Valorization of Spent Manganese Filter Media as Sustainable Fine Aggregate in Cement Mortar: Mechanical Performance and Chemical Durability

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ABSTRACT

Spent Manganese Filter Media (SMFM) from municipal groundwater treatment systems can be used as an alternative source of fine aggregate for cement-based materials. This study investigated the feasibility of using SMFM as a volumetric replacement for natural river sand in cement mortar at replacement levels of 0%, 10%, 20%, and 30%. The fresh properties, mechanical performance, and chemical durability of the mortars were evaluated in terms of flowability, fresh density, 28-day compressive and flexural strengths, mass loss, and residual strength after exposure to sodium chloride, magnesium sulfate, and sulfuric acid solutions. Increasing the SMFM content reduced flowability from 115% for the control mixture to 106%, 101%, and 97% for the SMFM10, SMFM20, and SMFM30 mixtures, respectively. Meanwhile, the fresh density decreased slightly, dropping from 2,136.0 kg/m³ for the control mixture to 2,129.3 kg/m³, 2,120.7 kg/m³, and 2,110.0 kg/m³ for the SMFM10, SMFM20, and SMFM30 mixtures, respectively. Nevertheless, the 28-day compressive strength increased from 20.22 MPa for the control mortar to 24.97, 27.53, and 29.66 MPa for the SMFM10, SMFM20, and SMFM30 mixtures, respectively. Similarly, the 28-day flexural strength increased from 1.19 MPa for the control mortar to 1.59 MPa, 1.95 MPa, and 2.02 MPa for the SMFM10, SMFM20, and SMFM30 mixtures, respectively. Under chemical exposure conditions, mortars containing SMFM generally exhibited lower mass loss and better residual strength retention than the control mortar, especially at 20% and 30% replacement levels. The observed performance improvement may be associated with the physical characteristics of the processed particles and their interaction with the cement matrix.

Keywords-Spent Manganese Filter Media (SMFM); cement mortar; sustainable fine aggregate; groundwater treatment waste; compressive strength; chemical durability

I. INTRODUCTION

Globally, the consumption of sand and gravel for construction purposes is estimated to be 40–50 billion tons per year. This highlights the need to identify alternative fine aggregates that can reduce pressure on conventional mineral resources while maintaining acceptable engineering performance [1–3]. Consequently, research attention has been directed toward using waste-derived and industrial residual materials as partial sand replacements in cementitious systems. Many materials, including spent anthracite filter media, zeolite, activated carbon residues, biomass ashes, and recycled fine aggregates, were examined for the ability to reduce environmental impact while maintaining or improving material performance. However, the effectiveness of these alternatives depends strongly on their physical characteristics, water absorption behavior, particle grading, and interaction with the cementitious matrix. Excessive replacement or unsuitable aggregate properties may adversely affect porosity, interfacial bonding, workability, and overall mechanical performance. In parallel, waste materials generated from water treatment and filtration processes have emerged as promising secondary resources. Drinking water and groundwater treatment systems produce residuals from clarification, filtration, backwashing, and iron/manganese removal processes. Depending on plant design and regulatory practice, these residuals require appropriate treatment, disposal, or beneficial reuse. In this context, Spent Manganese Filter Media (SMFM), widely used for iron and manganese removal in groundwater and drinking water treatment, may be considered an underutilized waste stream once its service life ends. Authors in [4] showed that filter sands discarded from iron- and manganese-removal systems can be repurposed for adsorption-based environmental applications, while authors in [5-8] described the surface characteristics and functional role of manganese-coated sand and related media in groundwater treatment. However, the annual quantity discarded, the replacement frequency, the service life, and the regional availability of the specific SMFM used in the present study were not systematically recorded. Therefore, this study does not claim a fully quantified sustainability benefit at the regional or national scale, but focuses on the technical feasibility of using this water treatment residual as a replacement for fine aggregates in cement mortar. Research on manganese-bearing materials in cementitious systems has primarily examined manganese slag, manganese tailing sand, and electrolytic or desulfurized manganese residues, rather than SMFM from water treatment. These materials differ substantially in terms of their particle form, mineralogy, processing history, and incorporation route. Manganese slag and electrolytic residues are generally used as powder-type supplementary materials that influence hydration, setting behavior, and matrix refinement. In contrast, manganese tailing sand is more comparable to aggregate-type replacement, but it originates from mining or industrial processing rather than from water treatment. Although manganese-bearing industrial byproducts may improve the properties of cementitious materials, depending on the dosage, fineness, and pretreatment, these findings are not directly transferable to SMFM because their surface condition, residual coating, grading, and end-of-service characteristics differ from those of freshly processed mineral byproducts. From a comparative standpoint, authors in [9-16] showed that workability decreases as the level of replacement increases, especially when the substitute material has a rough texture, irregular shape, or high-water demand. However, the effect on strength depends significantly on the nature of the waste material. Porous or organic-derived waste often reduces both flowability and compressive strength at moderate to high replacement levels. In contrast, mineral-based and properly graded residual materials may maintain or improve strength within a limited substitution range [12, 15-17]. Regarding manganese-bearing waste, available literature focuses on the hydration-related or microstructural effects of powdered residues, while aggregate-type performance data remain limited. More importantly, studies specifically examining SMFM as a fine aggregate replacement in cement mortar remain scarce, and systematic data on its combined effects on flowability, fresh density, 28-day compressive strength, 28-day flexural strength, and chemical durability under chloride, sulfate, and acidic exposure are still lacking [18-23]. Accordingly, the present study advances existing knowledge in three significant ways. First, it examines an end-of-service manganese filter medium derived from municipal groundwater treatment. This medium differs from manganese slag, tailings, and chemical-process residues that are more commonly reported in the literature. Second, this material is evaluated as an aggregate-type replacement by volume, thereby addressing a more practical mortar application pathway. Third, the current study not only assesses fresh and mechanical properties but also chemical durability through exposure to sodium chloride, magnesium sulfate, and sulfuric acid solutions. This broader performance framework provides a more application-oriented basis for determining if SMFM can be valorized as a sustainable fine aggregate alternative in cement mortar.

