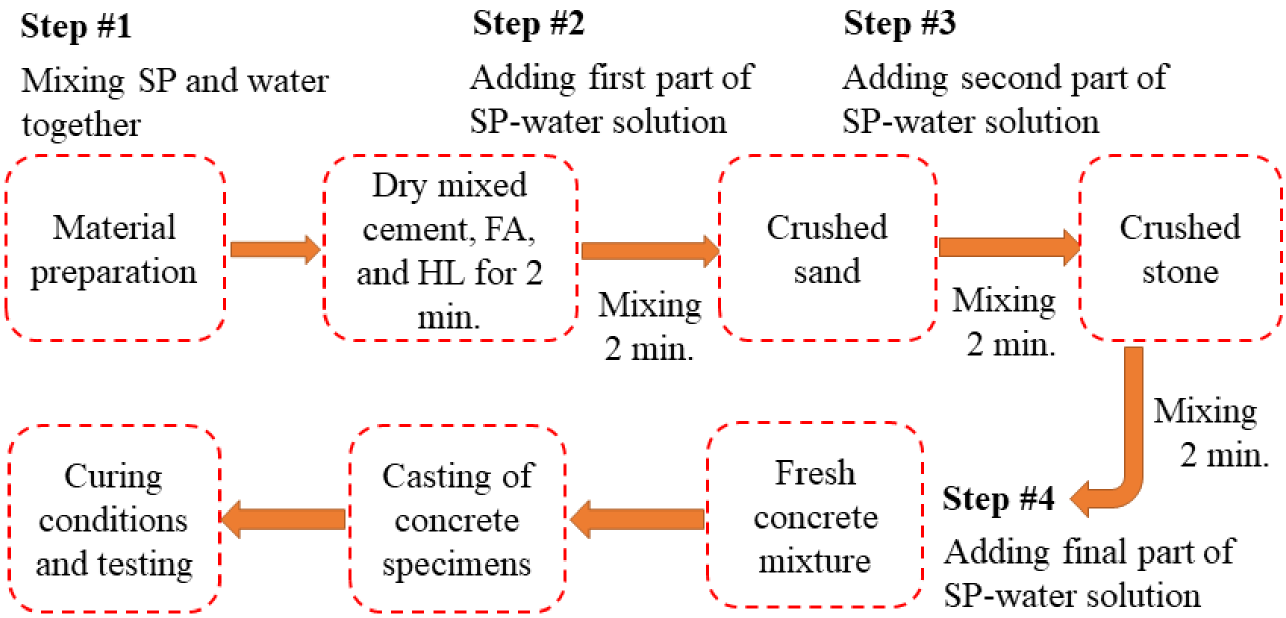


Fig. 2 Procedures of mixing and sample preparation

Fig. 3 MC equipment used in the study

Table 3 Curing conditions applied for HVFC specimens

Case ID.	Applied energy (W)	Curing duration (min)	Remarks
NC	-	-	NC = Normal water curing MC = Microwave curing
MC200-10	200	10	
MC200-20		20	
MC200-30		30	
MC600-10	600	10	
MC600-20		20	
MC600-30		30	
MC1000-10	1000	10	
MC1000-20		20	
MC1000-30		30	

Table 4 Summarization of test methods for concrete specimens

Test name	Sample size (mm)	Age (day)	References
Compressive strength	100 × 100 × 100	1, 7, 28	TCVN 3118:2022 [25]
Drying shrinkage	75 × 75 × 285	0, 3, 7, 14, 28	ASTM C157/ C157M-17 [26]
Rapid chloride ion penetration	∅100 × 50	1, 7, 28	TCVN 9337:2012 [27]
Resistance to sulfate attack	100 × 100 × 100	9 cycles	Loser and Leemann [28]

various testing procedures as summarized in Table 4 [25–28] to evaluate their mechanical properties and durability, facilitating a comprehensive assessment of the effectiveness of MC compared to the conventional curing method.

Importantly, to ensure the accuracy and consistency of microwave energy applied in the curing experiments, a rigorous calibration process was employed using a digital microwave power meter. Prior to the commencement of the experiments, the microwave oven was set at 1000 W of energy, and the actual power output was measured directly within the oven cavity. The power meter readings were used to adjust the microwave's internal power settings, ensuring that the displayed power corresponded accurately to the output. This calibration was conducted regularly throughout the experimental phase to compensate for any potential variations in power output. The entire calibration process was documented meticulously for each experimental run, guaranteeing that the applied microwave energy levels were both precise and reproducible.

