A Mechanical Investigation on the Recovery of Thermally Damaged Self-Compacting Concrete Using Magnetized Water

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ABSTRACT

Concrete exposed to high temperatures undergoes severe deterioration in strength and microstructural integrity, demanding effective post-fire rehabilitation. This study investigates Magnetized Water (MW) as a re-curing medium for restoring heat-damaged Self-Compacting Concrete (SCC). Specimens prepared with either MW or Normal Water (NW) were subjected to 200°C, 400°C, and 600°C, then re-cured for 28 days in magnetized or plain water. Performance recovery was assessed through compressive, flexural, and bond strength tests, complemented by porosity and Ultrasonic Pulse Velocity (UPV) measurements. The results showed that MW significantly improved recovery compared with NW: after 600°C exposure, re-cured SCC regained 75%–80% of its original compressive strength versus 60%–65% with NW, with a residual strength consistently higher by 5%–15% across all temperatures. The flexural and bond strength recovery exhibited similar trends. MW also reduced porosity by 5%–10% and increased UPV, indicating a denser matrix. Overall, MW re-curing proved an efficient technique for restoring the mechanical properties of thermally deteriorated concrete, highlighting its potential as a practical strategy for post-fire rehabilitation and durability enhancement.

Keywords-component; self-compacting concrete; elevated temperature; re-curing; residual strength

I. INTRODUCTION

SCC has exceptional workability and the ability to consolidate without the need for external vibration. As a highly flowable material, SCC spreads under its own weight, effectively filling formwork and encapsulating densely arranged reinforcement [1]. These characteristics make it particularly advantageous for complex structural elements, where conventional concrete may fail to achieve adequate compaction. In addition to its superior placement properties, SCC demonstrates mechanical strength and durability comparable to, or in some cases exceeding, those of traditional concrete, thereby reinforcing its role as a key material in contemporary construction practice [2]. Despite its advantages under ambient conditions, SCC remains highly vulnerable to deterioration at elevated temperatures. During fire exposure, concrete undergoes several forms of deterioration, including explosive spalling, loss of strength, extensive microcracking, and increased porosity [3]. Although the dense cementitious matrix of SCC provides superior strength and durability under normal conditions, it also makes SCC more vulnerable to thermal stress. The reduced permeability restricts internal pressure release during rapid heating, which can intensify cracking and spalling compared to conventional concrete. As a result, the structural safety and serviceability of SCC elements may be significantly compromised, posing risks to both immediate stability and long-term performance in post-fire scenarios [4].

Conventional post-fire rehabilitation methods, such as water re-curing, can partially restore the properties of heat-damaged concrete through autogenous healing. Immersion in water promotes the hydration of previously unhydrated cement particles and encourages the formation of additional binding phases, contributing to the partial recovery of strength and microstructural integrity [5]. MW utilization has attracted growing interest as a sustainable technique to further enhance this recovery. When water is passed through a magnetic field, its physicochemical properties are altered, surface tension decreases while ionic mobility and electrical conductivity increase [6]. Moreover, the magnetic field can break large water molecule clusters into smaller ones, improving water's ability to penetrate microcracks and react with cement particles. These effects accelerate hydration, refine the pore structure, and create a denser interfacial transition zone within the concrete matrix [7]. It has been demonstrated that concrete prepared with MW exhibits lower porosity and higher levels of hydration products, improving mechanical strength and durability. In many cases, MW has been reported to reduce micro-porosity and increase compressive strength by approximately 10%–25% compared to concrete mixed with normal water. These improvements have been observed in both conventional concrete and SCC, confirming the general effectiveness of MW in enhancing cementitious composites under standard curing conditions [8, 9].