II. MATERIALS AND METHODS

A. Materials

All mixtures used Ordinary Portland Cement (OPC) that conformed to ASTM C150/C150M as the primary binder. The cement had a specific gravity of 3.15, meeting the requirements for general-purpose hydraulic cement. Natural river sand was used as the reference fine aggregate. It was clean, well-graded, and compliant with ASTM C33/C33M. Its fineness modulus was approximately 2.6, and its specific gravity was 2.63. The SMFM used in this study were obtained from a municipal groundwater treatment facility after they reached the end of their service life in a filtration unit used for iron and manganese removal, as shown in Figure 1. The material was collected from a single replacement batch. Long-term variability associated with service duration, replacement cycle, or batch-to-batch differences was not systematically assessed. Prior to use, the SMFM were washed to remove loosely adhered surface impurities, and then were dried at 105 ± 5 °C for 24 h, and crushed and sieved to obtain a grading comparable to that of natural sand, in accordance with ASTM C33/C33M. The physical properties and grading characteristics of the SMFM are summarized in Table I, and the grading distribution is presented in Figure 2. The processed SMFM had a particle size distribution similar to the reference fine aggregate, showing that they were prepared properly for use as a partial sand replacement in mortar. Additionally, the SMFM had a lower specific gravity than natural sand and exhibited measurable water absorption. These properties may influence fresh density and workability. Direct particle morphology imaging was not performed in this study; therefore, interpretations related to morphology are based on the material's general description and previous literature rather than direct observation. In this study, the SMFM were treated as a fine aggregate replacement based on their role in the mortar mixture. However, no X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), strength activity index, or direct chemical characterization tests were conducted.

Fig. 1. SMFM.

TABLE I. PHYSICAL PROPERTIES OF NATURAL FINE AGGREGATE AND SMFM

Specification	Natural fine aggregate	SMFM
Specific gravity (g/cm³)	2.63	2.40
Bulk density (dry) (kg/m³)	1400	1600
Water absorption (%)	1	1.5

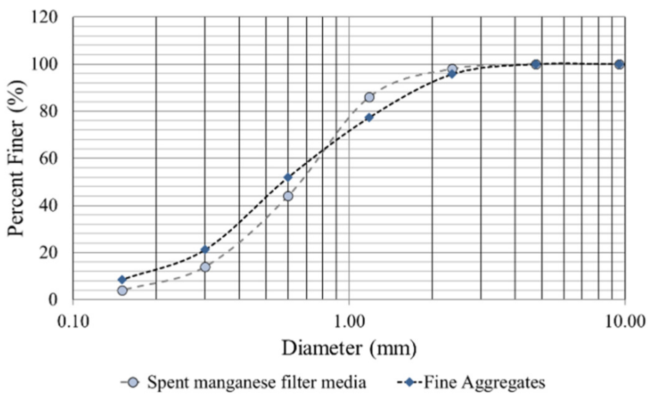

Fig. 2. Particle size distribution (grading curve) of natural fine aggregate and SMFM.

Because spent filtration media may contain accumulated trace constituents resulting from long-term exposure to service, potential environmental concerns, such as metal leaching, should be considered before proposing large-scale reuse. In the present study, leaching or toxicity screening was not performed; therefore, the environmental suitability of the SMFM was not fully assessed. To improve transparency regarding recycled material preparation, the SMFM underwent washing, oven drying at 105 ± 5 °C for 24 h, crushing, and sieving to obtain a grading comparable to natural sand. This sequence constitutes the basic processing inventory adopted in the present study. While reusing SMFM can reduce dependence on natural sand and divert a water treatment residual from disposal, the sustainability benefits should be interpreted with caution, because the water demand for washing, the energy associated with oven drying, and the mechanical effort required for crushing and sieving were not quantified in detail. Therefore, a more comprehensive processing inventory and life cycle assessment are proposed for future work. The particle size distribution of the SMFM is similar to that of natural fine aggregate, suggesting that the material was processed successfully to achieve a particle size distribution suitable for mortar applications. Throughout the experimental program, potable tap water that conformed to ASTM C1602/C1602M was used for mixing and curing.