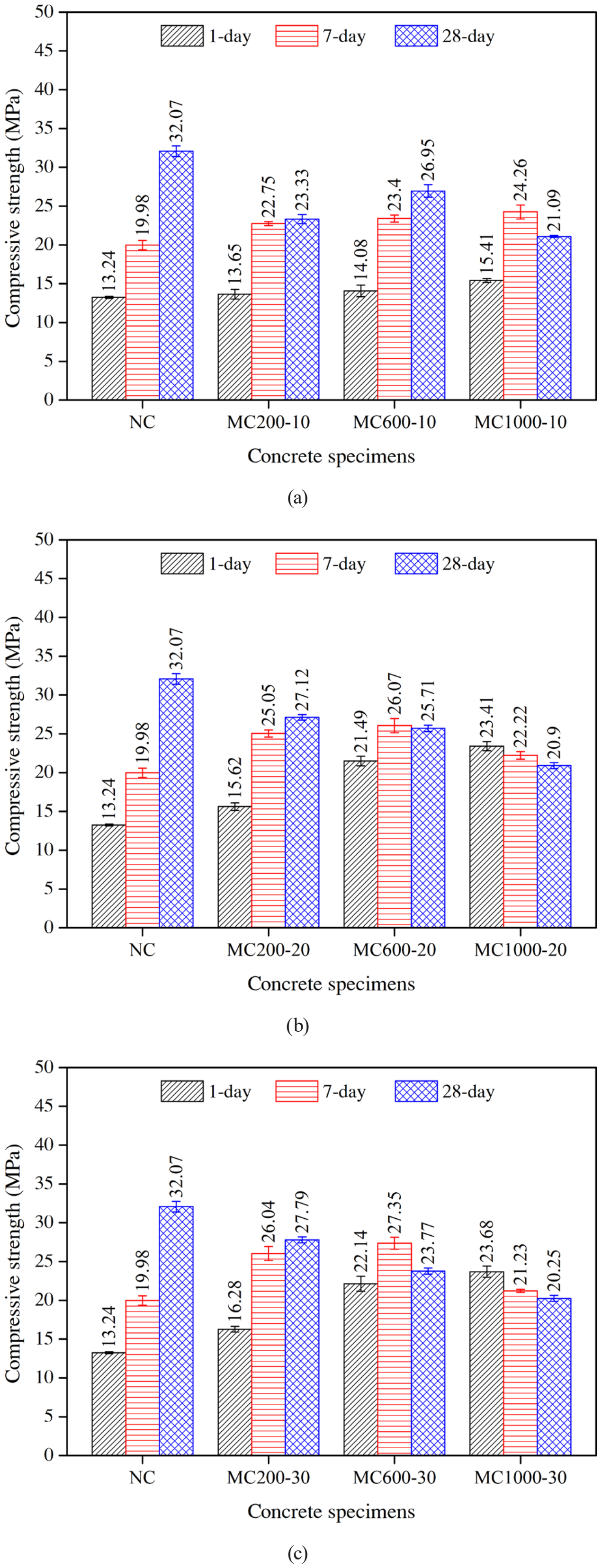
In particular, the resistance to sulfate attack of HVFC under both NC and MC was conducted by assessing the changes in sample mass after 9 cycles of immersion-drying. Each cycle includes the full immersion of concrete specimens in a 5% Na_2SO_4 solution for 3 days followed by drying at 50 °C for 3 days following the methodology recommended by Loser and Leemann [28]. Through systematic analysis of the mass changes in the samples after each immersion-drying cycle, insights into the extent and progression of sulfate-induced deterioration in concrete are obtained. This investigation contributes valuable information to the understanding of concrete degradation mechanisms and aids in the development of strategies to mitigate sulfate attacks and enhance the durability of concrete structures.

3 Results and discussion

3.1 Compressive strength

Fig. 4 illustrates the impact of varying MC energy levels on the compressive strength of HVFC under maintaining a constant MC duration of 10 min (Fig. 4 (a)), 20 min (Fig. 4 (b)), and 30 min (Fig. 4 (c)). In general, the compressive strength in the early days (i.e., 1 day) of microwave-cured specimens was higher than the control specimen, which is considered a general trend of heat-treated materials. In this case, concrete absorbs energy from microwaves and heat from water evaporation, increasing the internal temperature of the specimens, and thereby promoting the hydration reaction, resulting in increased compressive strength [29, 30].

Day 1 comparisons between NC and MC specimens show varied outcomes. For instance, the NC specimen recorded a compressive strength of 13.24 MPa, while the MC200-30 specimen showed an enhanced strength of 16.28 MPa, a 22.76% increase, illustrating MC's effectiveness in boosting early-age strength. The MC600-10 specimen saw a modest increase to 14.08 MPa. At 7 days, differences in strength development were more pronounced as the compressive strength of the MC600-30 specimen surged to 27.35 MPa, a 36.89% rise, while the MC1000-10 specimen also showed strength improvement at 24.26 MPa. After 28 days, while the NC's compressive strength was maintained at 32.07 MPa, the compressive strength of the MC-treated specimens like MC200-10 increased to 23.33 MPa, but the compressive strength of the higher energy specimens (i.e., MC600-30 and MC1000-30) decreased to 23.77 and 20.25 MPa respectively, highlighting the risks of either high-energy or prolonged curing time. These results stress the importance of fine-tuning MC energy and duration to balance early benefits against long-term performance.