The present study introduces a new approach by applying MW as a re-curing medium for thermally damaged SCC. This is the first research to investigate the use of MW for improving the post-fire recovery of SCC exposed to high temperatures up to 600 °C. The results confirm that re-curing with MW enhances the recovery of compressive strength, flexural and bond performance, and internal integrity compared to NW, indicating more effective microcrack closure and secondary hydration. This contribution offers a practical and low-cost rehabilitation technique that can support the reutilization of fire-affected structural elements, the reduction of demolition waste, and the promotion of sustainable construction. The outcomes also enable validating long-term durability and analyzing microstructural changes associated with MW treatment in post-fire concrete recovery [6]. The potential of MW in the context of fire-damaged concrete remains largely unexplored. Research has recently examined the behavior of concrete made with MW when exposed to elevated temperatures. Normal concrete specimens cast and cured with MW have demonstrated significantly higher residual compressive, tensile, and flexural strengths after heating to 200 °C–600 °C, with strength retention 10%–40% greater than their counterparts produced with ordinary water [6]. To date, however, no research has specifically investigated the use of MW for rehabilitating thermally damaged SCC. The combined application of MW during both mixing and post-fire curing stages presents a novel approach with the potential to overcome the limitations of conventional re-curing methods.

II. EXPERIMENTAL PROGRAM

A. Materials

Ordinary Portland Cement (OPC), conforming to [13], was used as the primary binder. Crushed stone 12 mm–14 mm, complying with [10], served as coarse aggregate, while natural sand was employed as fine aggregate. Both were oven-dried, sieved, and prepared in a single batch to ensure consistency. The aggregate properties, including specific gravity, absorption, and abrasion resistance, were verified following [11, 12]. Silica sand filler was incorporated to improve particle packing. The OPC composition (Table I) showed CaO as the dominant oxid. A polycarboxylate-based superplasticizer (Fosroc Structuro 520), free of chlorides, was added at 2% of cement weight to ensure adequate flowability in SCC. Mixing water was either NW or MW, the latter was produced by passing tap water through a ~1 Tesla magnetic device, as depicted in Table II and Figure 1. For the bond strength tests, deformed steel bars of 16 mm diameter and ~420 MPa yield strength were employed. The magnetic device used in this study had a magnetic field intensity of approximately 1 Tesla. During the mixing stage, the water was passed through the magnetic field five consecutive times to ensure uniform magnetization before being added to the mix.

TABLE I. CHEMICAL COMPOSITIONS OF OPC

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O
20.3	6.3	3.12	63.6	1.6	0.4

TABLE II. MECHANICAL PROPERTIES OF THE MAGNETIC SHAFT DEVICE

Flow rate (m^3/h)	Inlet and outlet (mm)	Weight (kg)	Magnet power (Tesla)	Size(mm)
4.9	25	3	1	76 (diameter) × 600 (height)

Fig. 1. Water magnetizer shaft.

B. Mix Proportions

Two concrete mixes were prepared for the study: SCC-MW and SCC-NW, both designed with a water-to-cement ratio of 0.42. The detailed proportions of cement, water, aggregates, silica sand, and superplasticizer are provided in Table III. The incorporation of MW was intended to reduce water surface tension and enhance cement hydration, while the inclusion of silica sand aimed to improve particle packing density and decrease overall porosity.

TABLE III. MIX PROPORTIONS OF THE CONCRETE USED IN THIS STUDY (PER 1 M³)

Mix ID	**Water type**	**Cement (kg)**	**Water (kg)**	**Coarse agg. (kg)**	**Fine sand (kg)**	**Silica sand (kg)**
SCC-MW	Magnetized	390	163	822	668.5	286.5
SCC-NW	Normal	390	163	822	668.5	286.5

C. Specimen Preparation and Casting

Dry materials were mixed for ~1 min, after which NW or MW was gradually added over 2 min. In SCC mixes, the superplasticizer was introduced with the final portion of water, and mixing continued for 3 min to ensure uniformity. Fresh properties were assessed following EFNARC guidelines, showing improved flow in SCC-MW over SCC-NW. Specimens were cast into standard molds: 150 mm cubes (compressive strength), 100 mm × 100 mm × 400 mm prisms (flexural strength), 100 mm × 200 mm and 150 mm × 300 mm cylinders (modulus and bond), and 100 mm cubes (porosity). The full specimen dimensions are provided in Table IV.