B. Mix Proportions

The mortar mixtures were prepared using OPC as the sole binder and natural river sand as the reference fine aggregate. SMFM were used as a volumetric replacement for natural sand at 0%, 10%, 20%, and 30% (designated as OPC, SMFM10, SMFM20, and SMFM30, respectively). The mixture proportions are given in Table II. These levels were chosen for an initial feasibility study to represent low, intermediate, and relatively high substitution conditions while maintaining workable mixtures and consistent specimen preparation. The control mixture was intended to represent a conventional, nonstructural cement mortar for plastering, rendering, and related applications, rather than a high-strength, structural mortar. This baseline was chosen because the objective of the study was to evaluate the feasibility of using SMFM as a substitute for fine aggregate in a mortar system relevant to common field applications [24]. Thus, the control mixture served as the reference for evaluating changes in fresh properties, density, mechanical performance, and chemical durability due to SMFM incorporation. Its moderate strength level is consistent with its intended nonstructural use and should not be interpreted as a target for structural performance.

TABLE II. MIX PROPORTIONS

Mix proportions (kg/m³)				
Name	Cement	FA	SMFM	Water
Control	490	1350	-	210
SMFM10	490	1215	83	210
SMFM20	490	1070	166	210
SMFM30	490	945	249	210

To facilitate comparison, the binder content and water-to-cement ratio were held constant across all mixtures. Only the level of volumetric replacement of natural sand with SMFM varied, allowing to systematically assess the effect of the replacement material on mortar performance. Volumetric replacement was used to account for the difference in specific gravity between natural sand and SMFM, providing a more meaningful basis for aggregate substitution within the mortar matrix. No chemical admixture was used to evaluate the direct effects of SMFM incorporation on fresh and hardened properties. The SMFM was used in an oven-dried state after preprocessing, while the natural sand was used in its laboratory state at the time of mixing. No additional water correction was applied to compensate for the SMFM's absorption. This should be considered when interpreting the reduction in flowability observed in the SMFM-modified mixtures.

C. Specimen Preparation and Curing

All mortar mixtures were prepared in the laboratory under controlled conditions. First, the dry materials—including cement, natural river sand, and SMFM—were blended to ensure uniform distribution of the constituents. Then, water was gradually added while mixing continued until a homogeneous mortar was obtained. Immediately after mixing, the fresh mortar was used to determine flowability and fresh density according to the relevant test procedures. After testing the fresh properties, the mortar was placed into molds for mechanical and durability evaluation. Specimens were cast in 50 mm × 50 mm × 50 mm cube molds for compressive strength testing and in 40 mm × 40 mm × 160 mm prism molds for flexural strength testing. The specimens were compacted according to applicable standards to minimize entrapped air and ensure consistent quality. The top surfaces were leveled and finished immediately after casting, where all specimens were covered with plastic sheets to prevent moisture loss. They were stored at a laboratory temperature of 28 ± 2°C for 28 ± 2 h prior to demolding. After demolding, the specimens were cured in clean water until the designated testing age. For the mechanical property tests, the specimens were cured for 28 days prior to testing. For durability evaluations, specimens were first cured for 28 days and then transferred to designated chemical exposure solutions. In accordance with the test protocol adopted in this study, the specimens were conditioned to a laboratory-dry state before immersion in the chemical solutions. To ensure comparable measurement conditions, the specimen surfaces were gently dried using a consistent surface-drying procedure before weighing for mass change measurements. Then, the specimens were immersed in sodium chloride, magnesium sulfate, and sulfuric acid solutions for the specified exposure periods. To improve reproducibility, separate sets of specimens were prepared for evaluating compressive strength, flexural strength, and durability. Unless otherwise stated, all reported results represent the average of three specimens (n = 3).

D. Test Methods

1) Flowability

The flowability of the fresh mortar was determined in accordance with ASTM C1437. For each mixture, three specimens were tested, and the reported value is the average of those three measurements (n = 3), as shown in Figure 3.

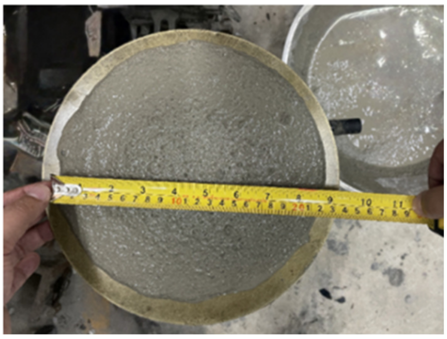

Fig. 3. Flowability test.

2) Density

The fresh density of the mortar was determined according to ASTM C138/C138M. Fresh mortar was placed into the measuring container according to the applicable procedure. The density was then calculated using the measured mass and the known volume of the container. Three measurements were taken for each mixture, and the reported value represents the average of the three specimens (n = 3).