(a)

(b)

(c)

Fig. 4 Effect of applied MC energy on compressive strength of HVFC with a fixed MC duration of (a) 10 min, (b) 20 min, and (c) 30 min

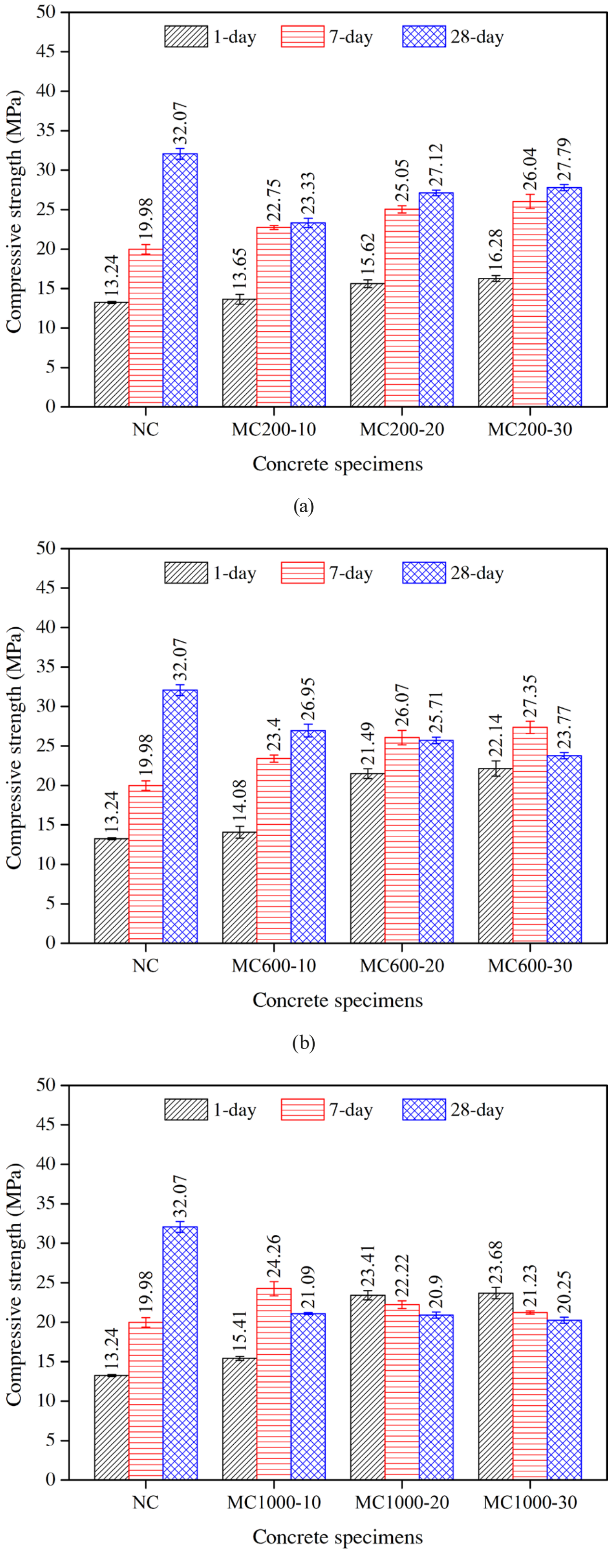
Analyzing compressive strength changes over 1, 7, and 28 days for HVFC specimens subjected to 10-min and 20-min MC durations revealed notable variations across different energy levels. For the 10-min duration, 1-day strengths increased from 13.65 MPa for MC200 to 15.41 MPa for MC1000, with enhancements up to 16.5% compared to the NC group's 13.24 MPa. However, at 28 days, the MC1000 strength decreased by 34.24%, contrasting with NC's maintenance at 32.07 MPa. Similarly, for the 20-min duration, initial strengths on 1 day ranged from 15.62 MPa for MC200 to 23.41 MPa for MC1000, reflecting gains of up to 17.3% over NC. Yet, a decline to 20.90 MPa was observed in the MC1000 specimen at 28 days, while MC200 and MC600 showed less fluctuation, underscoring the critical impact of energy levels and curing times on strength trajectories.

