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Study on the reuse of high-silica by-product from Lionas Metals Plant to partially replace cement in concrete production

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Abstract:

This study investigates the reuse of high-silica by-product (HSB) from the Lionas Metals Plant as a partial replacement for cement in concrete production. Four mixtures with 0, 10, 20, and 30% cement replacement by HSB were designed using the absolute volume method at a fixed water-to-binder ratio of 0.45. The study evaluated the effects of HSB on concrete properties, including fresh and dry unit weights (UW), water absorption (WA), compressive strength (CS), ultrasonic pulse velocity (UPV), thermal conductivity (TC), and rapid chloride ion penetration (RCPT). Results showed that increasing the HSB content led to a reduction in both fresh and dry UWs. WA decreased with longer curing times and higher HSB content, while resistance to chloride ion penetration improved significantly. The HSB content resulted in higher CS and UPV while reducing WA, TC, and RCPT. Higher HSB content resulted in greater CS and durability, with the 30% HSB mixture demonstrating outstanding 28-day performance: a maximum CS of 65.04 MPa, the highest UPV of 4902 m/s, the lowest WA of 1.14%, a reduced TC of 1.96 W/(m×K), and an extremely low RCPT value of 179 Coulombs. Microstructural analysis supported these observations. The findings demonstrate HSB's effectiveness in improving concrete performance and confirm its viability for sustainable concrete production.

Keywords: **compressive strength, high-silica by-product, rapid chloride ion penetration, ultrasonic pulse velocity, water absorption.**

Classification numbers: **2.3, 5.3**

1. Introduction

Concrete is the most widely used construction material globally due to its excellent mechanical properties, durability, and versatility. However, the production of cement, the primary binder in concrete, contributes significantly to global CO_2 emissions, accounting for approximately 7-8% of total anthropogenic CO_2 emissions. This is due to the fact that approximately one ton of CO_2 is generated for every ton of cement produced [1]. The emissions arise primarily from the calcination of limestone to produce lime and the energy-intensive processes involved in cement manufacturing. Additionally, cement production depletes non-renewable natural resources (limestone). In the construction industry, the production of materials like mortar and concrete further depletes natural resources, including sand and gravel. Consequently, extensive research has been devoted to finding solutions that reduce cement and aggregate usage, thereby promoting sustainability.

A.M. Tahwia, et al. (2024, 2025) [2, 3] explored the development of geopolymer concrete (GPC), a high-performance material with superior mechanical strength and durability, synthesised through the alkali activation process, without the need for cement. The incorporation of recycled powders from readily available and cost-effective pozzolanic waste materials as binders in GPC offers a promising solution for reducing construction waste and advancing sustainable material production. In their work, A.M. Tahwia, et al. (2024) [2] developed GPC using rice husk ash, granite waste powder, and volcanic pumice powder. In a subsequent study, they investigated the impact of recycled concrete powder, clay brick powder, and volcanic pumice powder on the mechanical, durability, and thermal properties of GPC, incorporating fly ash and slag under water curing conditions [3]. M. Hadjadj, et al. (2024a, 2024b) [4, 5] investigated the feasibility of using seashell powder as a binder to partially replace cement, combined with industrial granite waste to partially replace fine aggregates (sand), in the development of a new type of green flowable sand concrete. In several studies [6-9], researchers investigated the production of concrete using waste materials as sand replacements, such as rubber waste [6], coffee waste [7], marble waste powder [8], and floor tile waste [9]. These studies showed that reusing waste materials

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in concrete production offers a positive approach to reducing material costs and addressing certain environmental issues.

Alongside efforts to replace natural aggregates and develop alkali-activated, cement-free concrete, another crucial strategy in advancing sustainable concrete is the reduction of cement usage through the integration of supplementary cementitious materials (SCMs). In response to growing global concerns about sustainability, the adoption of SCMs as partial substitutes for cement has become an essential approach to mitigating the environmental impact of cement concrete production. Currently, many studies have tested the properties of ordinary cement concrete with the influence of SCMs from industrial by-products rich in silica, such as silica fume, rice husk ash, fly ash, and ground granulated blast-furnace slag. In Vietnam, the requirements for the use of these industrial by-products in construction materials have been specified and incorporated into standards such as TCVN 8827:2011 [10], TCVN 10302:2014 [11], and TCVN 11586:2016 [12]. These materials demonstrate remarkable pozzolanic activity, primarily attributed to their high amorphous silica content. Upon incorporation into cementitious systems, they undergo a secondary hydration reaction with calcium hydroxide ($Ca(OH)_2$), forming supplementary calcium silicate hydrate (C-S-H) phases that enhance the binding matrix [13]. This pozzolanic reaction mechanism provides dual benefits: It significantly improves the composite's mechanical properties while simultaneously decreasing the clinker factor, thereby reducing the carbon footprint of concrete production [1].

