Hue University Journal of Science: Natural Science
Vol. 134, No. 1S-1, 27–41, 2025 (Special Issue: IFGTM 2025)

pISSN 1859-1388
eISSN 2615-9678

Recycling steel slag as substitute for natural aggregate in construction: dual benefits for GHG emission reduction and environmental protection in Vietnam

Duong Trung Quoc[1], Tran Thanh Nhan[1]*, Tran Thi Ngoc Quynh[1], Nguyen Thi Le Huyen[1], Do Quang Thien[1], Tran Xuan Thach[2], Nguyen Thanh Hai[3], Nguyen Huu Dong[4]

[1] University of Sciences, Hue University, Hue City, Vietnam
[2] Construction Department of Ha Tinh Province, Ha Tinh City, Vietnam
[3] Construction Department of Quang Nam Province, Tam Ky City, Vietnam
[2] Ha Tinh University, Cam Vinh, Ha Tinh City, Vietnam

* Correspondence to Tran Thanh Nhan <ttnhan@hueuni.edu.vn>

(*Received: 10 May 2025; Revised: 29 June 2025; Accepted: 30 June 2025*)

Abstract. In Vietnam, the annual production of steel slag, a byproduct of the steel-making process, has exceeded 3 million tons since 2018. Due to its advantageous properties, over 85% of steel slag is recycled and utilised in construction in developed countries. However, in Vietnam, a significant portion remains either stockpiled at steel plants or used as backfill material, posing risks of soil and water pollution. Meanwhile, natural construction materials such as river sand are becoming depleted, and the extraction of resources like crushed stone leads to various environmental issues. Therefore, recycling steel slag as a substitute for natural construction materials not only mitigates environmental pollution associated with the steel industry but also reduces the depletion of natural resources, contributing to energy conservation and lower greenhouse gas emissions in the construction sector. This study presents initial findings on the use of steel slag as an aggregate in concrete for coastal protection structures, such as wave-breaking blocks, which are essential as coastal erosion has become a critical issue in numerous areas of Vietnam.

Keywords: coastal protection, environmental sustainability, grade 400 concrete, recycled aggregate, steel slag

1 Introduction

Steel slag (SS), the main type of steelmaking by-product, averaged ca. 11 to 15% by mass of crude steel production. This share is approximately 15% for the main (big) steel plants in Vietnam [1]. In 2024, the world SS production is between 190 million and 290 million tons [2]. Therefore, recycling SS is a heavy duty of the steel industry, becoming a cumulatively attractive topic among researchers worldwide.

Steel slag possesses outstanding physico-mechanical properties over those of natural aggregates (e.g. basalt and limestone), such as anti-abrasion, rough surface texture, rich angularity, high hardness, higher crushing resistance [3, 4], and higher shear strength [5]. These advantages bring to this material a great potential in serving as a substitute for natural aggregate in building construction. In Europe, the European Slag Association (EUROSLAG), with official statutes and harmonics standards and specifications, has enforced the systematic management and utilisation of SS in the region. The statistics in 2018 from 18 country members indicated total utilisation of SS in Europe was 11.8 million tons, occupying 72.3% of the production of 16.3 million tons [6]; meanwhile, this proportion was over 85% in Japan and the United States [7].