Additionally, analyzing the changes in compressive strength over 1, 7, and 28 days for HVFC specimens subjected to a 30-min MC duration reveals significant differences across various energy levels (Fig. 4 (c)). In the MC1000 group, the 1-day compressive strength reached a peak of 23.68 MPa, an approximate 11.1% increase over the NC group's strength of 21.29 MPa. However, at 28 days, a substantial decline was observed in the MC1000 group's strength, which decreased to 20.25 MPa, a 36.33% reduction from its initial strength, while the NC group maintained its strength at 32.07 MPa. This reduction in strength may result from the continued hydration in the NC specimens, facilitated by the presence of residual water that supports further development of hydration products. In contrast, the rapid evaporation during microwave curing likely removed much of the free water in the specimens, diminishing the water available for hydration reactions in later stages and consequently reducing concrete strength [12]. Besides, the decline in the MC1000 group's strength could also be linked to the generation of microcracks, predominantly induced by rapid water evaporation under high temperatures and energy conditions [31]. Meanwhile, the MC200 and MC600 groups showed varied strength developments, with values ranging from 16.28 MPa to 27.35 MPa at 1 day, which represents percentage changes from −22.43% to 28.17% compared to the NC group. These observations emphasize the need to balance MC energy levels and exposure durations to optimize HVFC performance for practical applications.

In HVFC structures, MC plays a pivotal role by utilizing electromagnetic radiation to swiftly and uniformly heat the HVFC mix. This process accelerates the hydration of cementitious materials, promoting the formation of hydration products and enhancing early strength development. As MC energy penetrates the HVFC matrix, it excites water molecules, leading to heat generation through molecular friction. This rapid heating expedites moisture removal and facilitates hydration reactions, ultimately reinforcing the mechanical properties of the HVFC. Evaluation of the impact of applied MC energy on compressive strength with fixed durations of 10, 20, and 30 min demonstrates an initial strength advantage, particularly within the first week of curing. While lower MC energy levels may yield significant strength gains, higher levels may not proportionally enhance strength over longer durations. Despite its effectiveness in promoting early-age strength, the efficacy of MC diminishes over extended periods, such as 28 days, possibly due to limitations in sustained hydration and moisture distribution within the HVFC. Thus, optimizing MC parameters, including energy level and duration, is crucial to achieving a balance between rapid strength enhancement and long-term durability in HVFC structures.

On the other hand, Fig. 5 demonstrates how different MC durations influence the compressive strength of HVFC while maintaining a consistent applied MC energy of 200 W (Fig. 5 (a)), 600 W (Fig. 5 (b)), and 1000 W (Fig. 5 (c)). Analyzing the effect of MC duration on the compressive strength of HVFC with a fixed applied MC energy reveals intriguing insights across various curing energy. Beginning with a fixed energy level of 200 W, the compressive strength trends indicate notable differences based on curing duration (see Fig. 5 (a)). At 1 day, the MC200-10 mix showed a strength of 13.65 MPa, while the MC200-30 mix exhibited a higher strength of 16.28 MPa, marking an increase of approximately 19.35%. This pattern continued at 7 days, with the MC200-10 mix recording a strength of 22.75 MPa, compared to 26.04 MPa for the MC200-30 mix, reflecting a gain of approximately 14.51%. However, the 28-day compressive strength of the MC200-10 mix slightly decreased to 23.33 MPa, while the MC200-30 mix demonstrated further improvement to 27.79 MPa, showcasing a notable gain of approximately 18.30% with longer curing durations at this energy level.

Moving to a fixed energy level of 600 W, similar trends emerged but with varying magnitudes of improvement (see Fig. 5 (b)). At 1 day, the MC600-10 mix displayed a strength of 14.80 MPa, which increases to 22.14 MPa for the MC600-30 mix, indicating an increase of approximately 49.19%. By 7 days, the compressive strength ranged



(a)

(b)

(c)

Fig. 5 Effect of MC duration on compressive strength of HVFC with a fixed applied MC energy of (a) 200 W, (b) 600 W, and (c) 1000 W

from 23.40 MPa for the MC600-10 mix to 27.35 MPa for the MC600-30 mix, representing a gain of approximately 17.95%. Interestingly, at 28 days, while the strength of the MC600-10 mix peaked at 26.95 MPa, there's a decline in strength for the MC600-30 mix to 23.77 MPa, suggesting potential limitations or adverse effects associated with longer curing durations at this energy level, resulting in a decrease of approximately 13.72%.

At a fixed energy level of 1000 W, contrasting trends are observed compared to lower energy levels (see Fig. 5 (c)). Initially, the compressive strength at 1 day ranged from 15.41 MPa for the MC1000-10 mix to 23.68 MPa for the MC1000-30 mix, showcasing a percentage increase of approximately 53.75%. However, by 28 days, there's a substantial reduction in strength across all mixes, with values declining to 21.09 MPa for the MC1000-10 mix and 20.25 MPa for the MC1000-30 mix, representing a decrease of approximately 31.47% and 14.21%, respectively. This decline suggests potential limitations associated with prolonged exposure to high MC energies, indicating the importance of optimizing both energy level and curing duration for consistent and sustainable strength enhancement in HVFC.