3) Compressive Strength

Compressive strength was determined in accordance with ASTM C109/C109M using 50 mm ×50 mm × 50 mm cube specimens after 28 days of curing. Three cube specimens were tested for each mixture, and the reported value represents the average of the three measurements (n = 3), as displayed in Figure 4. The load was applied at a rate of 0.5 MPa/s, as specified in ASTM C109/C109M.

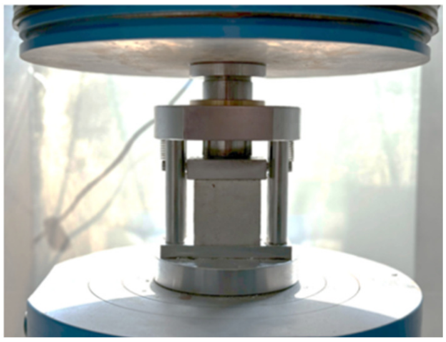

Fig. 4. Compressive strength test.

4) Flexural Strength

The flexural strength was determined according to ASTM C348 using prism specimens measuring 40 mm × 40 mm × 160 mm after 28 days of curing. The test was performed using a three-point loading configuration with a support span of 100 mm. Three prism specimens were tested for each mixture, and the reported flexural strength value is the average of the three measurements (n = 3), as illustrated in Figure 5. The loading procedure was conducted in accordance with ASTM C348.

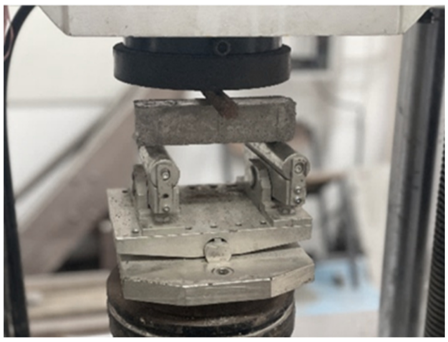

Fig. 5. Flexural strength test.

5) *Chemical Durability Tests*

The chemical durability of mortar specimens was evaluated by exposure to aggressive chemical solutions after water-curing them for 28 days. The exposure media consisted of solutions of 5% sodium chloride (NaCl), 5% magnesium sulfate ($MgSO_4$), and 3% sulfuric acid (H_2SO_4), prepared by mass relative to water. The immersion procedure followed the general principles of ASTM C1012/C1012M with modifications suitable for mortar specimens.

Prior to immersion, all specimens were conditioned to a laboratory-dry state. Before each mass measurement, the surfaces of the specimens were gently dried using a consistent procedure to ensure comparable weighing conditions. The specimens were fully immersed in separate containers at a solution-to-specimen volume ratio of at least 4:1 and stored at a temperature of 25 ± 2 °C. The solution level was maintained throughout the test period to ensure that the specimens were completely immersed. To reduce concentration drift during exposure, the solutions were renewed every seven days. For the sulfuric acid solution, pH was periodically checked to confirm that acidic conditions were maintained during the exposure period. After 90 days, the specimens were removed, surface-dried, visually examined, and weighed to determine mass loss. Residual compressive strength was subsequently evaluated using the same procedure adopted for the 28-day compressive strength test. For each mixture and exposure condition, three specimens were tested (n = 3), and the reported values represent the mean of the three specimens. Figure 6 depicts the immersion setup used for chemical durability testing.

(a) (b) (c)

Fig. 6. Immersion setup for chemical durability testing in: (a) NaCl, (b) $MgSO_4$, and (c) H_2SO_4 solutions.

III. RESULTS AND DISCUSSION

A. *Flowability*

Figure 7 shows the flowability of fresh mortar mixtures with different levels of SMFM replacement. The control mixture had the highest flow value, 115%. The SMFM10, SMFM20, and SMFM30 mixtures had progressively lower values: 106%, 101%, and 97%, respectively, showing a reduction in flowability, while increasing SMFM replacement. This reduction may be primarily attributed to the physical characteristics and moisture content of the processed SMFM. Since the spent material was crushed before use, the resulting particles were likely more angular and irregular than natural river sand. This increased interparticle friction and reduced the ease of flow [12, 13]. Additionally, the SMFM exhibited measurable water absorption and was used in an oven-dry condition, whereas the natural sand was used in its laboratory condition. Since no separate absorption correction was applied, part of the mixing water may have been absorbed by the SMFM particles, thereby reducing the amount of free water available for lubrication during mixing [14]. These combined factors contributed to the lower workability observed in the SMFM-modified mortars. However, since no direct particle morphology analysis was conducted in the present study, this explanation should be interpreted as a reasonable hypothesis based on physical behavior and previous literature rather than as direct experimental confirmation.