According to Vietnamese Steel Association, there are currently about 47 steelmaking plants in Vietnam [8] and with the rapid growth of the steel industry, SS production significantly increased, surpassing 3 million tons (Mt.) by 2018 [1, 9] and is projected to continue rising with the operation of new steel plants in the coming time. Notably, Ha Tinh Formosa steel plant (FHS steel plant) and Hoa Phat Dung Quat steel plant, the two biggest steel plants in Vietnam, have annually produced about 2 Mt. of SS since 2018. Generally, the information on SS produced in Vietnam is limited, and further investigation is required, particularly regarding its long-term behaviour and environmental impact when used in construction. Currently, SS is classified as regular solid waste in Vietnam [10]. In 2017, the Ministry of Construction issued technical guidelines on iron slag and SS for use as building materials [11]. Most recently, in 2024, the Ministry of Science and Technology issued two standards on the use of SS as backfill material (TCVN 13906:2024) [12] and as aggregate for concrete (TCVN 13908-2:2024) [13]. This serves as a foundation for promoting SS use in the construction sector in Vietnam, contributing to the recycling and utilisation of a large volume of this material, while reducing the burden on disposal sites and mitigating associated environmental issues for steel plants. However, owing to the lack of systematic research and sufficient scientific evidence, all of these standards and technical guidelines are based on or referenced from foreign documents. This poses challenges for stakeholders in recycling and utilising SS, and highlights the need to assess the applicability of these standards to the SS produced in Vietnam. Consequently, the recycling and utilisation of SS in Vietnam remain very limited, primarily involving its use as backfill material or storage at disposal sites of steel plants. The accumulation and disposal of unusable SS have led to excessive land occupation and unresolved environmental issues. Therefore, initiating a systematic investigation of SS for its safe and effective utilisation as an alternative construction material in Vietnam holds great significance, particularly in light of the rapidly increasing volume of SS and the severe shortage of natural construction materials.

2 Results and discussions

2.1 Used materials and their properties for potential application as aggregates for concrete

Different types of SS generated from the steelmaking process of the FHS steel plant (called Formosa SSs) were collected and used for this study. The plant uses the Blast Furnace – Basic Oxygen Furnace system (BF-BOF system), and there are three types of SS in the FHS plant, including desulfurisation slag (named as DeS slag) generated during the desulfurisation of pig iron (before being fed into the BOF for primary steelmaking); BOF slag is generated during the conversion of pig iron into crude steel in the BOF, and casting slag (referred to as CAST slag) is formed during the refining process of crude steel into finished steel. Since DeS slag is not suitable for use as concrete aggregate, it was excluded from this study. Meanwhile, BOF slag and CAST slag, after cooling, crushing, screening, and magnetic separation, were classified into two ranges of particle size: 0–10 mm (designated as BOF 010 and CAST 010) and 0–40 mm (designated as BOF 040 and CAST 040). The photos of these four types of Formosa SS are shown in Figs. 1a–1d. Differences in particle size are evidently observed among the used SSs.