Across all MC energy levels and curing durations, microwave-cured specimens consistently exhibit varying degrees of strength enhancement compared to the control group. For instance, at 28 days, while the control group achieved a compressive strength of 32.07 MPa, select microwave-cured mixes such as MC200-30 and MC600-30 demonstrated strengths of 27.79 MPa and 27.35 MPa, respectively. This represents a decrease in strength of approximately 13.35% for the MC200-30 mix and 14.72% for the MC600-30 mix compared to the control group. However, other microwave-cured mixes like MC600-30 and MC1000-30 showed even more substantial decreases in strength compared to the control group, underscoring the nuanced relationship between MC energy levels, curing durations, and HVFC performance.

In summary, the experimental results underscore the complex interaction between MC energy levels and curing durations, as well as their collective impact on the strength development of HVFC. At lower MC energy levels, exemplified by the 200 W setting, there was a steady improvement in strength over extended durations. This enhancement is attributed to the gradual but sustained acceleration of hydration reactions, facilitated by moderate temperatures that prevent rapid water loss while promoting continuous cement hydration. Conversely, higher MC energy levels, such as the 1000 W setting, may initially accelerate strength development due to rapid and intense heat generation. However, this rapid heating can also lead to negative outcomes, including excessive evaporation of water, increased thermal gradients, and potential microcracking within the concrete matrix. Over time, these factors can undermine the structural integrity of the HVFC, leading to diminished strength gains. This delineation of effects based on MC energy settings emphasizes the need for careful selection and optimization of curing conditions to harness the benefits of microwave curing while mitigating its potential drawbacks.

The intermediate MC energy level of 600 W struck a balance between these extremes, offering notable early-age strength enhancement while maintaining stability over extended curing periods. These insights underscore the need for a nuanced understanding of MC dynamics to optimize parameters effectively and achieve desired HVFC performance in real-work applications. Previous studies on MC demonstrate its potential to accelerate HVFC strength development, aligning with the objectives of related research in this field [10]. The findings emphasize the importance of optimizing both energy levels and curing durations to achieve consistent and sustainable strength enhancement in HVFC.

Fig. 6 illustrates the impact of specimen size on the efficiency of MC and its effect on HVFC strength. The finding outlines the variation in compressive strength of HVFC mixtures cured in a 1000 W microwave for 30 min, with different sample shapes and sizes. In detail, the compressive strength values of the cubic (100 × 100 × 100 mm) specimen showed a gradual decrease over time, with values of 23.68 MPa at 1 day, indicating a decrease of approximately 10.55% at 7 days, and a further decrease of about 14.97% at 28 days. This decline could be attributed to factors such as increased exposure to environmental conditions or internal curing processes. Conversely, cubic specimens with dimensions of 150 × 150 × 150 mm exhibited a different trend, with compressive strength values starting at 19.23 MPa at 1 day, showing an increase of roughly 14.33% at 7 days and further rising by approximately 28.74% at 28 days. The larger size of these samples might contribute to better curing efficiency and internal cohesion, resulting in improved strength over time. Additionally, cylindrical specimens with a diameter of 100 mm and a height of 200 mm (∅100 × 200 mm) displayed compressive strength values of 20.75, 22.79, and 24.56 MPa at 1, 7, and 28 days, respectively. This represents an increase of around 9.46% from 1 day to 7 days and a further increase of about 18.59% from 7 to 28 days. Comparing the sample sizes, at early ages, the smaller cubic specimens (100 × 100 × 100 mm) exhibited higher compressive strength, with values of 23.68 MPa at 1 day, while the larger cubic specimens (150 × 150 × 150 mm) started at 19.23 MPa. This represents an approximate difference of 18.59% in favor of the smaller samples. However, at 28 days, the larger cubic specimens demonstrated superior strength development, with a value of 24.75 MPa, compared to 20.25 MPa for the smaller cubic specimens. This data reveals that larger cubic specimens, measuring 150 × 150 × 150 mm, demonstrated an increase in compressive strength by approximately 22.22% over the curing period compared to the smaller cubic specimens. This indicates that larger samples benefit from a more gradual and uniform heat distribution, which enhances the ongoing hydration process critical for strength development. Additionally, cylindrical specimens, with their unique geometry, showcased notable strength improvements throughout the MC curing period. The cylindrical shape potentially allows for a more even distribution of microwave energy and less susceptibility to thermal stresses, contributing to a more consistent gain in strength. These observations underscore the significant influence of both sample size and shape on the early and later strength performance of HVFC. Considering the dimensions and geometrical configuration of samples is crucial in HVFC testing and application to ensure accurate and reliable results that reflect the true performance characteristics under varied curing conditions.

