RESEARCH ON THE MECHANICAL PROPERTIES OF MORTAR UTILIZING CARBONATED STEEL SLAG

NGHIÊN CỨU THUỘC TÍNH CƠ HỌC CỦA VỮA SỬ DỤNG XỈ THÉP CACBONAT

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Abstract - This study evaluates the performance of cement mortar utilizing 100% carbonated electric arc furnace (EAF) steel slag substitute for sand. Raw slag underwent aqueous carbonation, achieving a 2% CO_2 uptake by transfer CaO into $CaCO_3$, verified via XRD and TGA. Three formulations, a reference, untreated slag (100SS), and carbonated slag (100SS-C), were assessed for mechanical and volumetric properties. While 100SS reduced baseline strengths compared to the control, carbonation mitigated these deficits. Specifically, the 100SS-C mixture demonstrated a 4.27% increase in flexural strength and enhanced compressive performance relative to 100SS. Furthermore, precipitated $CaCO_3$ densified the microstructural matrix and obstructed capillary pores, significantly reducing drying shrinkage. These findings confirm viability of carbonated EAF slag in mortar, presenting approach to waste valorization, resource conservation, and carbon sequestration.

Key words - Carbonated steel slag; CO_2 uptake

Tóm tắt - Nghiên cứu đánh giá hiệu suất vữa xi măng sử dụng 100% xỉ thép điện hồ quang điện (EAF) cacbonat hóa thay thế hoàn toàn cát tự nhiên. Quá trình xử lý xỉ EAF thô đạt tỷ lệ hấp thụ 2% lượng CO_2. Phản ứng giúp chuyển đổi CaO thành $CaCO_3$ bền vững, điều này đã được thể hiện qua các phân tích XRD và TGA. Thực nghiệm tiến hành trên ba cấp phối, mẫu đối chứng, vữa xỉ thô (100SS) và vữa xỉ cacbonat hóa (100SS-C). Kết quả cho thấy, xỉ thô làm giảm các đặc tính cơ lý so với đối chứng, nhưng quy trình cacbonat hóa đã khắc phục sự suy giảm này. Cụ thể, mẫu 100SS-C ghi nhận hiệu suất nén được cải thiện và tăng 4,27% cường độ uốn so với 100SS. Xét về vi cấu trúc, tinh thể $CaCO_3$ làm đặc chắc, chèn lấp hiệu quả các lỗ rỗng mao quản, giúp khống chế hiện tượng co ngót khô. Kết quả khẳng định tính khả thi của xỉ EAF cacbonat hóa, mang đến giải pháp vật liệu nhằm tận dụng chất thải, bảo tồn tài nguyên và lưu trữ carbon.

Từ khóa - Xỉ thép cacbonat; CO_2 hấp thụ

1. Introduction

The iron and steel industry generates large quantities of steel slag as a by-product, posing significant challenges for waste management and environmental sustainability. Globally, the utilization of steel slag as an aggregate in concrete and mortar has attracted considerable research attention as a viable strategy for industrial waste valorization and natural resource conservation. Previous studies have consistently reported that incorporating steel slag into concrete reduces workability and increases unit weight, while its effects on compressive strength, ultrasonic pulse velocity, porosity, water absorption, drying shrinkage, and chloride ion penetration resistance vary depending on the slag type and replacement ratio [1], [2], [3].

To mitigate these performance variations, researchers have investigated the synergistic use of supplementary cementitious materials (SCMs) [4], including fly ash (FA)[5], ground granulated blast-furnace slag (GGBFS), and silica fume (SF) in steel-slag concrete systems [6], [7]. Dri et al. [8] demonstrated that high-performance concrete (HPC) containing steel slag aggregate and a 20% cement replacement with GGBFS exhibited superior compressive strength compared to conventional limestone aggregate concrete, achieving mechanical performance comparable to mixtures incorporating 10% SF, despite a reduction in slump and an increase in density. Ho Van Quan et al. [9] further confirmed that HPC with 100% steel slag coarse aggregate, 15% FA, and 35% GGBFS developed compressive and flexural strengths 9% higher than the reference mixture after 210 days of curing, while reducing drying shrinkage by 15.7% and satisfying durability requirements for pulse velocity, surface electrical resistivity, and chloride ion penetrability. These findings collectively affirm the technical feasibility of directly substituting natural aggregates with steel slag in mortar and concrete production.