Silica fume is a secondary material generated in electric arc furnaces during the production of silicon metal and ferrosilicon alloys. It is formed through the reduction of high-purity quartz using carbon-based materials such as coal, coke, and wood chips. According to American Concrete Institute (ACI) 234 (2006) [14], the SiO_2 content of the resulting fume is directly correlated with the type of silicon alloy being manufactured. In concrete technology, silica fume with SiO_2 concentrations exceeding 85% has become well-established and is commonly referred to as high-grade silica fume. This material, typically obtained from ferrosilicon alloys containing no less than 75% silicon, has been the subject of comprehensive scientific study. Its use is standardised in specifications such as American Society for Testing and Materials (ASTM) C1240-20 [15] and TCVN 8827:2011 [10]. The specific surface area of silica fume particles typically ranges from 13,000 to 30,000 m^2/kg [1]. These particles are ultrafine and spherical in shape, with sizes generally smaller than one micrometre, which is approximately 100 times smaller than the particle size of ordinary cement [16, 17]. Silica fume is a highly refined mineral additive, notable for its fine particle size and pronounced pozzolanic reactivity, which significantly enhances the mechanical properties of concrete. Its expansive surface area contributes to the formation of C-S-H gel within the concrete's microstructure, improving the CS, durability, and resistance to chloride ion penetration. According to findings by M.I. Khan, et al. (2011) [18], and R. Banar, et al. (2022) [19], the incorporation of silica fume contributes to improved cement hydration kinetics and provides greater resistance to chloride ion ingress in concrete. K.G. Babu, et al. (1995) [20] reported that even up to a 40% replacement of cement with silica fume resulted in higher strength than control concrete. S. Bhanja, et al. (2002) [21] found that incorporating silica fume into concrete mixtures can enhance strength by 30 to 100%, depending on factors such as the type of mix, type of cement, silica fume content, use of plasticisers, aggregate types, and curing conditions. S. Nasrin, et al. (2021) [22] reported an increase of 9.4, 30.76, and 34% in the CS for the concrete containing 10, 15, and 20% of silica fume, respectively. In the study by U. Bakhbergen, et al. (2022) [23], silica fume contents of 15, 20, and 25% were used in reactive powder concrete with a low water/binder ratio, with a reduced CS observed at 15% silica fume content. However, increasing the silica fume content from 20 to 25% resulted in higher CS. Meanwhile, P.C. Aitcin, et al. (1990) [24] concluded that the optimal silica fume content for achieving the highest strength ranged between 15 and 20%.

Conversely, low-grade silica fume, hereafter referred to as HSB, derived from the production of ferrosilicon alloys containing approximately 50% silicon [3], typically exhibiting SiO_2 contents ranging from 61 to 84%, has received limited attention in practical concrete applications. Despite its substantial annual output, estimated at 2.1 to 2.4 million tons globally [25], HSB remains underutilised in concrete applications due to its lower purity compared to high-grade silica fume. However, emerging evidence suggests that HSB possesses comparable pozzolanic activity and could serve as a promising alternative to cement [25, 26]. This research addresses a clear knowledge gap by systematically evaluating the potential of HSB as a partial cement replacement in concrete production.

In Vietnam, high-grade silica fume is primarily imported due to the limited number of domestic facilities capable of meeting ASTM C1240-20 [15] and TCVN 8827:2011 [10] standards. The high production cost and technological barriers have restricted its availability, leading to elevated prices. In contrast, several local ferrosilicon alloy plants within the country, such as the recently established Lionas Metals facility in Thanh Hoa province, may generate large volumes of HSB with SiO_2 content below the 85% threshold defined by these standards [10, 15]. The limited supply of high-grade silica fume has led to increased costs, which in turn has sparked growing interest in the use of HSB. Instead of allowing this by-product to be wasted or cause environmental concerns, it could be recycled into construction materials. This approach offers both economic and environmental benefits, serving as an alternative to high-grade silica fume. Currently, there is very limited research on the use of HSB in concrete production [25, 26]. Moreover, the chemical composition and properties of HSB vary depending on the plant of origin due to differences in input materials. As a result, concrete made with HSB from different sources will exhibit different characteristics. Hence, this study was conducted to evaluate the feasibility of using HSB as a partial replacement for cement in concrete, with the aims of promoting environmental responsibility and resource efficiency in Vietnam's construction industry.

As mentioned above, most high-grade silica fume is primarily imported from abroad, while HSB from a new local plant should be investigated before use. This investigation represents the first detailed assessment of HSB utilisation from Lionas Metals Company Limited in Thanh Hoa province. The research methodology involved formulating concrete mixtures incorporating HSB at replacement levels of 0, 10, 20, and 30% by weight of cement. Comprehensive performance evaluation was conducted through multiple characterisation techniques: fresh and dry UWs, CS testing, UPV measurements, WA analysis, TC measurement, RCPT, and microstructure analysis. The results demonstrate that HSB-modified concrete can improve concrete performance compared to the control mixture. This study offers an innovative contribution to the field by addressing a research gap concerning the application of HSB in concrete and by highlighting its potential as a sustainable, locally available supplementary cementitious material in Vietnam's construction industry.

2. Materials and methods

2.1. Materials

The concrete samples prepared in this study were composed of a blend of cement, HSB, natural river sand, gravel, superplasticiser, and tap water. The cement used was PCB40, manufactured by Bim Son Cement Plant, which has a specific gravity of 3.12 t/m^3 and an average particle size of 20.87 µm. The HSB used in this study was sourced from Lionas Metals Company Limited, located in Thanh Hoa province, Vietnam. This material has a specific gravity of 2.1 t/m^3 and an average particle size of 9.79 µm, which is finer than that of the cement. The chemical properties of these binder materials are summarised in Table 1. Cement and HSB served as binary binders in the mix. Cement predominantly contains SiO_2 and CaO, which together account for more than 73.03% of its mass. The microstructures of the cement and HSB were examined using scanning electron microscopy (SEM) at a magnification of 1000x, as depicted in Figs. 1A and 1B. The SiO_2 content of the HSB is 81.75%, which is below the minimum requirement specified in ASTM C1240-20 [15] and TCVN 8827:2011 [10]. It is also important to note that the average particle size of the HSB used in this study is significantly larger than that of silica fume commonly utilised in previous studies, as summarised in the review by H.M. Hamada, et al. (2023) [1]. Cement particles exhibit an irregular shape, while HSB consists of fine particles that exhibit a spherical form. The fine aggregate used was natural river sand, with particle sizes ranging from 0.15 mm to 5 mm, a fineness modulus of 2.83, a density of 2.62 t/m^3, a moisture content of 4.35%, and a WA capacity of 1.08%. The coarse aggregate was gravel with a nominal maximum size of 12.5 mm, a density of 2.69 t/m^3, a moisture content of 0.25%, and a WA capacity of 0.1%. Tap water was employed for mixing, and the superplasticiser (SP) type F, with the main composition of naphthalene formaldehyde sulphonate supplied by Sika company, has a specific gravity of 1.15 t/m^3 and was incorporated to decrease water content and achieve the desired workability of the mixture.