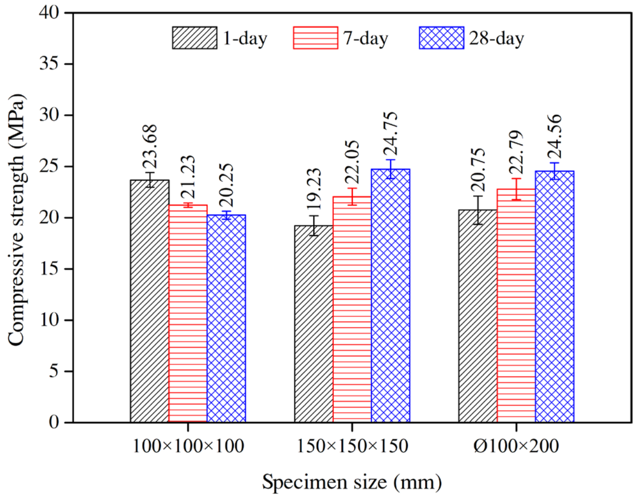


Fig. 6 Effect of sample size on the efficiency of MC and concrete strength

3.2 Drying shrinkage

The drying shrinkage of HVFC specimens under both NC and MC conditions is illustrated in Fig. 7. The drying shrinkage data for HVFC specimens subjected to different curing methods reveals distinctive trends in dimensional changes over various time intervals. In the conventional curing specimen, the drying shrinkage progressed steadily over time. A noticeable shrinkage of −0.0240% was recorded for the 3-day-old specimen, indicating a rapid increase in moisture loss. This trend continued with shrinkage values of −0.0432%, −0.0688%, and −0.0784% at 7, 14, and 28 days, respectively. This represents a consistent increase in shrinkage over the curing period, suggesting ongoing moisture loss and subsequent volume reduction within the HVFC matrix. In contrast, HVFC specimens subjected to MC at 1000 W for 30 min exhibited different shrinkage behavior. The rate of shrinkage was notably lower in the microwave-cured samples compared to the NC one regardless of the curing age. At 3 days, the shrinkage was recorded at −0.0046%, indicating a slower rate of moisture loss. This trend continued with drying shrinkage values of −0.0068%, −0.0092%, and −0.0132% at 3, 14, and 28 days, respectively. As a result, the MC specimens consistently exhibited lower shrinkage values at each time interval as compared to the NC specimen. It is a fact that the MC specimens demonstrated a significant reduction in drying shrinkage of approximately 84.28% (at 7 days) and 83.12% (at 28 days) in comparison with the NC specimen. The investigation reveals that employing MC at 1000 W for 30 minutes effectively reduces drying shrinkage in HVFC. This reduction is likely attributable to the enhanced control over moisture evaporation facilitated by microwave energy, which allows for a more uniform and rapid removal of moisture compared to traditional methods. Such controlled evaporation helps maintain a balanced moisture content, preventing the development of large internal stresses that typically lead to shrinkage [32]. Additionally, the rapid heating during MC promotes a quicker hydration reaction, resulting in a denser concrete matrix with lower porosity. This densification further contributes to the material's stability by minimizing the volume of voids that can absorb and subsequently release water, thereby mitigating potential shrinkage. The reduced internal stresses within the HVFC matrix are a direct result of the uniform temperature distribution during curing, which prevents the formation of thermal gradients known to cause differential drying and associated shrinkage. These mechanisms highlight the critical role of finely tuned MC parameters (i.e., energy levels and exposure durations) in optimizing the physical properties of HVFC. Prior studies have underscored the potential of MC to enhance concrete performance, aligning with our findings [10].