pISSN 1859-1388
eISSN 2615-9678

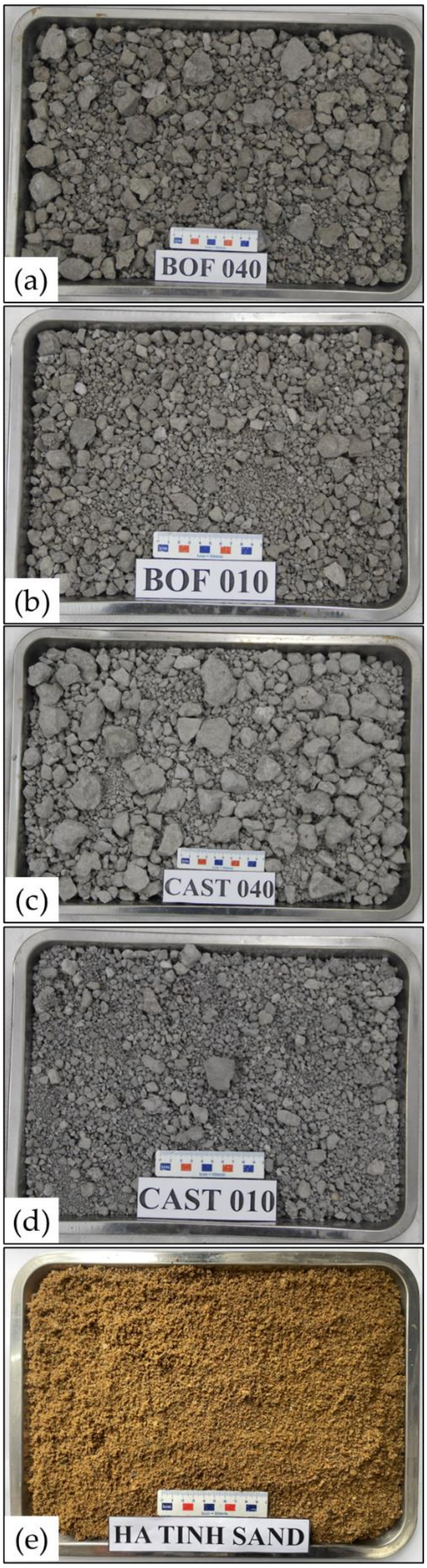

Fig. 1. Photos of original samples of Formosa SSs: (a) BOF 040; (b) BOF 010; (c) CAST 040; (d) CAST 010; (e) Ha Tinh sand

Additionally, because of the rapid cooling of molten slag, originally at approximately 1500 °C and subsequent crushing, the SS particles exhibit rough surfaces with numerous open pores. After collecting from the disposal site of the FHS steel plant, Formosa SSs were selected in accordance with the TCVN 7572-1:2006 standard [14] for tests of grain size and physico-mechanical properties to evaluate their suitability as aggregates for concrete.

Although SS can be used to fully replace both fine and coarse aggregates in cement concrete and asphalt concrete, initial studies should focus on the substitution of coarse aggregates to better control and predict the adsorption of water and binders [7]. Therefore, a type of coarse river sand, which is commonly used in the concrete production in Ha Tinh province, was collected and used as fine aggregate in this study. For convenience, the used sand is referred to as "Ha Tinh sand", and its photo is shown in Fig. 1e.

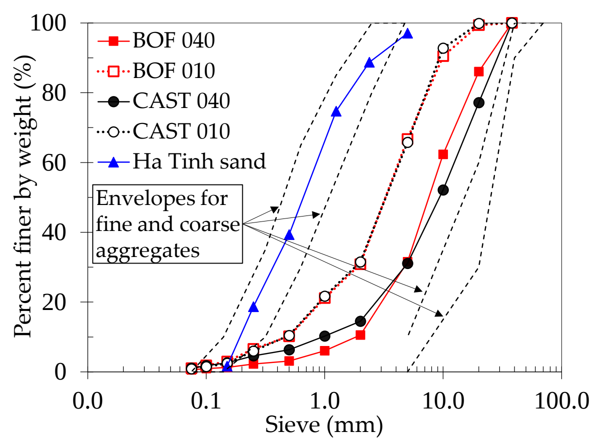

Fig. 2. Grain size distribution curves of Formosa SSs and Ha Tinh sand

The grain size of the materials was tested in accordance with the TCVN 7572-2:2006 standard [15], and the obtained results are presented in Fig. 2. Also in Fig. 2, the dashed lines represent the envelopes for coarse aggregate (type 5–40 mm) and fine aggregate for concrete, as specified by the TCVN 7570:2006 standard [16]. It can be observed that the particle size of the same type of Formosa SSs differs significantly, depending on treatment and product recovery processes at the source (i.e., between BOF 010 and BOF 040, and between CAST 010 and CAST 040). In contrast, different types of Formosa SSs following crushing and screening with identical size exhibit relatively similar particle size distributions (i.e., between BOF 040 and CAST 040, and between BOF 010 and CAST 010). Moreover, the particle size distributions of all four Formosa SS samples lie outside the standard grading envelopes for both coarse and fine aggregates specified for concrete. Meanwhile, the particle size distribution of Ha Tinh sand meets the fine aggregate requirements well. Ha Tinh sand used in this study has a fineness modulus of 2.77; thus, it is classified as coarse sand in accordance with TCVN 7570:2006.