Table 1. Main chemical compositions of binder materials (in percentage, %).

Items	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI*
Cement	22.49	7.92	4.41	50.54	2.72	1.31	6.62
HSB	81.75	0.99	11.57	1.96	1.41	0.50	1.75

*LOI: Loss on ignition.

2.2. Mixture proportions

Four concrete mixtures were designed using the absolute volume method according to ACI 211.1 [27], with a constant water-to-binder (W/B) ratio of 0.45. The proportions of the concrete constituents are shown in Table 2. The reference mixture, designated as HSB00, utilised only cement as the binder material. Three additional mixtures were created by substituting 10, 20, and 30% of the cement with HSB, referred to as HSB10, HSB20, and HSB30, respectively. The purpose of these mixtures was to investigate the influence of HSB content on the properties of concrete, including fresh UW, dry UW, WA, CS, UPV, TC, and RCPT. The SP content was adjusted to control the slump values of all fresh concrete mixtures, which ranged from 75 to 100 mm.

Table 2. Mixture proportions and slump measurements.

Mixtures	Water-to-binder	Ingredient proportions (kg/m^3)						Slump (mm)
		Cement	*High-silica by-product*	*Sand*	*Gravel*	*Water*	*SP*	
HSB00	0.45	432.5	0.0	768.1	998.6	194.6	6.5	82
HSB10		385.4	42.8	760.6	988.9	192.7	9.8	80
HSB20		339.6	84.9	754.0	980.4	191.0	11.9	89
HSB30		294.4	126.2	747.1	971.3	189.3	14.7	82

SP: Superplasticiser.

2.3. Sample preparation

The ingredients for the concrete were prepared based on the proportions outlined in Table 2. The mixing process took place in a laboratory mixer, in accordance with the technical guidelines [28] issued by the Vietnam Ministry of Construction for using silica fume in concrete. Fig. 2 shows the dry materials prepared prior to mixing. The procedure began with the addition of 75% of the total mixing water, along with gravel, into the mixer. While the mixer was operating, HSB was gradually introduced and mixed for 1.5 minutes to ensure even distribution. Following this, cement was added, and mixing continued for another 1.5 minutes. Then, sand and the remaining 25% of water, containing dissolved SP, were incorporated into the mix. The batch was mixed for 5 minutes, allowed to rest for 3 minutes, and then subjected to a final 5-minute mixing cycle to achieve a homogeneous fresh concrete mixture. Fig. 3 demonstrates the sample preparation process in this study.

The workability of the concrete mixture was evaluated by measuring the slump in accordance with ASTM C143 [29]. The slump was maintained within the range of 75-100 mm, with the SP dosage adjusted as necessary to achieve the desired consistency. Once the workability was deemed acceptable, the fresh concrete was poured into standardised steel moulds of various sizes (cylindrical specimens of ϕ100×200 mm for RCPT tests and cubes of 100×100×100 mm for CS, UPV, dry density, and WA tests) and vibrated to remove air bubbles and ensure proper consolidation, following ASTM C192 [30]. All samples were initially cured for 24 hours under laboratory conditions. After demoulding, the samples were submerged in water at room temperature for continued curing until the designated testing ages.

(A) (B)