In Vietnam, the recycling of steel slag has been pioneered by Green Materials Ltd. since 2012, primarily as a crushed stone alternative in asphalt concrete. The rough surface texture and high alkalinity of steel slag promote excellent adhesion with asphalt binders, and research by Tran Van Mien [10] confirmed that steel-slag asphalt concrete possesses higher density, greater Marshall stability, and superior compressive strength compared to conventional crushed-stone mixtures at identical asphalt contents. More recently, Vu Hong Son et al. [11] developed a sustainable concrete incorporating large volumes of waste steel slag for a major highway construction project. However, domestic applications remain largely confined to the direct use of untreated slag or its combination with mineral admixtures, without adequately addressing the fundamental issues of its highly porous surface morphology and aggressive water absorption, which lead to severe early-age drying shrinkage.

Concurrently, the escalating threat of climate change, evidenced by a global mean temperature increase of

approximately 0.8°C over the past century, has intensified the demand for CO_2 mitigation strategies across all industrial sectors [12], [13], [14]. Research worldwide has demonstrated that CO_2 treatment significantly improves the physical and mechanical properties of secondary aggregates [15], [16]. When calcium-rich materials are exposed to carbon dioxide, reactive phases (such as free CaO, MgO, and $Ca(OH)_2$) convert into stable calcium carbonate ($CaCO_3$) and silica gel [17]. This mineralogical transformation densifies the aggregate matrix, clogs capillary pores, and improves the Interfacial Transition Zone (ITZ) between the aggregate and the cement paste [18]. International studies have extensively investigated the carbonation of recycled concrete aggregates (RCA) and recycled fine aggregates (RFA). For instance, recent studies on fully recycled aggregate concrete have shown that carbonation treatments can reduce aggregate water absorption by over 14% and significantly lower chloride permeability [19]. Consequently, concrete mixtures incorporating 100% carbonated recycled aggregates frequently exhibit compressive and split tensile strength recoveries of 15% to 30% compared to those utilizing untreated recycled aggregates [20]. In this context, recent global advancements have integrated accelerated carbon mineralization technology as a pre-treatment method for steel slag prior to its incorporation into cementitious materials [19]. Chang et al. [21] investigated CO_2 sequestration through aqueous carbonation of steel slag under various operational parameters, demonstrating the dual benefit of permanent carbon capture and mineralogical stabilization of the slag. Through accelerated carbonation, reactive calcium phases are converted into stable carbonate phases (predominantly $CaCO_3$). This microstructural densification fundamentally limits the aggregate's water absorption capacity, mitigating the early-age drying shrinkage concerns that have historically limited the reliable application of steel slag as a complete natural sand replacement. Studies utilizing slurry reactors and accelerated wet carbonation have confirmed that CO_2 uptake fundamentally stabilizes the slag, mitigating expansion risks and improving its specific gravity [22], [23]. However, a review of the global literature reveals two prevalent constraints: (1) researchers typically limit the substitution of natural sand to modest levels (e.g., 20% to 50%) to avoid excessive mechanical degradation, or (2) they rely on energy-intensive, high-pressure, and high-temperature autoclave systems to achieve deep carbonation.

Despite these international advancements, the application of a low-energy, atmospheric wet carbonation process tailored specifically for Electric Arc Furnace (EAF) steel slag to facilitate a full 100% fine aggregate replacement remains insufficiently explored. This study addresses this gap by bridging the global knowledge on accelerated carbonation with a practical, scalable treatment protocol for 100% natural sand substitution in mortar. The research outcomes are expected to contribute simultaneously to CO_2 emission reduction, industrial solid waste valorization, and natural aggregate conservation, thereby aligning with strategies for sustainable green development.