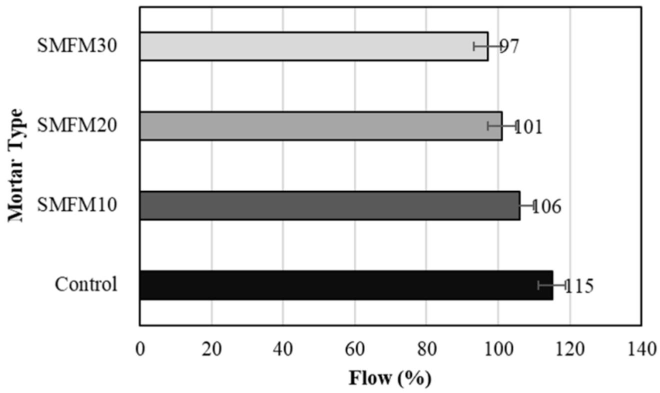

Fig. 7. Flowability.

B. *Density*

Figure 8 presents the fresh density of mortar mixtures that use SMFM. The control mixture had a density of 2,136.0 kg/m³, whereas the SMFM10, SMFM20, and SMFM30 mixtures had slightly lower densities of 2,129.3, 2,120.7, and 2,110.0 kg/m³, respectively, presenting a reduction in fresh density as the amount of SMFM increased. This reduction is primarily attributed to the lower specific gravity of SMFM compared to natural river sand [12].

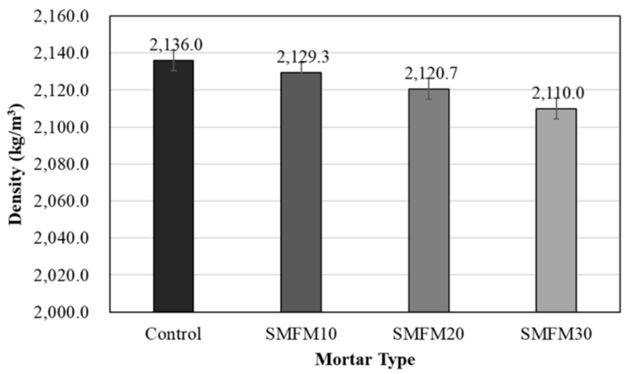

Fig. 8. Density.

Additionally, the crushed nature of the SMFM particles may have slightly affected packing density relative to natural fine aggregates [13]. Nevertheless, the maximum reduction in density was only about 1.2%, suggesting that the SMFM acted as a mineral-based fine aggregate rather than a lightweight material [14]. The small magnitude of this decrease suggests that the significant increase in compressive strength observed in SMFM-modified mortars cannot be explained by bulk density alone, rather, the results imply that the mechanical response was influenced by the physical characteristics of the replacement aggregate and its interaction with the mortar matrix.

C. Compressive Strength

Figure 9 shows the 28-day compressive strength of mortar mixtures that use SMFM. The control mortar achieved a compressive strength of 20.22 megapascals (MPa), while the SMFM10, SMFM20, and SMFM30 mixtures reached 24.97, 27.53, and 29.66 MPa, respectively. These values represent increases of approximately 23.5%, 36.2%, and 46.7%, respectively, relative to the control mixture, showing an increase in compressive strength as the amount of SMFM increased. The relatively small error bars indicate that this trend was consistently reproduced among replicate specimens within the scope of the present study. The observed strength enhancement suggests that incorporating SMFM did not reduce the mortar's load-bearing capacity, despite the slight reduction in fresh density, but the improvement may be associated with the rigid mineral nature of the processed particles, their surface characteristics, and their interaction with the cementitious matrix, which may have promoted more effective stress transfer [15, 16, 25]. Additionally, volumetric replacement may have helped maintain an appropriate aggregate skeleton despite the difference in specific gravity between SMFM and natural sand. However, as no SEM analysis, interfacial transition zone characterization, porosity measurement, or fracture-surface analysis was performed, the observed strength increase should be interpreted in the context of the specific mixture proportions, processing conditions, and curing regime investigated in this study.

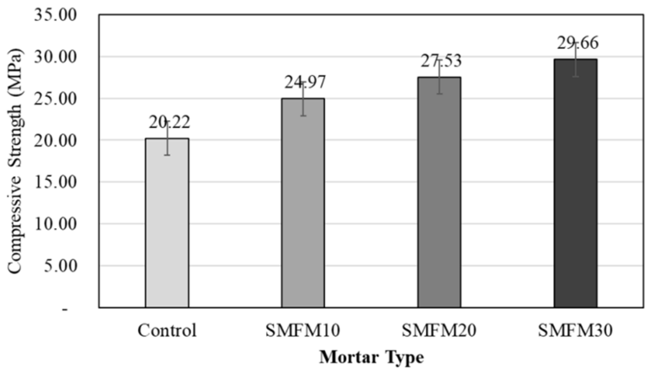

Fig. 9. Compressive strength.