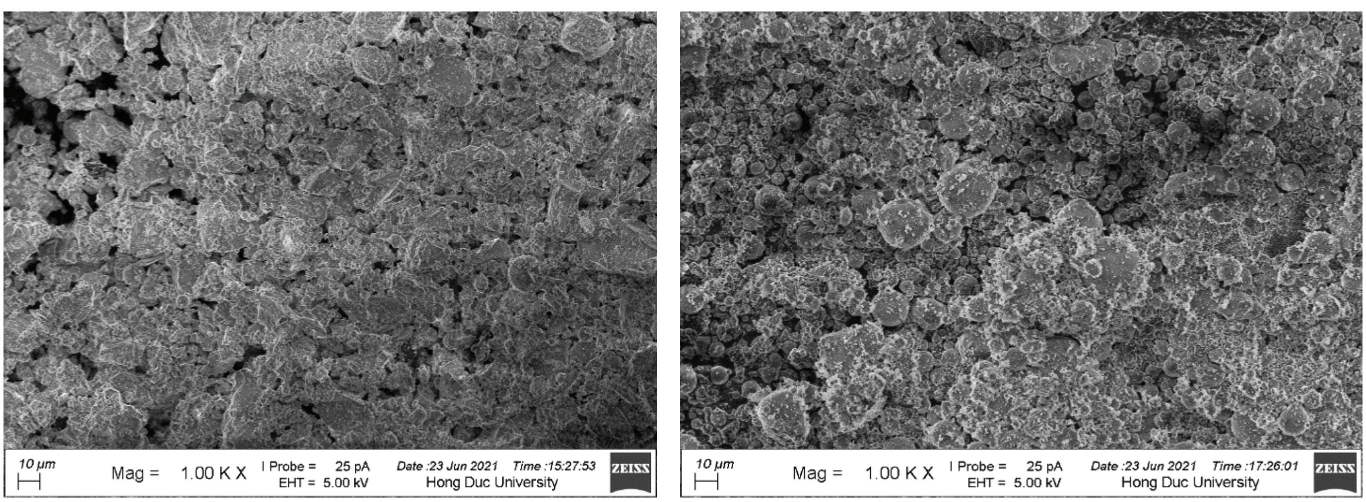

Fig. 1. Scanning electron microscopy images of cement (A) and high-silica by-product (B).

Fig. 2. Dry material for mixing.

Fig. 3. Sample preparation.

2.4. Test methods

After the mixing process, the properties of the fresh concrete, including workability and both fresh and dry UWs, were determined according to ASTM C143 [29] and ASTM C138 [31], respectively. The WA and UPV were evaluated using 100 mm cube samples, in compliance with ASTM C642 [32] and ASTM C597 [33], respectively. TC measurements were carried out with the ISOMET-2014 apparatus using 100 mm cube samples. The CS test was performed in accordance with ASTM C39-12 [34] on modified 100 mm cube specimens. The microstructure of the concrete samples was examined using a SEM technique provided by the manufacturer ZEISS.

The resistance of the concrete samples to chloride ions was assessed at 28 days and 56 days using ASTM C1202 [35], based on the total charge passed through 100×50 mm cylindrical specimens over six hours. These specimens were cut from larger 100×200 mm concrete cylinders. CS and UPV tests were conducted at 3, 7, 14, 28, and 56 days, while WA, TC, and RCPT tests were carried out at 28 and 56 days. The reported results represent the average values obtained from a minimum of three specimens. Additionally, surface microstructure images of the concrete samples at 28 days were captured using an EVO 18 scanning electron microscope at 1000× magnification.

3. Results and discussion

3.1. Properties of fresh concrete and dry unit weight

The slump value of fresh concrete is detailed in Table 2, while the fresh and dry UWs are depicted in Fig. 4. Generally, for all mixtures targeting a slump range of 75-100 mm, the dosage of SP increased from 1.5 to 3.5% as the HSB content rose from 0 to 30%, in order to maintain the desired workability (Table 2). This result aligns with the findings reported by I. Sharaky, et al. (2019) [36] and S. Diamond, et al. (1987) [37]. An increase in HSB content results in a higher demand for SP to maintain the desired workability and consistency. This increase can be attributed to several mechanisms, particularly the physical and chemical interactions between SP molecules and HSB particles. Due to their finer particle size and significantly higher specific surface area compared to cement, HSB tends to adsorb a considerable amount of SP onto its surface. As the HSB content increases, the total surface area exposed in the mix also increases, leading to greater adsorption of SP and, consequently, a reduction in the free SP available in the paste to perform its dispersing function on cement particles. Moreover, the sulfonate groups of SP may interact with functional groups or reactive sites on the HSB surface through electrostatic attraction or hydrogen bonding, further enhancing the binding affinity between SP and HSB. As a result, the dispersing efficiency of SP is reduced, necessitating higher dosages to achieve the same level of fluidity, as previously noted by S. Diamond, et al. (1987) [37], R.P. Khatri, et al. (1995) [38], and M. Mazloom, et al. (2004) [39]. The increased demand for superplasticiser from 1.5 to 3.5% with higher HSB content indicates that further research is necessary to optimise admixture use in order to meet both technical and economic requirements when incorporating this material into concrete mixtures.

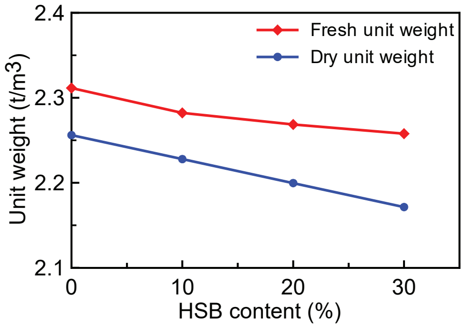

Fig. 4. Effect of high-silica by-product content on unit weights.

As the HSB content increases from 0 to 30%, a consistent decline is observed in both the fresh and dry UWs. Specifically, at HSB contents of 10, 20, and 30%, the fresh UW decreases by 1.26, 1.86, and 2.32%, respectively, compared to the control mix. Similarly, the dry UW decreases by 1.25, 2.50, and 3.75% corresponding to the 10, 20, and 30% HSB replacement levels, respectively. This trend is mainly attributed to the lower specific gravity of HSB (2.21 t/m^3) compared to that of cement (3.12 t/m^3). Consequently, the rise in HSB content leads to a proportional reduction in the quantities of cement, sand, gravel, and water, as outlined in Table 2, thereby contributing to the observed decrease in UW.