Table 1. Content (%) by grain size of used materials

Grain size (mm)		BOF 040	BOF 010	CAST 040	CAST 010	Ha Tinh sand
20–40	Coarse aggregate	14.0	0.6	22.8	0.1	0.0
10–20		23.7	8.9	25.0	7.1	0.0
5–10		30.8	23.8	21.0	27.0	2.9
0.14–5	Fine aggregate	30.3	63.8	28.5	63.3	95.5
< 0.14		1.2	2.9	2.6	2.4	1.6

Additionally, the content (in percentage) by grain size requirements for coarse and fine aggregates used in concrete, as specified in TCVN 7570:2006, is shown in Table 1. After being treated at the source, including hydration of free components (including free CaO and free MgO) and cooling, crushing, sieving, and magnetic separation, Formosa SSs were recovered, transported by specialised vehicles, and stored separately at a designated landfill site within the plant, following a closed-loop process. Therefore, Formosa SSs contain virtually no impurities (including sludge, clay dust and organic matter). Although Formosa SSs were separated into particle size ranges of 0–10 mm and 0–40 mm, the results in Table 1 show that the content of particles smaller than 0.14 mm in Formosa SSs ranges from approximately 1.2 to 2.9%, compared with 1.6% in Ha Tinh sand, thus fully complying with the requirements specified in TCVN 7570:2006.

In addition, the physico-mechanical properties of Formosa SSs and Ha Tinh sand were tested, including apparent specific gravity (ρ_a, g/cm^3), bulk specific gravity (when dried: ρ_k, g/cm^3 and saturated: ρ_{bh}, g/cm^3) and water absorption (w_a, %) (following the TCVN 7572-4: 2006 standard [17]); bulk density (ρ_x, kg/m^3) and porosity (v_w, %) (following the TCVN 7572-6: 2006 standard [18]); moisture content (w, %) (following the TCVN 7572-7: 2006 standard [19]); crushing value (at dried: N_{dk},% and at saturated: N_{ds}, %) and softening coefficient (K_M) (following the TCVN 7572-11: 2006 standard [20]); Los Angeles abrasion value (at 100 cycles: H_{m100}, % and 500 cycles: H_{m500}, %) (following the TCVN 7572-12: 2006 standard [21]). The obtained results are shown in Table 2.

pISSN 1859-1388
eISSN 2615-9678

Table 2. The physico-mechanical properties of the used materials

Properties	Grain size (mm)	BOF 040	BOF 010	CAST 040	CAST 010	Ha Tinh sand
ρ_a, g/cm^3	0.14–5	3.52	3.59	3.43	3.50	2.69
	5–40	3.54	3.47	3.43	3.51	
ρ_k, g/cm^3	0.14–5	3.11	3.13	2.98	3.07	2.45
	5–40	3.33	3.26	3.24	3.27	
ρ_{bh}, g/cm^3	0.14–5	3.22	3.26	3.11	3.19	2.54
	5–40	3.39	3.32	3.29	3.34	
w_a,%	0.14–5	3.75	4.03	4.44	3.95	3.68
	5–40	1.76	1.91	1.76	2.03	
ρ_x, kg/m^3		1958	2025	2057	1918	1436
v_w, %		39.2	36.6	35.6	39.5	41.4
w, %		1.9	3.0	3.1	3.8	5.7
N_{dk}, %	5–10	3.75	3.38	4.25	3.00	
	10–20	6.91	7.88	6.63	5.88	
	20–40	12.24		12.52		
N_{ds}, %	5–10	4.13	5.52	4.75	4.00	
	10–20	9.25	8.75	8.00	8.00	
	20–40	13.34		15.35		
K_M	5–10	0.91	0.64	0.89	0.75	
	10–20	0.75	0.90	0.83	0.73	
	20–40	0.92		0.82		
H_{m100}, %	A	2.5		3.6		
	B	3.4	3.9	3.1		
	C	2.8	3.8	2.9	3.2	
	D	2.9	4.1	2.6	4.2	
H_{m500}, %	A	16.9		21.0		
	B	16.0	19.3	16.5		
	C	12.3	13.8	14.4	13.9	
	D	13.9	15.1	12.8	14.8	