D. Flexural Strength

Figure 10 shows the 28-day flexural strength of mortar mixtures that use SMFM. The control mortar had the lowest strength, at 1.19 MPa. The SMFM10, SMFM20, and SMFM30 mixtures had strengths of 1.59, 1.95, and 2.02 MPa, respectively. These values represent increases of approximately 33.6%, 63.9%, and 69.7%, respectively, relative to the control mixture. Overall, flexural strength increased with increasing SMFM replacement; however, the rate of improvement became less apparent at the highest replacement level. The enhancement in flexural strength observed indicates that incorporating SMFM did not impair the mortar's bending performance and may have contributed to greater resistance to crack initiation and propagation. This behavior may be associated with the physical characteristics of the processed SMFM particles and their interaction with the cementitious matrix [26]. However, since no direct fracture analysis or microstructural characterization was performed, the relatively low absolute flexural strength values should also be considered in relation to the nonstructural nature of the investigated mortar system and the ASTM C348 prism test configuration.

Based on the combined compressive and flexural strength results, the control mortar is suitable for conventional, nonstructural applications, such as plastering and rendering, where moderate strength is sufficient. In contrast, the SMFM20 and SMFM30 mixtures demonstrated improved mechanical performance, being more appropriate for non-structural mortar applications that require greater crack resistance and a higher load-bearing capacity. However, this would depend on whether the associated reduction in workability remains acceptable in practice.

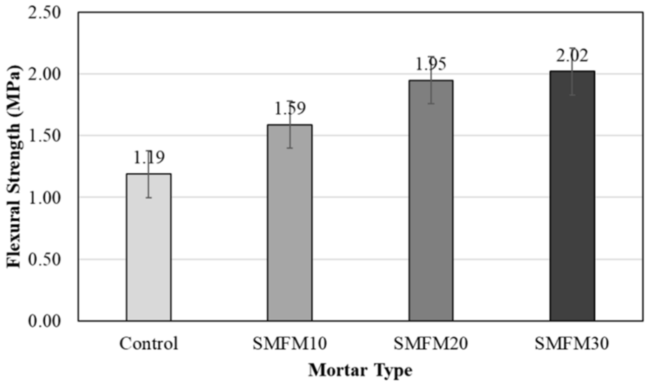

Fig. 10. Flexural strength.

E. Chemical Durability Performance

Examining the durability performance of mortar mixtures after exposure to solutions of sodium chloride, magnesium sulfate, and sulfuric acid provides further insights into how SMFM influence mortar's resistance to chemically aggressive environments. This study evaluated durability in terms of mass loss, residual compressive strength, and visual observation after 90 days of exposure.

1) Mass Loss after Chemical Exposure

Figure 11 presents the mass loss of mortar specimens after 90 days of immersion in solutions of NaCl, $MgSO_4$, and H_2SO_4. The control mixture exhibited the highest mass loss under all exposure conditions, whereas the SMFM-modified mortars showed progressively lower values with increasing replacement levels. With NaCl exposure, the control mixture lost 2.4% of its mass, while the SMFM10, SMFM20, and SMFM30 mixtures lost 1.7%, 1.5%, and 1.3%, respectively.

Under $MgSO_4$ exposure, the control specimen recorded a mass loss of 4.9%, while the SMFM-modified mixtures showed reduced values of 3.1%, 2.6%, and 2.1%, respectively. The most severe deterioration occurred under H_2SO_4 exposure: the control mixture exhibited an 11.8% mass loss, compared to 9.4%, 8.2%, and 7.5% for SMFM10, SMFM20, and SMFM30, respectively. These results suggest that using SMFM improves mortar's resistance to chemically induced material loss under all investigated exposure conditions. This improvement may be associated with the relatively denser and stronger matrix observed in the SMFM-modified mixtures, which may reduce the severity of surface deterioration and material disintegration during exposure [27, 28]. Additionally, this trend may be related to the reduced proportion of vulnerable Ca-rich phases and the relatively higher stability of manganese-bearing, oxide-rich constituents within the matrix [29–31].

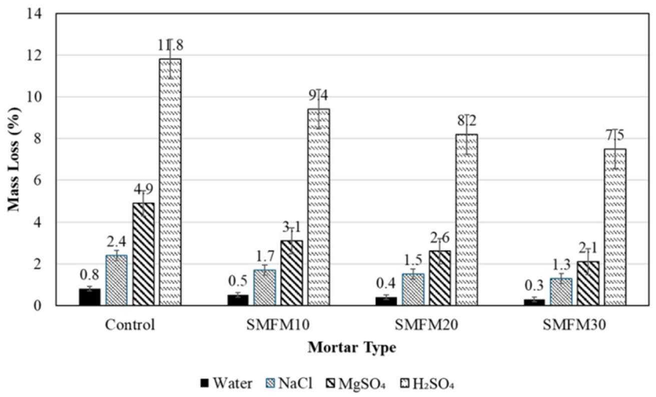

Fig. 11. Mass loss of mortar specimens after 90 days of chemical exposure.

2) *Residual Compressive Strength after Chemical Exposure*

Figure 12 displays the residual compressive strength of mortar specimens after 90 days of chemical exposure. Generally, all mixtures showed some reduction in strength after immersion. However, the SMFM-modified mortars had higher residual strength than the control mixture under all exposure conditions.