TABLE IV. SPECIMEN TYPES AND DIMENSIONS FOR EACH TEST

Test	**Specimen type**	**Dimensions (mm)**
Compressive strength	Cube	150 × 150 × 150
Flexural strength	Prism	100 × 100 × 400
Bond strength (pull-out)	Cylinder + rebar	300 × 150 (with Ø16 mm rebar)
UPV	Cube	150 × 150 × 150
Porosity	Cube	100 × 100 × 100

D. Heating Regime

After specimen preparation and 28 days of standard curing, the SCC samples were subjected to a controlled high-temperature exposure regime in which four target temperature levels were selected: 25 °C (ambient), 200 °C, 400 °C, and 600 °C. Heating was applied at a uniform rate of 5 °C/min, a commonly adopted rate in residual performance studies to minimize thermal shock and promote uniform heat penetration. The applied time–temperature profile followed in this study is illustrated in Figure 2. Upon reaching the target temperature, the specimens were soaked for 120 min to ensure complete thermal stabilization across the concrete cross-section and were subsequently allowed to cool naturally in air to simulate realistic post-fire cooling conditions, typically experienced by structural members.

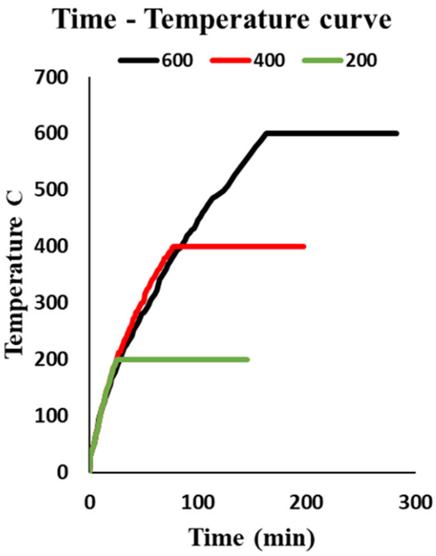

Fig. 2. Time-temperature curve.

E. Recuring Conditions

For the curing stage, a continuous magnetic circulation system was employed to maintain the magnetization of the curing water throughout the entire curing period.

1) Testing Methods

Mechanical properties were evaluated following standard procedures. The compressive strength was measured on 150 mm cubes, as portrayed in Figure 3. The flexural strength was assessed using third-point loading. The bond strength between concrete and reinforcing steel was evaluated by pull-out testing with slip monitored by LVDTs. The durability indices included UPV and porosity measurements, as shown in Figure 4.

Fig. 3. Compressive strength test and flexural strength test.

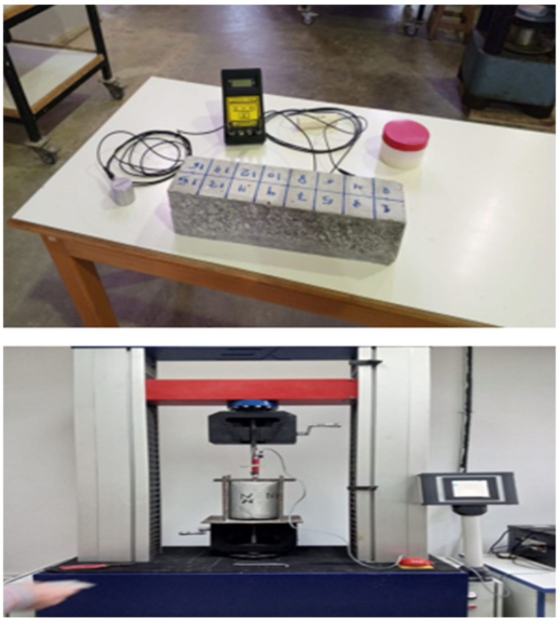

Fig. 4. Pull-out bond test setup and UPV test.

III. RESULTS AND DISCUSSION

As summarized in Tables V and VI, the specimens re-cured in MW showed a superior recovery of the mechanical and durability properties compared with those treated in NW. MW enhanced compressive, flexural, and bond strength, improved stiffness, reduced slip, and consistently lowered porosity. These outcomes suggest that MW promotes denser microstructures and more effective crack healing, thereby improving post-fire performance. Overall, the results highlight the potential of MW re-curing as an efficient and sustainable method for rehabilitating thermally damaged SCC.