2. Materials and Methodology

2.1. Materials

The steel slag applied is an EAF slag procured from the VAS steel plant situated in Hai Van ward, Da Nang city. River sand with a particle size distribution ranging from 0.14 to 5 mm was employed. Experimental analyses confirmed that the particle size distributions of both the steel slag and sand satisfy the fine aggregate grading parameters for concrete and mortar stipulated in TCVN 7572:2006 [24]. The cement is a PCB40 Song Gianh blended Portland cement complying with TCVN 6260:2009 [25], possessing a Blaine specific surface area ≥ 2800 cm^2/g. The study also utilized Sika ViscoCrete 8713, a highly effective polycarboxylate-based superplasticizer. Table 1 presents the physical properties of materials used in the study. Table 2 presents the chemical composition of cement and steel slag used in the study.

Table 1. *Properties of materials used in this study*

Physical properties	Sand	Steel slag	Cement
Apparent density (g/cm^3)	2,64	3,4	3,15
Bulk density (g/cm^3)	2,58	2,82	-
Water absorption (%)	1,2	6,1	-

Table 2. *Chemical compositions of cement and steel slag*

Chemical composition (%)	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	P_2O_5	SO_3
Cement	19,2	4,5	64,77	4,3	3,2	0,8	0,05	3
Steel slag	N/A	N/A	30,19	27,29	4,64	N/A	N/A	N/A

2.2. Wet Carbonation Protocol

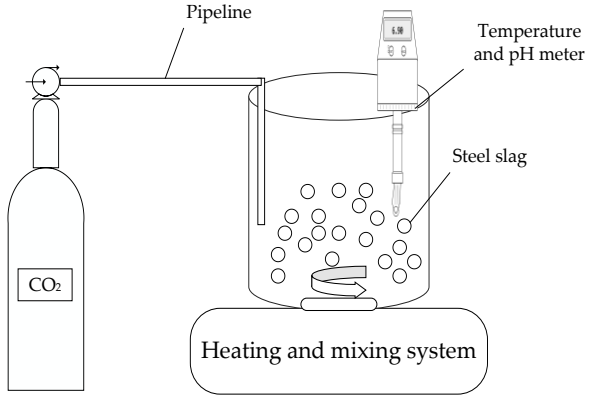

Figure 1. *Accelerated carbonation method of steel slag*

Figure 1 presents the wet carbonation scheme of steel slag used in this study. The specific operational parameters for the wet carbonation process - namely 65°C, an hour duration, and an agitation speed of 200 rpm - were carefully selected based on preliminary optimization trials and established literature regarding the carbonation kinetics of alkaline solid wastes [26], [27], [28]. This investigation employed an aqueous (wet) carbonation technique for the steel slag by injecting CO_2 gas directly from a cylinder through a delivery mechanism connected to a six-port gas distributor, ensuring uniform gas dispersion throughout the reaction vessel. An aluminum receptacle containing 5 liters of purified distilled water and

500 g of steel slag was heated on an induction unit until reaching 65°C, at which point continuous agitation commenced to facilitate optimal CO_2 dissolution into the slag matrix. A mechanical overhead stirrer operated continuously at 200 rpm, maintaining the suspension's thermal state at 65°C for a duration of one hour. Upon completion of this one-hour phase, both agitation and CO_2 injection were terminated. The carbonated steel slag was then successfully recovered by evaporating the residual suspension to dryness.