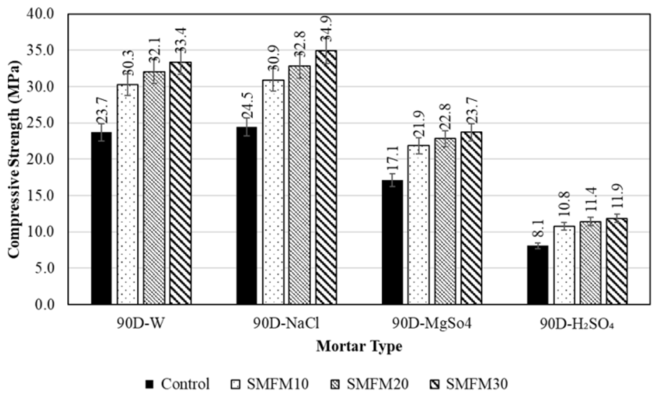

Fig. 12. Residual compressive strength of mortar specimens after 90 days of chemical exposure.

Residual compressive strength was evaluated alongside strength retention, which is defined as the ratio of the compressive strength after exposure to the original compressive strength at 28 days for the corresponding mixture. This paired analysis is important because the SMFM-modified mortars exhibited higher initial compressive strengths prior to exposure. Therefore, the durability advantage of the SMFM-containing mixtures should be evaluated in terms of both absolute residual strength (MPa) and retention of the original mechanical capacity. Overall, the SMFM-containing mortars demonstrated better post-exposure mechanical stability than the control mixture, particularly at replacement levels of 20% and 30%. This trend is consistent with the mass loss results and suggests that replacing some of the sand with SMFM improves the mortar's resistance to chloride-, sulfate-, and acid-related deterioration under the adopted exposure conditions [28, 30–32].

From a durability perspective, the improved resistance to mass loss and higher residual compressive strength observed in the SMFM-modified mortars indicate their potential use in nonstructural applications exposed to chloride-, sulfate-, or mildly acidic environments. However, this application-oriented interpretation is conditional because the present study did not include transport-property testing, long-term field validation, leaching assessment, or detailed microstructural characterization.

3) *Visual Observation after Exposure*

Figure 13 illustrates the visual appearance of the control and SMFM-modified mortar specimens after 90 days of exposure to solutions of water, NaCl, $MgSO_4$, and H_2SO_4.

Specimens stored in water remained intact and showed no visible signs of deterioration. Similarly, specimens exposed to NaCl exhibited only minor visible changes, indicating limited macroscopic damage during the test period. More noticeable deterioration occurred under $MgSO_4$ exposure, especially in the control mixture, which exhibited surface roughening and slight scaling. In contrast, the SMFM-modified mortars maintained comparatively better surface integrity. The most severe deterioration occurred in the H_2SO_4-exposed specimens. The control mortar exhibited extensive surface erosion, edge deterioration, and a friable texture. While all mixtures were adversely affected by acid exposure, the SMFM-containing mortars showed comparatively less severe surface degradation, particularly at higher replacement levels. These observations are consistent with the mass loss and residual strength results. Within the specific mixture proportions and exposure conditions investigated in this study, replacement levels of 20% to 30% SMFM appear to provide the most favorable balance of fresh properties, mechanical performance, and chemical durability.