TABLE V. MECHANICAL PROPERTIES AFTER 28 DAYS OF RECURING

Mix	Temp (°C)	Compressive strength (MPa)	Flexural strength (MPa)	Bond strength (MPa)	Slip (mm)
SM	R-200	52.8	6.08	8.76	1.65
SM	R-400	43.56	5.47	8.10	1.96
SM	R-600	37.78	3.74	7.10	2.30
SN	R-200	44.67	5.42	7.71	1.75
SN	R-400	36.22	3.80	6.20	2.23
SN	R-600	28.12	2.80	5.37	2.70

TABLE VI. POROSITY RESULTS AFTER 28 DAYS OF CURING

Mix	R-200 (%)	R-400 (%)	R-600 (%)
SM	3.5	6.23	7.5
SN	4.1	7.3	9.5

A. Compressive Strength Recovery

The SM mix showed the highest recovery performance. At 200 °C, re-curing increased compressive strength from 49.38 MPa to 52.8 MPa, a gain of 3.42 MPa, representing 106.77% of the original strength at 25 °C. This indicates that moderate heating may have activated unhydrated cement particles, while the use of MW further enhanced ongoing hydration. It has been confirmed that re-curing promotes secondary hydration and microstructural densification. This trend is displayed in Figure 5, which compares the compressive strength of SCC samples after 28 days of re-curing, highlighting SM mixes' superior performance. At 400 °C, compressive strength improved from 40.66 MPa to 43.56 MPa after re-curing, a gain of 2.9 MPa, equaling 88.09% recovery. Despite the thermal degradation, MW helped regenerate bonds and heal the matrix during re-curing. At 600 °C, re-curing increased strength from 24.4 MPa to 37.78 MPa, a significant gain of 13.38 MPa, or 76.4% recovery, demonstrating MW’s strong capacity to assist in post-fire strength restoration.

The SN mix also benefited from re-curing, but the improvement was less pronounced compared to other mixes. At 200 °C, strength increased from 44.08 MPa to 44.67 MPa, a modest gain of 0.59 MPa, with 103.16% recovery. Although additional hydration occurred, the lack of magnetic treatment limited efficiency. This modest recovery is also exhibited in Figure 5, where the SN samples show a lower strength gain after 28 days of re-curing. At 400 °C, strength rose from 32.00 MPa to 36.22 MPa, recovering 4.22 MPa (83.65%). At 600 °C, strength increased from 20.88 MPa to 28.12 MPa, a gain of 7.24 MPa, or 64.94% recovery, the lowest among all mixes at this temperature, highlighting the reduced effectiveness of NW under extreme thermal damage. These results demonstrate that re-curing significantly improves strength recovery, especially with MW. SM consistently outperformed SN in both the recovery percentage and actual strength regained. For example, at 600°C, the MW mix recovered over 11 MPa–13 MPa, while the NW mix recovered only 7.24 MPa. These findings confirm that MW improves hydration kinetics, internal healing, and microstructural repair, making it an effective method for post-fire concrete rehabilitation.

The improved recovery with MW can be explained by well-known physicochemical effects. Magnetization reduces water surface tension and breaks large molecular clusters, enhancing water diffusion into microcracks and pores. It also increases ionic mobility, promoting dissolution of the remaining clinker phases and faster secondary hydration during re-curing. Consequently, more C–S–H gel forms, and pores are filled more effectively, which aligns with the lower porosity and higher UPV recorded here. These mechanisms provide a rational explanation for the better restoration of the mechanical properties in SCC re-cured with MW after thermal damage. It has been demonstrated that post-fire re-curing with NW typically yields about 80% strength recovery. However, in this work, magnetized-water re-curing achieved nearly 90% recovery at 400 °C, demonstrating a significant improvement in the restoration of mechanical performance under thermal damage conditions [8].