2.3. Specimen Preparation and Experimental Procedures

The mortar mix proportions were scientifically computed and designed in accordance with TCVN 3121-2:2022 [29]. Table 3 presents the mix design in the study. The experimental objective was to benchmark the 28-day flexural strength, compressive strength, unit weight, and drying shrinkage across three designated mortar mixtures: the reference mortar (REF), 100SS (mortar mix using 100% steel slag as a volume substitute for sand), and 100SS-C (mortar mix using 100% carbonated steel slag as a volume substitute for sand). The parameters maintained an effective water-to-cement ratio (W_{eff}/C) of 0.45, an aggregate-to-cement ratio (S/C) of 2.75, and a strictly regulated flow spread of 18 ± 2 cm. Prior to mixing, all steel slag aggregates were conditioned to a saturated surface-dry (SSD) state; the exact mass for volumetric replacement was defined using Equation:

$$m_{ss} = p_{ss} \times \frac{\rho_{ss}}{\rho_s} \times m_s$$

where, m_{ss} indicates the mass of steel slag acting as sand replacement; p_{ss} is the volumetric substitution percentage (100%); ρ_{ss} stands for the specific gravity of the steel slag; ρ_s is the specific gravity of the river sand; and m_s is the initial mass of the sand. Table 3 shows the mix design in this study. Because of the difference in specific gravity between steel slag and carbonated steel slag, the mass will vary in each aggregate mix.

Regarding test properties of mortar, compressive and flexural strengths were evaluated according to TCVN 3121-11:2022 [30]. Fresh unit weight was determined per TCVN 3121-6:2022 [31]. Subsequently, prismatic specimens measuring 40 × 40 × 160 mm were cast for mechanical testing. For each mixture, a total of three replicate specimens were prepared to ensure statistical reliability. After casting, the molds were kept in a moist climate chamber at a temperature of 27 ± 2 °C and a relative humidity of ≥ 95% for 24 hours. The specimens were then demolded and continuously cured in standard water baths at 27 ± 2 °C until the designated testing age of 28 days. Specifically, the flexural strength was determined using a three-point bending setup on the three individual prisms, and the six resulting half-prisms were subsequently subjected to the compressive strength test. Drying shrinkage was quantified by monitoring the longitudinal deformation of prismatic specimens. Curing persisted until the standard 28-day testing age was reached, complying with TCVN 8824:2011 [32]. Furthermore, this study uses the thermogravimetric method TGA to evaluate the amount of CO_2 uptake during the carbonation process, and X-ray diffraction (XRD) (is an analytical technique used here to identify and characterize the $CaCO_3$ crystals in the carbonation product.

Table 3. *Mix design in the study*

Mix design	Cement (g)	Sand (g)	Steel slag (g)	Effective water(g)	Admixture (g)
REF	500	1375	0	225	5,5
100SS	500	0	1770	225	5,5
100SS-C	500	0	1906	225	5,5

3. Results and Discussion

3.1. Fresh Mortar Unit Weight

Table 4 shows the results of the fresh unit weight of all samples. The reference sample (REF) generated the lowest unit weight, an outcome attributed to the inherent morphological properties of natural sand, which possesses lower porosity and a more uniform macro-structure than steel slag. The 100SS and 100SS-C mix displayed the highest fresh unit weight amongst the three iterations. This elevation is driven by the fundamentally high specific gravity of the raw slag, combined with the dense $CaCO_3$ precipitates deposited during the carbonation process. Assessing the fresh unit weight is a pivotal preliminary verification step during batching, functioning as a primary indicator of compositional accuracy.

Table 4. *Fresh Unit Weight of all mix designs*

Mix design	REF	100SS	100SS-C
Fresh Unit Weight (kg/m^3)	1867±82	2644±79	2800±87

3.2. Compressive Strength

Figure 2 shows the compressive strength of all samples. The REF samples sustained the highest compressive strength (49.1 MPa), validating the exceptional density and load-bearing efficacy of the traditional cement-sand composite. In contrast to the control, the 100SS and 100SS-C mortars exhibited compressive strength reductions of 33,8% and 13,4%, respectively. The decline in the untreated slag mixture (100SS) is fundamentally governed by the intrinsic morphological flaws of the raw aggregate. The highly porous and heterogeneous architecture of raw steel slag creates internal microscopic voids that act as critical stress concentration points under compressive loading. Furthermore, the aggregate's aggressive water absorption capacity locally disrupts the hydration kinetics at the boundary layer, leading to a highly porous and weakened ITZ. Upon the application of mechanical stress, this inferior ITZ fails to transfer loads efficiently, resulting in premature structural yielding [33]. However, the carbonated slag mortar (100SS-C) demonstrated a notable strength recovery compared to the untreated 100SS mixture. The accelerated aqueous carbonation pre-treatment successfully converted reactive calcium phases into stable $CaCO_3$ precipitates. This process densified the microstructural matrix, clogged capillary voids, and reduced the aggregate's aggressive water absorption. By stabilizing the aggregate surface, the carbonation treatment strengthened the ITZs and mitigated the severe segregation effects, yielding a significantly higher compressive capacity for 100SS-C relative to the untreated slag [34].