3.2. Water absorption

The WA capacity of concrete is closely associated with its permeability and resistance to chemical attack, as highlighted by S.P. Zhang, et al. (2014) [40]. A lower WA typically indicates reduced permeability, thereby improving the material's ability to withstand chemical ingress. The WA of concrete samples at 28 and 56 days is illustrated in Fig. 5. The results demonstrate that higher HSB content corresponds to lower WA. At 28 days, the control mix exhibited a WA of 2.67%. As HSB content increased, the absorption rate decreased to 2.14, 1.47, and 1.14% for 10, 20, and 30% HSB incorporation, corresponding to reductions of 19.91, 45.02, and 57.34%, respectively. This trend continued at 56 days, with the HSB30 mix showing the lowest WA of 1.10%, representing a further reduction of 58.62% compared to the control. This enhancement can be ascribed to the dual function of HSB as both a micro-filler and a pozzolanic material. The fine particles help fill micro voids in the cementitious matrix, while the pozzolanic reaction generates additional calcium silicate hydrate (C-S-H) gel, leading to a denser and more refined pore structure. Specifically, HSB reduces the pore size within the concrete, leading to a decline in WA, as supported by the studies of H.M. Hamada, et al. (2023) [1] and A. Mehta, et al. (2020) [41]. This densification effect enhances the overall durability and performance of the concrete. Furthermore, it can be observed that as the HSB content increased, the WA at 56 days showed a reduction compared to that at 28 days. This trend can be attributed to the progressive formation of hydration products over time, which results in a denser microstructure and, consequently, lower WA [42].

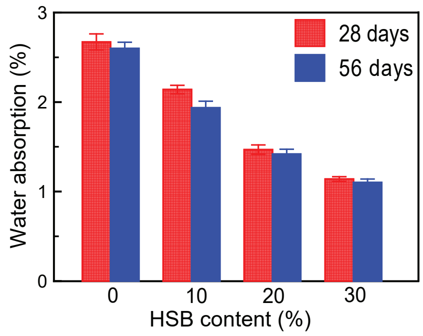

Fig. 5. Effect of high-silica by-product content on water absorption.

3.3. Compressive strength

The development of CS in concrete mixtures incorporating varying contents of HSB is presented in Fig. 6. A consistent increase in strength was observed with the addition of HSB, confirming its beneficial role in enhancing the mechanical properties of concrete.

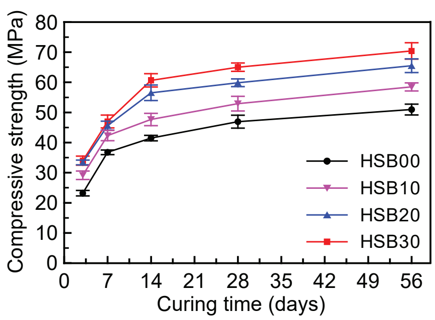

Fig. 6. Effect of high-silica by-product content on compressive strength.

At 3 days, the control mixture (HSB00) exhibited a CS of 23.19 MPa. In contrast, mixtures with 10, 20, and 30% HSB achieved 29.16, 33.40, and 33.99 MPa, respectively, corresponding to improvements of 25.72, 44.03, and 46.57%. This notable early-age strength enhancement is advantageous for construction activities requiring rapid formwork removal and reduced waiting times. The improvement can be attributed to the fine particle size of HSB, which provides additional nucleation sites for hydration, facilitating the formation of calcium silicate hydrate (C-S-H), the primary binding phase in cementitious materials. Additionally, the high silica content of HSB promotes pozzolanic reactivity, further strengthening the microstructure at early ages.

At 28 days, the control mix reached a CS of 46.93 MPa, while the HSB10, HSB20, and HSB30 mixtures achieved 52.93, 59.85, and 65.04 MPa, representing increases of 12.75, 27.53, and 38.59%, respectively. This continued strength development is indicative of ongoing pozzolanic activity, which enhances matrix cohesion and reduces porosity. The micro-filler effect of the ultrafine HSB particles contributes to matrix densification, resulting in a more compact and durable concrete.

At 56 days, the control mix exhibited a CS value of 50.96 MPa. Mixtures containing 10, 20, and 30% HSB attained 58.48, 65.50, and 70.42 MPa, corresponding to gains of 10.48, 23.75, and 33.04% over the control, respectively. This prolonged strength development beyond 28 days is a typical characteristic of pozzolanic materials, which continue to react with calcium hydroxide over time, contributing to long-term strength and durability improvements. These results are consistent with prior findings by H.M. Hamada, et al. (2023) [1] and M. Mazloom, et al. (2004) [39], reinforcing the positive impact of supplementary cementitious materials, such as silica fume, on the mechanical performance of concrete. In summary, the results demonstrate that HSB is an effective supplementary material that improves both early and long-term CS, supporting its potential for sustainable and high-performance concrete applications.

As presented above, the CS and WA have a close relationship. Fig. 7 shows a clear relationship between CS and WA, although it should be noted that the dataset is limited in scope. Consequently, while the observed trend is compelling, its application in broader practical contexts should be approached with caution. At 28 days, the correlation follows the linear equation $y = -0.086x + 6.706$ with $R^2 = 0.995$, and at 56 days, $y = -0.077x + 6.491$ with $R^2 = 0.995$.

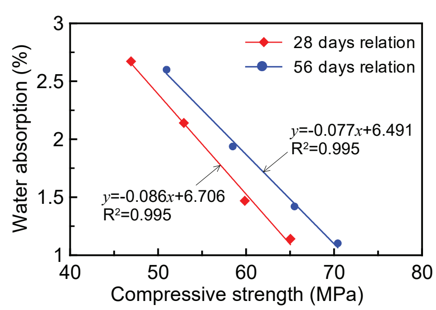

Fig. 7. Relation between compressive strength and water absorption.