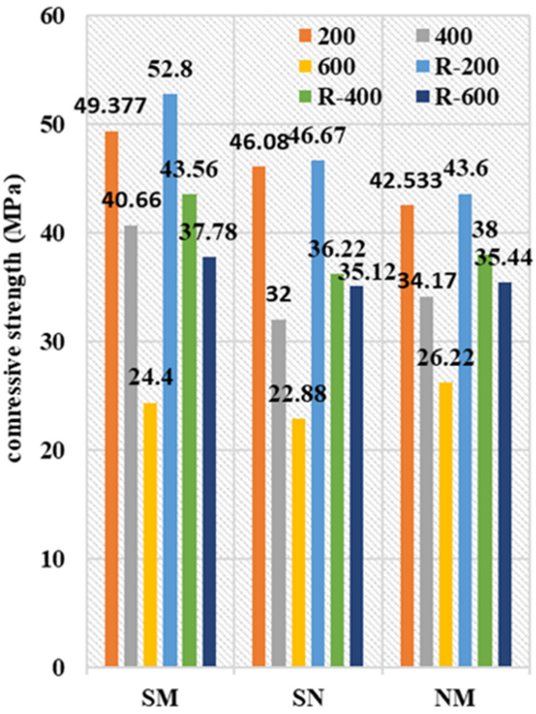

Fig. 5. Comparison between the compressive strength of SCC samples after the recuring process for 28 days.

B. *Flexural Strength Recovery*

Re-curing with MW resulted in a notable improvement in flexural strength recovery. For the SM mix, re-curing after exposure to 200 °C increased the flexural strength to 6.08 MPa, equivalent to 110.5% of its original value at 25 °C. At 400 °C and 600 °C, the recovered strengths were 4.73 MPa (86.0%) and 3.7 MPa (67.3%), respectively. These results indicate that MW effectively promotes continued hydration, microcrack healing, and refinement of the pore structure, particularly under moderate thermal damage. As shown in Figure 6, the SM mix consistently achieved higher flexural strength recovery compared to the SN mix. For the SN mix re-cured with NW, flexural strength recovered to 5.42 MPa (115.3%) at 200 °C, but declined to 3.8 MPa (80.9%) at 400 °C and 2.8 MPa (59.6%) at 600 °C. Although NW re-curing provided some recovery at lower temperatures, its effectiveness diminished as thermal damage increased. This trend, also visible in Figure 6, suggests that conventional water cannot sufficiently reactivate hydration or restore microstructural integrity when severe microcracking has occurred. Overall, re-curing with MW consistently produced greater flexural strength recovery across all temperature levels. The enhanced performance can be attributed to accelerated hydration kinetics, improved pore structure, and reactivation of unhydrated cement particles. These findings highlight the potential of MW as an effective and practical approach for post-fire rehabilitation and durability enhancement in SCC and other concrete types.

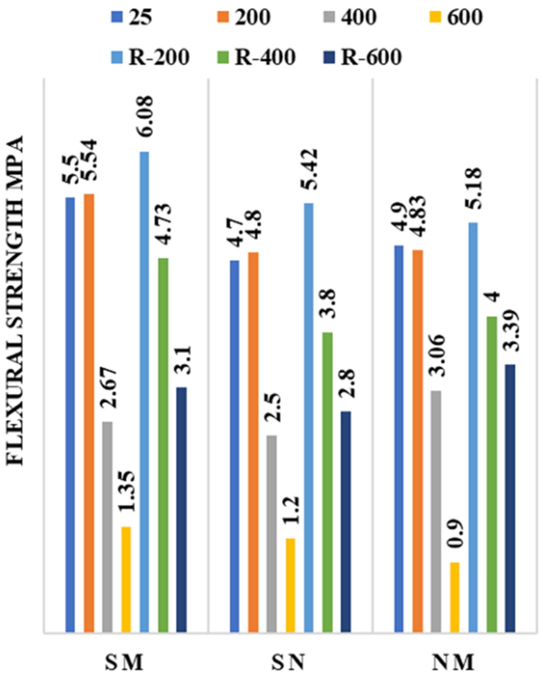

Fig. 6. Comparison between the flexural strength of concrete samples after the recuring process for 28 days.