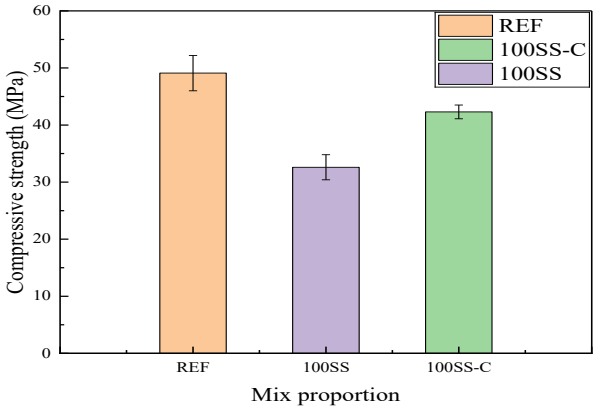

Figure 2. *Compressive strength of all mix designs at 28 days*

3.3. Flexural Strength

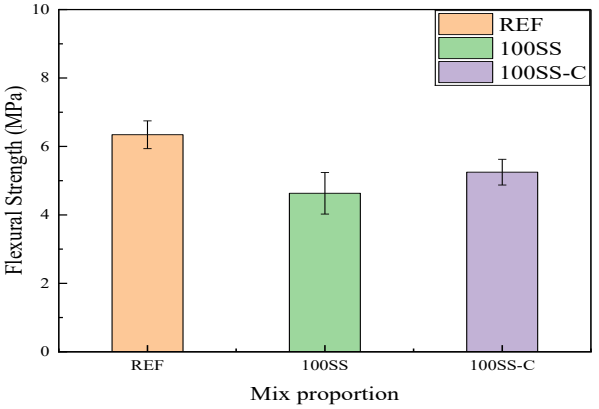

Figure 3. *Flexural strength of all mix designs at 28 days*

Figure 3 presents the flexural strength of all samples. The reference mix (REF) demonstrated the highest 28-day flexural strength at 6,3 MPa. A discernible degradation in flexural capacity was noted upon integrating the steel slag. Specifically, the raw steel slag mortar (100SS) yielded the lowest flexural results at around 4.6 MPa. This behavior is intrinsically tied to the untreated slag's highly porous and heterogeneous architecture; under flexural loading, critical stresses concentrate around internal microscopic voids, accelerating crack propagation and ultimately diminishing the bending threshold [35]. Alternatively, the specimen containing carbonated steel slag (100SS-C) reached a flexural strength of 5,3 MPa, outperforming the 100SS sample by 15,2%. This improvement confirms that aqueous carbonation substantially rectifies the slag's flexural deficiencies. Although direct microstructural imaging was not conducted in this study, the observed strength recovery in the 100SS-C mixture is highly consistent with the well-documented microstructural densification mechanism of carbonated aggregates [34], [36]. As corroborated by our quantitative TGA findings (which confirm the precipitation of solid carbonates) and the increased macroscopic unit weight of the 100SS-C matrix, the carbonation protocol effectively alters the aggregate morphology. Fundamentally, the mineralogical conversion of reactive oxides into stable $CaCO_3$ precipitates involves a substantial molar volume expansion. This localized expansion intrinsically reduces capillary porosity and fortifies the aggregate structure, thereby providing a logical mechanism for the rectification of the slag's flexural deficiencies. Still, both slag-modified mortars presented flexural values slightly below the control, primarily because natural sand's stable and relatively non-porous structure facilitates a superior, homogenized stress distribution under bending loads [37].