3.4. Ultrasonic pulse velocity

The UPV non-destructive testing method has been widely applied in the study of the mechanical properties and structural integrity of concrete [43-45]. This method is easy to use and provides rapid results in the field. Fig. 8 illustrates the UPV values of concrete samples at curing ages of 3, 7, 14, 28, and 56 days, with varying HSB contents. These UPV values show a progressive increase over time, indicating ongoing densification and refinement of the concrete's internal microstructure. The results are consistent with findings from previous studies where the incorporation of supplementary cementitious materials, such as HSB, was shown to improve the UPV due to microstructural densification and enhanced material continuity [43].

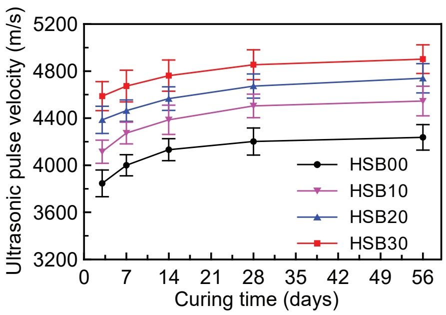

Fig. 8. Effect of high-silica by-product content on ultrasonic pulse velocity.

At 3 days, the control mixture (HSB00) gained a UPV of 3846 m/s. In contrast, mixtures with 10, 20, and 30% HSB achieved 4115, 4386, and 4587 MPa, respectively, corresponding to improvements of 7.00, 14.04, and 19.27%. This early increase in UPV can be attributed to the micro-filler effect of the finer HSB particles, which help reduce the porosity of the mix by filling voids in the cement matrix and enhancing acoustic transmission through the material.

At 28 days, the UPV of concrete incorporating 0, 10, 20, and 30% HSB reached 4202, 4505, 4673, and 4854 m/s, respectively. By 56 days, these values further increased to 4237, 4545, 4739, and 4902 m/s, reflecting a consistent enhancement in the material's internal structure over time. This progressive increase in UPV mirrors the observed trend in CS, reinforcing the strong correlation between these two parameters as indicators of microstructural densification and improved cohesion. These findings are well-supported by earlier studies [43-46]. As noted by previous studies [45, 47-48], numerous relationships between UPV and CS have been proposed, particularly for normal weight concrete. Some researchers have suggested logarithmic relationships between UPV and CS, while others have proposed linear relationships [45, 47]. However, exponential relationships remain the most prevalent [45, 47]. Given the limited experimental data in this study, the relationship between CS and UPV is best characterised by a linear correlation, as shown in Fig. 9. At 28 days, the correlation follows the linear equation $y = 34.66x + 2611.07$ with $R^2 = 0.978$, and at 56 days, $y = 33.58x + 2546.11$ with $R^2 = 0.993$. The relationship between UPV and CS of concrete is not a standardised correlation, as it is influenced by various factors such as the type and size of aggregates, HSB particle size distribution, pozzolan content, physical properties of the cement paste, curing conditions, mixture composition, concrete age, water-to-cement ratio, moisture content, and the presence of microstructural cracks [45, 47, 48]. Under the circumstances of this study, with the HSB content not exceeding 40%, the correlation between UPV and CS is linear. If higher HSB contents were used, further studies should be conducted.

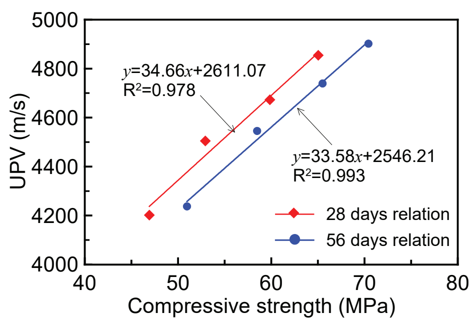

Fig. 9. Relation between ultrasonic pulse velocity and compressive strength.

The parallel improvements in both CS and UPV, as shown in Figs. 6 and 8, demonstrate the positive effect of HSB on refining the concrete matrix. Higher HSB content contributes to greater internal integrity and durability, consistent with the role of pozzolanic and filler effects. According to R.S. Carcaño, et al. (2008) [49], concrete with UPV values above 4100 m/s is classified as good quality. All mixtures in this study exceeded that benchmark, confirming that HSB is an effective supplementary material for enhancing both the mechanical performance and durability of concrete.

3.5. Thermal conductivity

Figure 10 illustrates the TC test results for all concrete samples under saturated surface dry conditions at both 28 and 56 days. At 28 days, the TC values ranged from 1.96 to 2.24 W/m·K, while at 56 days, they varied from 1.99 to 2.26 W/m·K. The TC of the concrete samples was observed to decrease with an increase in HSB content, and the TC values at 56 days were consistently higher than those at 28 days. Specifically, when HSB replaced 10, 20, and 30% of the cement, the TC of the concrete samples decreased by approximately 5.57, 9.07, and 12.36%, respectively, compared to the HSB-free concrete sample at 28 days. These findings align with the earlier study by R. Demirboğa, et al. (2003) [50], which reported a reduction in TC from 2.5 to 10% as the content of supplementary cementitious materials containing high SiO_2, such as silica fume, increased from 10 to 30% in the concrete mix. The reduction in TC is likely due to the finer particles of HSB compared to ordinary Portland cement, which reduces the overall porosity of the concrete and enhances pore size distribution [51]. Lower TC is essential for green buildings, as it helps reduce energy consumption.

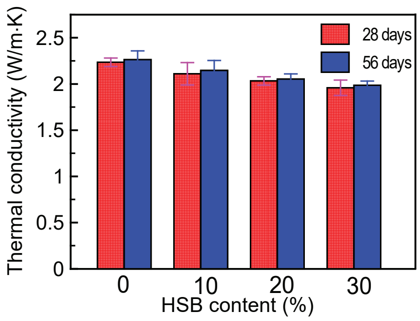

Fig. 10. Effect of high-silica by-product content on thermal conductivity.