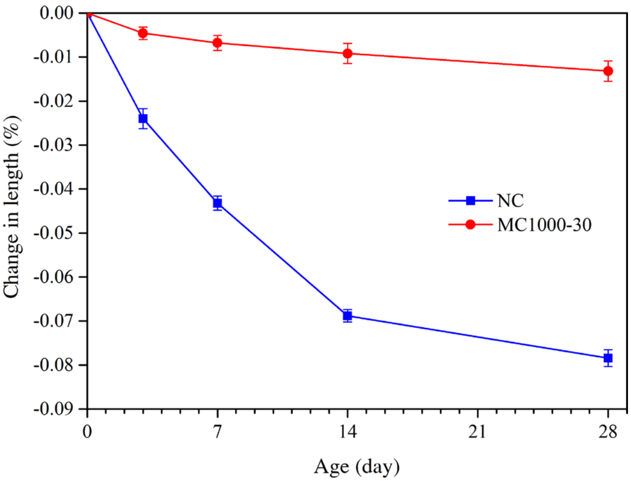


Fig. 7 Drying shrinkage of concretes under NC and MC conditions

3.3 Rapid chloride ion penetration

The RCPT results shown in Table 5 demonstrate the evolution of chloride permeability over time for the MC1000-30 specimen. At the onset, with a value of 1577 Coulombs in 1 day, the HVFC exhibited a moderate level of permeability to chloride ions. However, as the curing duration progressed, there was a discernible improvement in the HVFC's resistance to chloride penetration. Hence, the 7-day RCPT value decreased to 1310 Coulombs, marking a notable 16.8% reduction compared to the initial measurement. This reduction underscores the HVFC's increasing ability to resist chloride ingress as hydration and curing continue. The RCPT value further decreased to 1078 Coulombs, representing a significant 31.6% decrease from the 1-day measurement. This substantial reduction indicates a considerable enhancement in the HVFC's chloride resistance properties over the curing period, likely attributed to continued hydration and refinement of the cementitious matrix. A similar finding was also found by Zhou et al. [12]. On the other hand, the consistently low standard deviations associated with each RCPT measurement as shown in Table 5 implied a high level of consistency and reliability in the

Table 5 Results of the RCPT test for the MC1000-30 specimens

Test name	1-day	7-day	28-day
RCPT (Coulombs) ± Standard deviation	1577 ± 121	1310 ± 152	1078 ± 143

test results, bolstering confidence in the observed trends. Overall, the decreasing trend in RCPT values indicates the efficacy of MC in improving the chloride resistance of the HVFC mix, highlighting its potential for enhancing the durability and longevity of concrete structures exposed to chloride-rich environments.

Table 6 provides a comprehensive comparison of RCPT test results obtained from NC and MC specimens at 28 days, providing insights into the durability and performance of the HVFC under different curing conditions. As a result, normal-cured HVFC recorded an average RCPT value of 3176 Coulombs, indicating moderate chloride ion permeability while the RCPT value for microwave-cured HVFC showed a substantial decrease (only 1078 Coulombs), plummeting by 66.1%. This reduction implies a remarkable improvement in chloride ion penetration resistance, meeting the criteria for a low chloride ion penetration level as per the standard classification [27]. The enhanced chloride resistance of microwave-cured concrete underscores its potential for use in structures exposed to aggressive environments, where protection against chloride-induced corrosion is paramount.

Table 6 Comparison of test results of normal and microwave-cured (MC1000-30) concrete specimens at 28 days

Test name	Normal cured concrete	Microwave cured concrete (% change)	Standard classification
RCPT (Coulombs) ± Standard deviation	3176 ± 41	1078 ± 143 (−66.1%)	Low chloride ion penetration level [27]

3.4 Resistance to sulfate attack

Fig. 8 provides surface observations of the microwave-cured specimen (MC1000-30) during the sulfate resistance test for 9 cycles, while Fig. 9 illustrates the change in mass of the MC1000-30 specimen immersed in a 5% Na_2SO_4 solution. The resistance of the microwave-cured HVFC specimens to sulfate attack was evaluated by measuring the change in mass (%) over nine cycles of immersion in a sulfate solution and then drying in an electric oven as previously described in Section 2.3. The HVFC specimens exhibited varying responses to sulfate exposure throughout the testing period. Initially, during cycles 1–3, there was a progressive increase in mass (by 1.32%, 1.49%, and 1.65%, respectively), indicating sulfate ingress into the HVFC matrix and the formation of sulfate compounds. However, a deviation from this trend was observed in cycle 4, with a slight reduction in mass (by 0.35%), suggesting a possible reversal of the sulfate attack process or the activation of mitigation mechanisms within the HVFC. Subsequent cycles 5–9 demonstrated intermittent fluctuations in mass, with some cycles showing increases and others showing decreases. This phenomenon may be attributed to the swelling of the gypsum and the formation of ettringite within the system [33]. These unremarkable variations underscore the complex interaction between sulfate exposure, HVFC composition, and environmental conditions, highlighting the dynamic nature of sulfate attack resistance in microwave-cured HVFC. Generally, the tested HVFC specimens were mostly undamaged after 9 cycles (see Fig. 8), demonstrating good resistance to sulfate attack of the microwave-cured specimen.