3.4. Drying Shrinkage

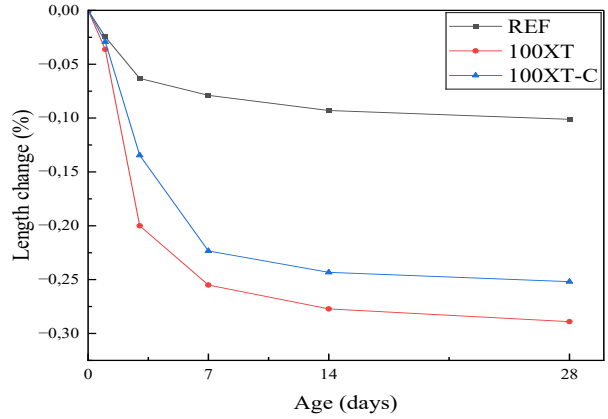

Figure 4. *Drying shrinkage of all mix designs*

Figure 4 presents the drying shrinkage of the samples. Volumetric drying shrinkage accelerated intensely during the preliminary 14 days of the curing cycle, exhibiting the sharpest gradient within the first 11 days. Following these 11 days, the shrinkage rate stabilized and decelerated. Analyzing the 28-day data revealed a hierarchical magnitude of shrinkage: 100SS > 100SS-C > REF. The 100SS mixture suffered the most severe shrinkage owing to the highly porous character of raw steel slag, which hosts an extensive capillary network and demonstrates aggressive water absorption. The severe drying shrinkage in the untreated slag mixture (100SS) directly compromises its mechanical capacities. The highly porous raw slag inherently creates stress concentration points and drives aggressive water evaporation. This evaporation generates high capillary tension and localized shrinkage strains that exceed the cement matrix's early-age tensile capacity, causing micro-cracks predominantly at the ITZ [34]. Under flexural loading, these pre-existing micro-cracks act as active initiation sites that rapidly accelerate crack propagation. Under compressive stress, the weakened ITZ and porous aggregate structure fail to transfer loads uniformly, causing premature failure [11]. Given this heightened retention capacity, transitioning the specimens from a saturated limewater curing environment into an arid desiccator triggered profound moisture evaporation; the resulting extreme capillary tension amplified the drying shrinkage [38]. Conversely, the 100SS-C specimen displayed reduced shrinkage behavior relative to the 100SS batch, as the secondary $CaCO_3$ formations successfully infiltrated the pore structures, cultivating a denser matrix that physically obstructed water evaporation [36]. The carbonation protocol effectively stabilized the aggregate's surface chemistry and depressed its inherent absorptivity, directly suppressing shrinkage strains. The control specimen preserved the lowest shrinkage profile, courtesy of the natural sand's compact

structure, negligible porosity, nominal water absorption, and superior innate volumetric stability.