According to H. Uysal, et al. (2004) [52], the TC of concrete is related to its density. Moreover, as curing progresses, more hydration products are formed, leading to a denser internal structure in the mortar samples at 56 days compared to those at 28 days. Consequently, the TC values at 56 days are higher than those at 28 days.

3.6. Rapid chloride ion penetration

The RCPT test was conducted to evaluate the resistance of concrete to chloride attack. The results of the RCPT test at 28 and 56 days are shown in Fig. 11. The control sample (HSB00) exhibited charge values of 2673 Coulombs at 28 days and 1781 Coulombs at 56 days. As the HSB content increased from 10 to 30%, the charge values decreased significantly, ranging from 179 to 651 Coulombs at 28 days and from 115 to 286 Coulombs at 56 days. This substantial reduction in RCPT results highlights the beneficial role of HSB in enhancing the concrete's resistance to chloride ion penetration. The improved performance can be attributed to two primary mechanisms. First, the pozzolanic activity of HSB reacts with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel, which refines the microstructure and lowers permeability. Second, the ultrafine particles of HSB serve as effective micro-fillers, filling voids within the matrix and further compacting the pore system, thereby limiting ion mobility. The continued decline in RCPT values from 28 to 56 days further reflects the progressive development of hydration products over time, contributing to a denser, more durable concrete matrix.

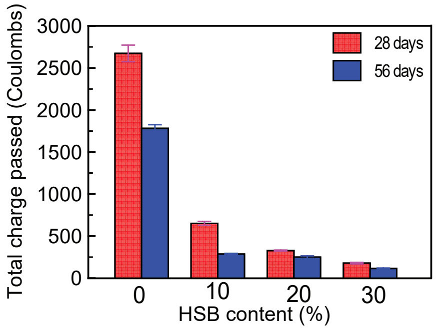

Fig. 11. Effect of high-silica by-product content on rapid chloride ion penetration.

Previous studies [1, 20, 53] have affirmed that the incorporation of mineral admixtures improves both impermeability and chloride resistance. Specifically, HSB enhances impermeability, leading to better chloride resistance. M.I. Khan, et al. (2011) [18] found that HSB significantly improves concrete durability, particularly by reducing chloride diffusion through the reduction of capillary pores. In the present study, HSB-containing samples exhibited lower WA (Fig. 4), which correlates with their higher resistance to chloride ion penetration [40].

The HSB-containing samples exhibited 56-day RCPT values between 100 and 1000 Coulombs, classifying them as having "very low" chloride penetration according to ASTM C1202 [35]. In contrast, the HSB-free concrete sample had 56-day RCPT values between 1000 and 2000 Coulombs, indicating "low" chloride penetration.

3.7. Microstructure analysis

Figure 12 illustrates SEM analyses of fracture surfaces in 28-day concrete specimens with progressively increased HSB content. Several studies have indicated that HSB can influence the cement hydration process as well as the microstructure of the hydration products [13, 54]. Distinct microstructural transitions emerge as HSB content increases. The reference sample (HSB00) and HSB10 in Figs. 12A and 12B reveal a microstructure that is porous and lacks compactness, marked by unhydrated cement particles, capillary voids, and microcracks. Such characteristics indicate insufficiently developed hydration products, which correlate well with the higher WA and RCPT results discussed in Sections 3.2 and 3.5. Incorporating higher than 10% HSB, designed as HSB20 and HSB30, demonstrates a more advanced level of refinement, featuring a dense matrix structure, uniform density, and a smooth, flat surface, as can be observed in Figs. 12C and 12D. The finer particle size and strong pozzolanic reactivity of HSB allow it to fill voids and react with $Ca(OH)_2$ to generate a significant amount of C-S-H gel, thereby reducing porosity. The formation of C-S-H gel due to the incorporation of HSB has also been experimentally confirmed by M. Amin, et al. (2022) [25], and H. Kim, et al. (2021) [54]. These structural changes align with the observed improvements in