C. *Bond Strength Recovery*

The SM specimens (SCC-MW) showed strong recovery in bond strength. After exposure to 200 °C, the recovered bond strength slightly exceeded the original value, with a recovery ratio of 103.31%. This improvement may be attributed to moderate thermal activation of unhydrated cement and pozzolanic materials, combined with the enhanced water diffusivity and hydration efficiency provided by MW. As presented in Figure 7, the SM mix demonstrated superior recovery performance. At 400 °C, although microstructural damage occurred, the bond strength recovery remained high at 95.53%, suggesting that MW supported continued hydration and partial regeneration of the C–S–H gel. Even at 600 °C, the SM mix retained a recovery of 83.72%, indicating that MW facilitated deeper moisture penetration and more effective healing of thermally induced cracks. In comparison, the SN specimens re-cured with NW also showed good recovery at 200 °C, achieving 105.47%, likely due to SCC's inherently dense matrix promoting rehydration at moderate thermal exposure. However, the recovery decreased more sharply at higher temperatures, dropping to 84.81% at 400 °C and 73.45% at 600 °C. As illustrated in Figure 7, the SN mix exhibited lower bond strength recovery than SM at elevated temperatures, highlighting the limited ability of conventional water to restore heavily damaged microstructures due to reduced penetration and slower hydration kinetics.

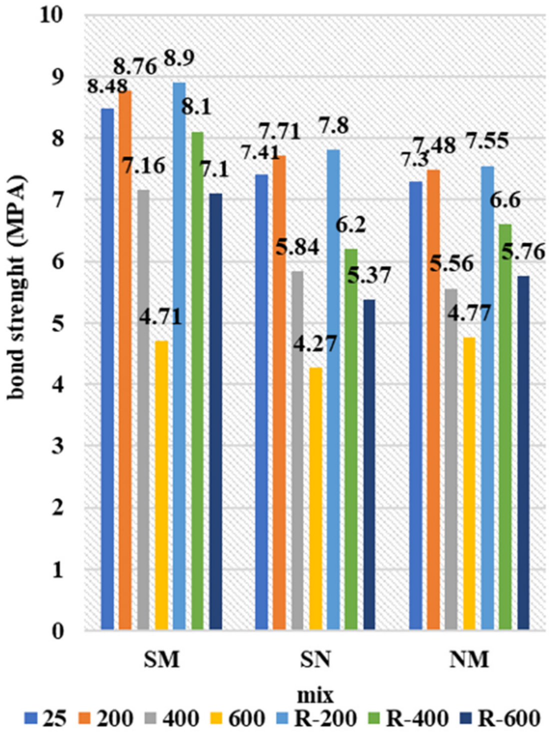

Fig. 7. Pull-out result of concrete samples after 28 days re-curing.

D. *Porosity*

Re-curing heat-exposed concrete with water, especially MW, has shown a measurable impact on reducing porosity and restoring microstructural integrity. For specimens heated to 200 °C (R-200), re-curing resulted in a modest decrease in porosity: SM dropped from 3.9% to 3.5% and SN from 4.3% to 4.1%. These reductions (~0.3–0.4 percentage points) reflect minimal thermal damage at this temperature range. The recurring effect here primarily involved desaturating the matrix, with limited generation of new hydration products. Since no significant decomposition of the cementitious phases occurred at 200 °C, porosity remained close to its original value at 25 °C. The observed reductions likely resulted from capillary pore filling and slight gel swelling, which narrowed microcracks. The final porosity levels of SM and SN (3.5%–4.1%) illustrate near-complete recovery of the original pore structure. This trend is illustrated in Figure 8, which compares the porosity data of SCC after the 28-day re-curing period, showing minimal changes at moderate heating. The most significant porosity recovery occurred at 600 °C (R-600), where thermal damage was most severe. After re-curing, SM dropped from 10.5% to 7.5% and SN from 11.4% to 9.5%, corresponding to reductions of 16%–30%. At this level, the widespread dehydration of C–S–H gel and full decomposition of portlandite leave the matrix highly desiccated. Upon re-curing, these anhydrous phases undergo secondary hydration. CaO transforms back into $Ca(OH)_2$, and the rehydration of C–S–H contributes to pore filling. The resulting solid products, precipitated within the voids, effectively seal microcracks. SM's porosity after re-curing at 600 °C (7.5%) nearly matches its 400 °C pre-re-curing level, indicating a high degree of healing. When comparing SM and SN, the role of MW becomes evident. Across all temperatures, SM consistently showed a slightly lower porosity than SN, 3.1% versus 3.8% at 25 °C, 7.42% versus 7.89% at 400 °C, and 10.5% versus 11.4% at 600 °C. Although the differences are relatively small, their consistency reflects the beneficial effect of MW in producing a denser and more refined microstructure. This observation is consistent with previous findings, according to which, magnetization lowers water surface tension, reduces water cluster size, and enhances the wetting and hydration of cement particles.