3.5. TGA and XRD of carbonated steel slag

Figure 5 and Figure 6 show the TGA and XRD curves of carbonated steel slag. The XRD pattern of the carbonated steel slag sample exhibits an exceptional correlation with the calcium carbonate phase. The distinct manifestation of these peaks confirms that the wet carbonation process was successfully executed, thoroughly converting the free calcium phases within the slag into stable crystalline $CaCO_3$ precipitates. This is most notably characterized by the primary diffraction peak located at $2\Theta \approx 29.4^o$, 39.4^o, 43.1^o, which verifies the thorough conversion of reactive free calcium phases within the raw slag matrix into stable crystalline precipitates. Furthermore, the sharp diffraction peak observed at $2\Theta \approx 60^0$ indicates the presence of highly crystalline residual phases, typically associated with iron oxides inherently found in EAF slag. Furthermore, thermogravimetric and derivative thermogravimetric (TGA/DTG) analysis results confirm the successful absorption and immobilization of CO_2 within the steel slag as stable carbonate minerals. Specifically, a sharp weight loss of 2 % occurring in the 650°C – 800°C temperature range (with a maximum DTG decomposition peak at 735°C) corresponds to the actual capacity of CO_2 uptake inside the slag matrix via thermal decomposition. These data clearly demonstrate the efficacy of the wet carbonation method for utilizing steel slag as a sustainable material for greenhouse gas sequestration. While a total CO_2 uptake of 2% may appear quantitatively modest compared to deep-carbonation treatments utilizing high-pressure autoclaves, this value holds significant microstructural and practical importance. The 1-hour, atmospheric wet carbonation protocol employed in this study is designed as a targeted surface-modification technique rather than a bulk-penetration process. EAF slag possesses a highly dense core but a porous, reactive surface. The 2% uptake indicates that the precipitation of stable $CaCO_3$ is predominantly localized at this outer boundary, effectively forming a crystalline passivation layer. From a materials engineering perspective, critical degradation mechanisms, such as aggressive water absorption, localized shrinkage, and the formation of a weak ITZ, are entirely dictated by the aggregate's surface interactions. Therefore, strategically densifying and passivating this surface layer with $CaCO_3$ is sufficient to obstruct capillary moisture transport and structurally reinforce the ITZ. This targeted surface stabilization explains how a relatively limited total CO_2 uptake can effectively recover the mechanical deficits of the raw slag mixture, demonstrating a highly efficient, low-energy pre-treatment strategy that balances processing cost with substantial structural improvements.

To contextualize the environmental significance of this 2% uptake, a quantitative assessment of the carbon sequestration capacity per unit volume of mortar was conducted. Based on the mixture proportions detailed in Table 3, steel slag constitutes approximately 70.78% of the total fresh mortar mass. Given the measured fresh unit weight of 2800 kg/m^3 for the 100SS-C mixture (Table 4), approximately 1982 kg of carbonated steel slag is incorporated into one cubic meter of mortar. Consequently, multiplying this mass by the 2% carbonation degree reveals that approximately 39.6 kg of CO_2 is permanently sequestered per cubic meter of the 100SS-C mortar. This substantial volume of captured greenhouse gas actively offsets the carbon footprint associated with cement production, proving that even a surface-level carbonation treatment yields highly convincing, large-scale environmental benefits.