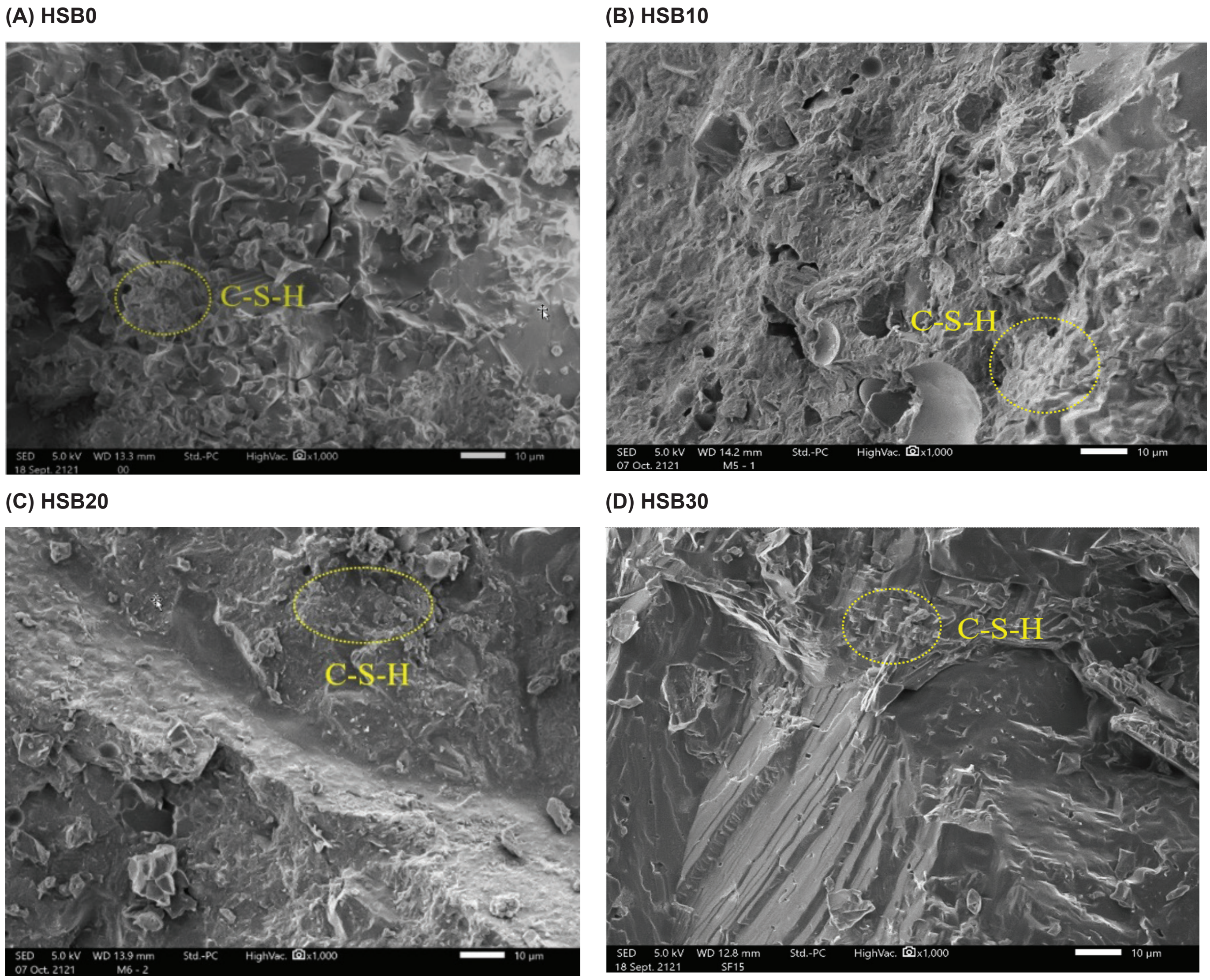

Fig. 12. Scanning electron microscopy micrographs of 28-day-old concrete.

both mechanical strength and durability. Altogether, these findings highlight the dual role of HSB in enhancing concrete microstructure through both physical densification and chemical activity. The results reinforce the potential of HSB as an eco-efficient SCM, capable of improving the long-term durability and sustainability of concrete systems.

4. Conclusions

This study explored the potential of reusing high-silica by-product (HSB) sourced from the factory of Lionas Metals Company Limited as a partial replacement for cement in concrete production. Even though the SiO_2 content in the HSB is lower than the minimum requirement for highly active pozzolanic admixtures specified in TCVN 8827:2011 [10], it still shows potential for use in producing high-quality concrete. The study led to several key conclusions, which are outlined as follows:

1. Increasing the HSB content led to a reduction in both fresh and dry unit weights (UWs), primarily due to the lower density of HSB compared to cement. With 30% HSB, the fresh and dry UWs decreased by 2.32 and 3.75%, respectively, compared to the control mix.

2. Water absorption (WA) decreased with longer curing times and higher HSB content, while resistance to chloride ion penetration improved significantly. After 56 days, the WA of HSB30 was 1.10%, a 58.62% reduction compared to the control. Similarly, the rapid chloride ion penetration (RCPT) values for HSB30 decreased dramatically, from 2673 Coulombs in the control mix to only 115 Coulombs in the HSB30 mix, indicating extremely low permeability and enhanced durability, particularly against moisture and chloride ingress.

3. Compressive strength (CS) improved with both longer curing times and higher HSB content. After 28 days, the 30% HSB mix (HSB30) reached 65.04 MPa, representing a 38.59% improvement over the control mix. The CS further increased between 28 and 56 days, with HSB30 attaining 70.42 MPa.

4. Concrete mixes incorporating HSB demonstrated significant improvements in UPV values, reflecting enhanced densification and microstructural refinement. At 56 days, the UPV of HSB30 reached 4902 m/s, well above the 4100 m/s threshold for good quality.

5. The incorporation of HSB led to a decrease in TC. When HSB replaced 10, 20, and 30% of the sand, the TC of the concrete samples dropped by approximately 5.57, 9.07, and 12.36%, respectively, compared to the control mix without HSB at 28 days.

6. Scanning electron microscopy (SEM) analysis showed that adding HSB, especially at 30% replacement, significantly enhanced microstructural density and uniformity. These changes correlate with higher strength and durability, demonstrating HSB's effectiveness in improving concrete properties.

The results of this study demonstrate that HSB from Lionas Metals Company Limited in Thanh Hoa province can be used to partially replace cement in concrete production. The findings highlight the effectiveness of HSB in enhancing density, increasing strength, and improving long-term durability due to its low WA and excellent resistance to environmental degradation. Further research is needed to optimise the use of HSB, evaluate additional properties such as shrinkage and sulphate expansion, and explore its long-term performance under various environmental conditions.

COMPETING INTERESTS

The author declares that there is no conflict of interest regarding the publication of this article.

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