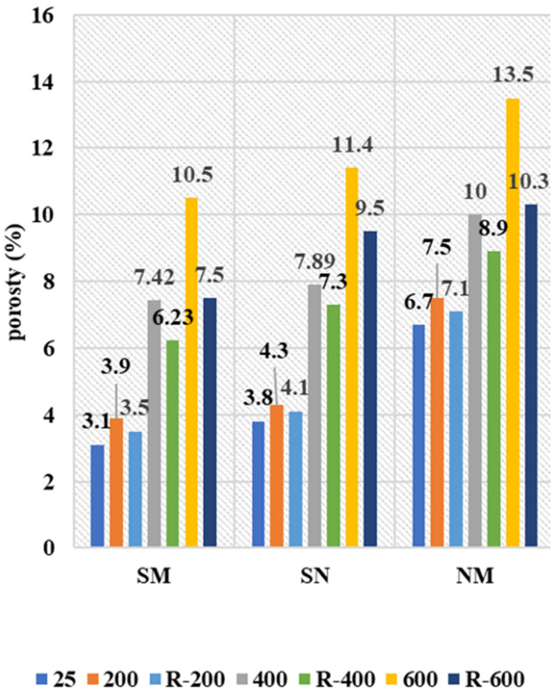

Fig. 8. Comparison between the porosity data collected from SCC after the 28-day re-curing period.

E. *Ultrasonic Pulse Velocity*

This section examines the influence of magnetic water treatment on the UPV of both SCC following exposure to elevated temperatures of 200 °C, 400 °C, and 600 °C. The reference UPV values at ambient temperature (25 °C) were: SM with SCC-MW = 4.67 km/s and SN with SCC-NW = 4.405 km/s. The SM mix consistently demonstrated superior recovery across all temperature levels. At 200 °C, the UPV declined from 4.67 km/s to 4.17 km/s due to thermal degradation; however, re-curing with magnetic water increased the velocity to 4.496 km/s, restoring approximately 96.1% of the original value. At 400 °C, the UPV dropped to 3.32 km/s, but was improved to 4.238 km/s post-treatment, representing a 90.7% recovery. At the highest temperature (600 °C), the UPV significantly decreased to 2.17 km/s. However, magnetic water treatment raised it to 3.96 km/s, achieving 85.6% of the original value. These results confirm the ability of the SM mix to recover structural integrity after severe thermal exposure, primarily due to the combined benefits of SCC's dense matrix and the hydration-promoting the characteristics of MW. The effectiveness of this recovery trend is demonstrated in Figure 9, which compares the ultrasonic velocity of the SCC samples after the 28-day re-curing process. In contrast, the SN mix, which used NW for both casting and re-curing, exhibited moderate recovery. At 200 °C, UPV decreased to 3.9 km/s, but recovered to 4.27 km/s after re-curing, equating to a 96.9% recovery. At 400 °C, the velocity dropped to 3.125 km/s and improved to 3.837 km/s post-re-curing (87.2%). After exposure to 600 °C, SN's UPV fell to 2.229 km/s, with re-curing restoring it to 3.527 km/s, approximately 79.7% of the original value. These results, as also reflected in Figure 9, highlight the limitations of NW in fully reversing microstructural damage at higher thermal intensities. Across all conditions, the SM mix emerged as the most thermally resilient, consistently achieving the highest UPV values following both exposure and re-curing. The results support the hypothesis that MW enhances internal hydration, reduces microcracking, and strengthens the bonding within the cementitious matrix. This leads to improved structural integrity and makes magnetized SCC an excellent candidate for applications exposed to high thermal stress, such as fire-resistant infrastructure or industrial environments.