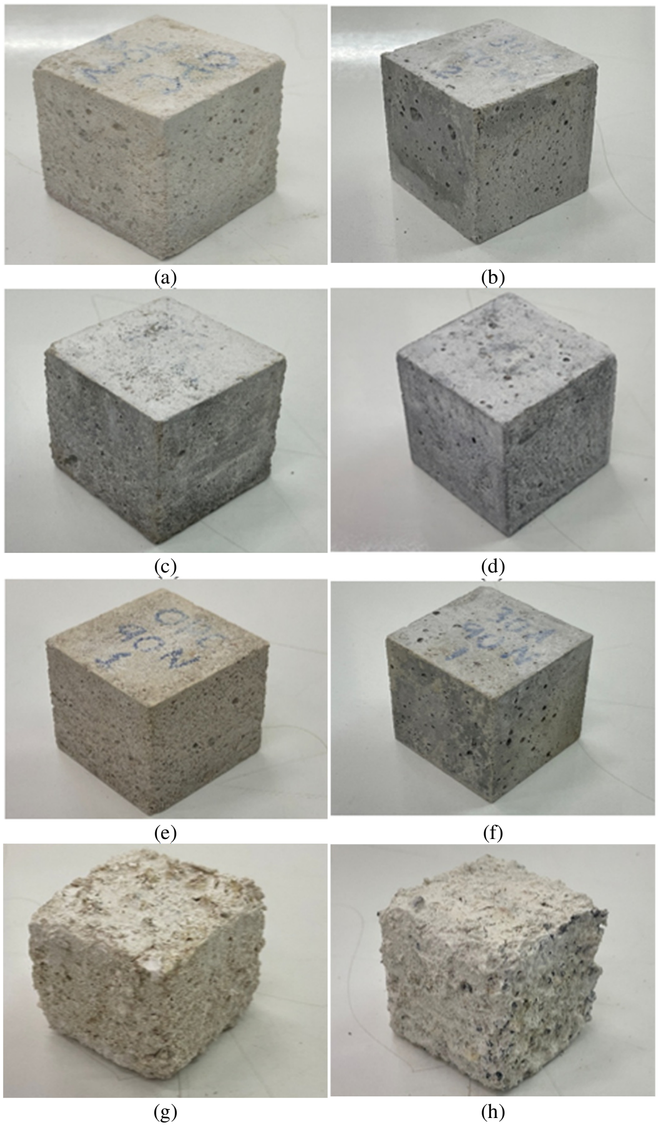

Fig. 13. Visual appearance of mortar specimens after 90 days of exposure to aggressive solutions: (a) control-W, (b) SMFM30-W, (c) control-$MgSO_4$, (d) SMFM30-$MgSO_4$, (e) control-NaCl, (f) SMFM30-NaCl, (g) control-H_2SO_4, and (h) SMFM30-H_2SO_4.

IV. CONCLUSIONS

This study evaluated the feasibility of using Spent Manganese Filter Media (SMFM) as a replacement for fine aggregate in cement mortar. Within the investigated range of 0–30% volumetric replacement, incorporating SMFM reduced flowability from 115% in the control mixture to 106%, 101%, and 97% in the SMFM10, SMFM20, and SMFM30 mixtures, respectively. It also slightly decreased fresh density from 2,136.0 kg/m³ to 2,129.3 kg/m³, 2,120.7 kg/m³, and 2,110.0 kg/m³, corresponding to a maximum reduction of approximately 1.2%. Despite this decrease, all mixtures remained workable within the scope of the study. Incorporating SMFM improved the mortar's mechanical performance. The 28-day compressive strength increased from 20.22 MPa for the control mixture to 24.97 MPa, 27.53 MPa, and 29.66 MPa for the SMFM10, SMFM20, and SMFM30 mixtures, respectively. This corresponds to a maximum increase of approximately 46.7%. Flexural strength increased from 1.19 MPa in the control mixture to 1.59 MPa, 1.95 MPa, and 2.02 MPa in the SMFM10, SMFM20, and SMFM30 mixtures, respectively. These results suggest that SMFM can be used to partially replace sand in non-structural cement mortar without adversely affecting mechanical behavior and with measurable improvement under the conditions examined.

The SMFM-modified mortars showed improved chemical durability under the adopted laboratory exposure conditions. After 90 days of immersion in solutions of NaCl, $MgSO_4$, and H_2SO_4, the control mixture exhibited mass losses of 2.4%, 4.9%, and 11.8%, respectively. In contrast, the SMFM30 mixture showed lower losses of 1.3%, 2.1%, and 7.5%, respectively. Additionally, the SMFM-containing mortars generally exhibited higher residual compressive strength than the control after exposure, indicating enhanced resistance to chloride-, sulfate-, and acid-related deterioration. This work contributes to the application-oriented evaluation of SMFM from a groundwater treatment system as a waste-derived fine aggregate candidate for cement mortar. Within the investigated range, replacement levels of 20–30% provided the most favorable balance of fresh properties, mechanical performance, and chemical durability. However, this recommendation is limited to the specific conditions of the present study, including a fixed water-to-cement ratio, 0–30% volumetric replacement, 28 days of water curing, and exposure to 5% NaCl, 5% $MgSO_4$, and 3% H_2SO_4 solutions for 90 days. These findings should be considered in light of several limitations. First, the SMFM was obtained from a single replacement batch, and no direct microstructural, mineralogical, transport property, reactivity-related, or failure mode analyses were performed, nor was any environmental leaching screening conducted. While the durability protocol included solution renewal, monitoring the pH of the acid solution, and maintaining a defined solution-to-specimen ratio, long-term field performance has not yet been confirmed. Similarly, while the reuse of SMFM could reduce the consumption of natural sand and divert a water treatment residual from disposal, the water and energy demands associated with washing, drying, crushing, and sieving were not quantified. Accordingly, broader sustainability claims should remain conditional pending a more complete processing inventory or life cycle assessment. From a practical perspective, the control mortar is suitable for conventional non-structural applications, such as plastering or rendering, under relatively mild service conditions. The SMFM-modified mortars, particularly SMFM20 and SMFM30, appear more suitable for non-structural mortar applications where improved mechanical performance and greater resistance to aggressive chemical environments are desirable. However, claims regarding structural applications, environmentally sensitive uses, and long-term performance are not yet justified without further validation. Further research is proposed to investigate the microstructure, reactivity, drying shrinkage, dimensional stability, long-term deformation, leaching behavior, failure mode, transport properties, and long-term chemical stability of manganese-bearing phases in the cementitious environment.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY

Data will be made available on request.

AI USE AND DECLARATION OF GENERATIVE AI USE

The authors used generative AI solely for language improvement during the preparation of this manuscript. All generated output was carefully reviewed and edited by the authors, who take full responsibility for the content of the final manuscript.

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