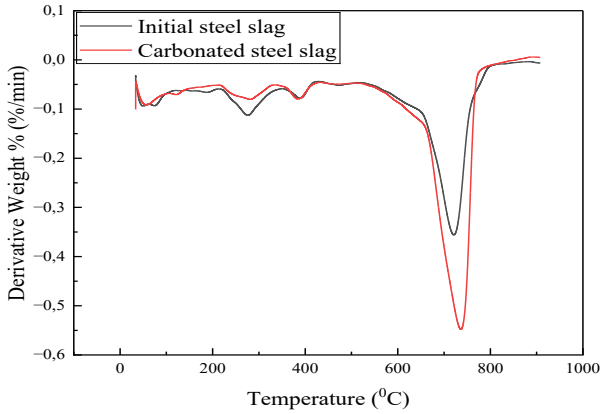

Figure 5. *TGA curve of initial and carbonated steel slag*

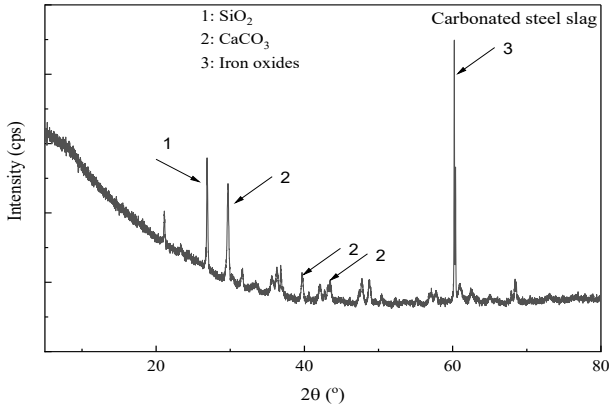

Figure 6. *XRD curve of carbonated steel slag*

While the wet carbonation process inherently introduces additional processing steps and energy requirements compared to the direct use of untreated slag, this techno-economic trade-off is justified by the resultant microstructural and environmental benefits. Unlike energy-intensive high-pressure autoclave methods frequently cited in the literature, the proposed protocol operates under atmospheric pressure with a short duration of one hour. This surface-targeted treatment is sufficient to precipitate a stabilizing $CaCO_3$ layer without requiring prolonged energy consumption. From a practical standpoint, the modest increase in pre-treatment cost is substantially offset by the ability to achieve a 100% replacement of natural river sand. By utilizing carbonated slag, the structural deficits associated with raw slag are recovered, and early-age drying shrinkage is significantly mitigated. Furthermore, the dual benefits of permanent

CO_2 sequestration and industrial waste valorization align with circular economy objectives, rendering the additional processing effort highly favorable for sustainable, large-scale construction applications.

In the context of existing literature, the performance of the 100SS-C mixture underscores a distinct approach to steel slag valorization. While numerous studies have reported superior absolute mechanical strengths in slag-incorporated concretes [9], [36], those outcomes typically rely on either partial aggregate replacement (often restricted to 20%–50%), the heavy incorporation of SCMs, or energy-intensive high-pressure carbonation protocols. Direct quantitative comparisons of absolute strength values with these studies are therefore constrained by fundamentally different boundary conditions. The present study deliberately challenges these conventional boundaries by implementing a 100% fine aggregate substitution coupled with a low-energy, atmospheric wet carbonation protocol. Although pushing the replacement ratio to 100% inherently results in mechanical capacities slightly below those of natural sand controls or heavily SCM-modified mixtures, the carbonation treatment successfully recovers structural deficits and severely limits early-age shrinkage relative to the raw slag. Consequently, the primary contribution of this work does not lie in maximizing peak mechanical strength, but rather in establishing a viable, low-cost methodology for total waste valorization (100% replacement) while maintaining acceptable structural and volumetric stability.

4. Conclusion

Based on the comprehensive experimental investigation into the properties of cement mortar utilizing raw and carbonated steel slag as a 100% fine aggregate replacement, the following primary conclusions are drawn:

- Total replacement of natural sand with steel slag systematically increases the fresh unit weight of the mortar matrix. The carbonated steel slag mixture (100SS-C) registered the highest density, an outcome attributed to the fundamentally high specific gravity of the raw slag coupled with the internal precipitation of dense $CaCO_3$ during the wet carbonation process.

- Substituting natural sand with steel slag intrinsically reduces both compressive and flexural strengths; however, the accelerated aqueous carbonation pre-treatment demonstrably ameliorates this mechanical degradation. The carbonated slag mortar (100SS-C) structurally outperformed the raw slag mortar (100SS), yielding enhanced compressive strength and a notable 4.27% improvement in flexural capacity. This strength recovery is governed by the $CaCO_3$ formations, which effectively clog capillary voids and densify the microstructural matrix.

- The untreated 100SS mixture experienced the most severe drying shrinkage due to the highly porous architecture and aggressive water absorption characteristic of raw steel slag. Conversely, the carbonation protocol successfully stabilized the aggregate's surface chemistry and physically obstructed evaporative pathways, substantially mitigating the drying shrinkage strains of the 100SS-C mortar relative to its untreated counterpart.

- Microstructural validations via XRD and TGA definitively verified the success of the aqueous carbonation methodology. The data confirmed the thorough transformation of free calcium phases into stable crystalline $CaCO_3$ precipitates, achieving an actual CO_2 uptake capacity of 2% within the slag matrix. Quantitatively, this treatment enables the permanent sequestration of approximately 39.6 kg of CO_2 per cubic meter of the 100SS-C mortar. This demonstrates that the proposed low-energy carbonation protocol not only successfully facilitates a 100% natural sand replacement but also delivers highly convincing environmental benefits, presenting a viable pathway for carbon reduction and industrial waste valorization in the construction sector.

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