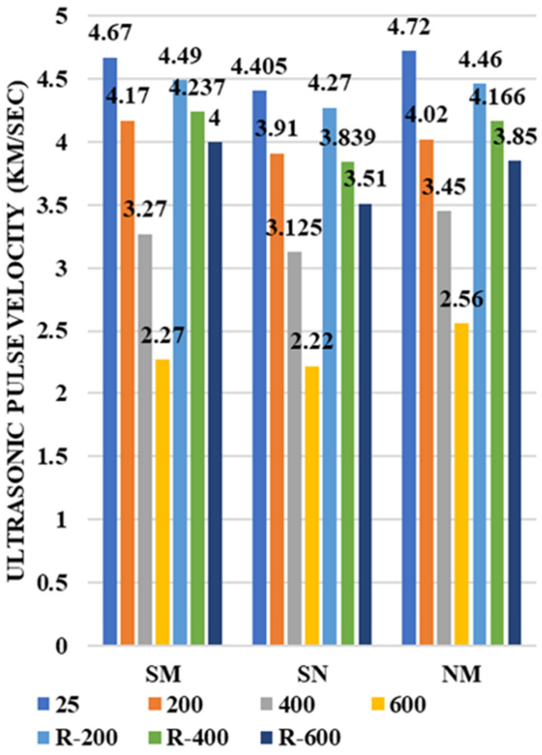

Fig. 9. Comparison between the ultrasonic velocity of the SCC sample after 28 days recuring.

IV. CONCLUSIONS

This study demonstrates that using MW both during mixing and as a post-fire curing medium markedly enhances the recovery of SCC after high-temperature exposure. SCC treated with MW consistently exhibited higher residual compressive, tensile, and flexural strengths than SCC cured with NW when subjected to 400 °C–600 °C. These improvements reflect more extensive secondary hydration of unreacted cement and effective crack healing. The accelerated hydration is attributed to the breakdown of large water molecule clusters during magnetization, which improves water penetration into cement particles and promotes the formation of additional C–S–H gel. As a result, MW-treated SCC can recover a larger fraction of its original strength after fire damage. In addition to the mechanical recovery, MW also improved durability indicators. The observed reduction in overall porosity and the higher UPV measured in MW-cured specimens indicate a denser, more homogeneous, and crack-free matrix. These microstructural benefits suggest that MW promotes the regeneration of hydration products and helps seal microcracks formed during heating, thereby enhancing recovery without the need for chemical additives.

Overall, the combined use of MW during both mixing and re-curing presents a practical and cost-effective method for rehabilitating heat-damaged SCC. Since this approach relies solely on modifying the curing water rather than adding chemical admixtures, it can be easily applied in field conditions. Previous studies also indicate that using MW in concrete production can maintain or improve workability and strength while potentially reducing cement and water demand. Future research should further evaluate the long-term durability of MW-treated concrete under different environmental conditions and optimize magnetization parameters such as field strength and exposure duration. Additionally, integrating MW with supplementary cementitious materials (e.g., silica fume, fly ash, or slag) may yield further enhancements in strength recovery and durability. This study was limited to a single SCC mix design and one magnetization configuration. The effects of MW on other concrete types, alternative admixture systems, and varying re-curing durations were not examined. Expanding investigations to a broader range of mix designs and curing conditions is necessary to better establish the applicability of MW in post-fire concrete rehabilitation.

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