The combination of MC and high-volume FA presents an intriguing avenue for enhancing HVFC performance, but its feasibility and long-term implications warrant careful consideration. While MC has shown promise in accelerating early-age strength development, the long-term performance associated with high-volume FA could potentially impact the strength of MC samples over time. The interaction between MC energy and high-volume FA constituents may influence the hydration process and microstructure development within the HVFC matrix, ultimately affecting its mechanical properties. Moreover, the inner mechanisms governing the synergistic effects of MC and high-volume FA remain to be fully elucidated. It is essential to conduct further research to investigate the compatibility of MC with high-volume FA, exploring factors such as optimal MC parameters, the influence of high-volume FA content on MC efficiency, and the durability performance of MC-treated HVFC mixes under prolonged exposure conditions. By gaining insights into the combined effect of MC and high-volume FA, the construction industry can harness the potential of these technologies to produce sustainable and resilient HVFC structures.

4 Conclusions

This study investigates the impact of applying various MC conditions on compressive strength, drying shrinkage, chloride ion penetration, and sulfate attack resistance of HVFC. Based on the experimental results, the following conclusion can be drawn:

- MC, particularly in the very short-term age of HVFC, provided significant effects on concrete strength compared to traditional curing methods. Across the 10-min, 20-min, and 30-min curing durations, the


(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 8 Surface observation of the microwave-cured specimen (MC1000-30) during the sulfate resistance test for 9 cycles: (a) Cycle #1, (b) Cycle #2, (c) Cycle #3, (d) Cycle #4, (e) Cycle #5, (f) Cycle #6, (g) Cycle #7, (h) Cycle #8, (i) Cycle #9

1000 W applied energy specimens consistently led to the greatest 1-day strength gain across all durations. However, after 28 days of curing, the trend reversed, with the normal curing group showing the highest strength while the MC1000-30 mix declined in strength (by approximately 36.85%). This suggests that while MC can accelerate early-age strength development, its effectiveness may wane over longer curing periods. Factors such as excessive heat generation and potential damage to the HVFC matrix could contribute to these diminishing returns.

- The study highlights how MC duration and energy levels interact to affect HVFC strength. At a low energy level (200 W), there was a steady improvement in strength over time, while at a high energy level (1000 W), initial strength gains were offset by

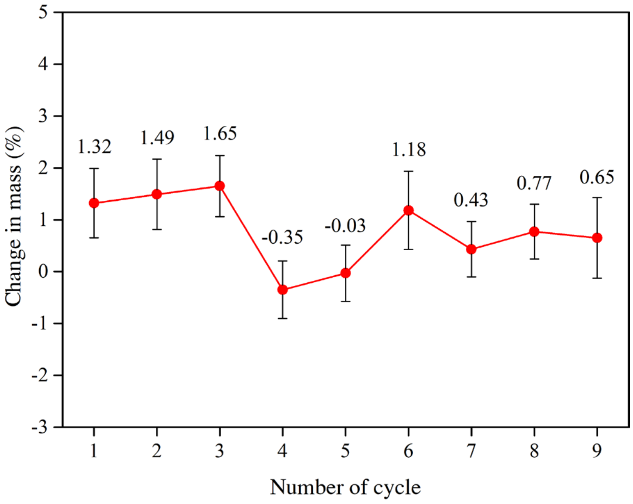


Fig. 9 Change in the mass of microwave-cured specimen (MC1000-30) immersed in a sulfate solution

long-term reductions due to heat-induced damage. An intermediate energy level (600 W) provided a balanced approach, enhancing early strength and maintaining stability over time. These results underline the critical need to optimize MC parameters to achieve the best HVFC performance for practical applications.

- Sample size and shape impact the strength gain of microwave-cured HVFC as smaller cubic specimens of 100 × 100 × 100 mm showed a decline (about 14.97%) in compressive strength while larger cubic specimens of 150 × 150 × 150 mm exhibited an increase in compressive strength (about 28.74%) over the same curing conditions.
- HVFC specimens subjected to MC at 1000 W for 30 min exhibited significantly lower drying shrinkage in comparison with the conventionally cured HVFC, with reductions of approximately 84.28% at 7 days and 83.12% at 28 days, indicating enhanced moisture control and reduced internal stresses in the specimen.
- The RCPT results for the MC1000-30 mix revealed a significant improvement in chloride resistance over the curing period. The continuous decrease in RCPT values with time indicates a substantial enhancement in chloride resistance, which was attributed to continued hydration and cementitious matrix refinement. Furthermore, the microwave-cured HVFC specimens exhibited good resistance to sulfate attack, indicated by the slight mass change and mostly undamaged after 9 cycles of testing.

In terms of research limitations, it is important to note that this study primarily focused on evaluating the change in compressive strength and may not fully represent other properties of HVFC, while the laboratory setup may limit the generalizability of findings to real-world conditions. Future studies should focus on evaluating the long-term performance of HVFC in large-scale constructions and real-work applications. Investigating the impact of different FA sources and utilizing advanced MC equipment and methodologies are also crucial. These efforts will provide deeper insights into refining HVFC mix designs and improving the efficacy of the curing process.

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