As the main oxide components of SS (CaO, SiO_2, Fe_2O_3, and MgO) account for approximately 80% of the total oxide content [7, 22], the specific gravity and bulk density of SS are considerably higher than those of conventional natural construction materials, such as granite and limestone. In addition to the advantage of being virtually free from lightweight materials, foreign matter, and organic impurities, experimental results in Table 2 indicate that the Formosa SSs meet the requirements for Type I recycled coarse aggregate for concrete as specified in TCVN 11969:2018 [23], based on properties such as bulk specific gravity (dry), water absorption, crushing value (both dry and saturated), and Los Angeles abrasion value (at both 100 and 500 cycles). Moreover, the saturated crushing values in Table 2 show that the Formosa SSs meet the crushed stone strength grade requirements ranging from 120 (for 20–40 mm particle size) to 140 (for 5–10 mm and 10–20 mm sizes), in accordance with TCVN 7570:2006. Therefore, they fully satisfy the strength criteria for use as coarse aggregate in grade 400 concrete.

2.2 Properties of Formosa SS mixture as coarse aggregate for concrete

To obtain the Formosa SS mixture as coarse aggregate for concrete, the (original) Formosa SSs were mixed at the mixing ratio equal to the production ratios from FHS steel plant, namely, BOF 040 = 73.7%; BOF 010 = 18.4%; CAST 040 = 6.3%; CAST 010 = 1.6%. This mixing ratio ensures complete recycling and utilisation of these four types of Formosa SSs. The mixture was then passed through sieves of 5, 10, and 20 mm to obtain coarse aggregate samples corresponding to the commonly used crushed stone sizes in the market: 5–10 mm, 10–20 mm, and 20–40 mm. These mixtures are named as BC510, BC1020 and BC2040, respectively, and their physico-mechanical properties are shown in Table 3.

Similar to the results of the (original) Formosa SS samples presented in Table 2, the experimental results in Table 3 indicate that the mixtures at different particle sizes of Formosa SSs meet the requirements for use as coarse aggregate in grade 400 concrete. In addition, the elongation and flakiness index of BC510, BC1020, and BC2040 mixtures ranges from 1.1 to 2.8%, which is significantly lower than the maximum allowable limit for coarse aggregate used in higher-grade concrete above B30 specified in TCVN 7570:2006 (≤15%), as well as for recycled coarse aggregates in concrete according to TCVN 11969:2018 (≤35%).

Table 3. Physico-mechanical properties of BC510, BC1020 and BC2040 mixtures

Properties	BC510	BC1020	BC2040
ρ_a, g/cm^3	3.51	3.50	3.42
ρ_k, g/cm^3	3.32	3.36	3.31
ρ_{bh}, g/cm^3	3.37	3.40	3.34
wa, %	1.68	1.18	1.03
ρ_x, kg/m^3	1724	1717	1707
v_w, %	48.1	49.0	47.7
N_{dk}, %	2.88	7.13	11.1
N_{ds}, %	3.25	7.63	13.19
K_M	0.88	0.93	0.84
H_{m100}, %	1.9	2.1	2.8
H_{m500}, %	10.2	14.5	13.9
Td, %	2.8	1.1	1.9

2.3 Mixture design for concrete using Formosa SSs as coarse aggregates

Based on the obtained results of the physico-mechanical properties of Formosa SSs and their mixtures in Tables 2 and 3, and to develop a concrete product for manufacturing seawave-breaking blocks, concrete mixtures were designed using BC510, BC1020, and BC2040 mixtures as coarse aggregate and Ha Tinh sand as fine aggregate. These mixtures were formulated to achieve a concrete grade of 400, with a slump of 6–8 cm and enhanced sulfate resistance. Accordingly, the materials used include PCB40 cement, Sikacrete PP-1 admixture to ensure sulfate resistance, Sikaplast-361 admixture to enhance the workability of fresh concrete, and tap water sourced from the laboratory faucet.

pISSN 1859-1388
eISSN 2615-9678

Corresponding to the names of the coarse aggregates used, concrete types are referred to as BC510 concrete, BC1020 concrete, and BC2040 concrete, respectively.

The general principle in concrete mixture design is to calculate the quantities of aggregates (both coarse and fine), cement, and water per 1 m^3 of concrete with the absolute volume method (the most commonly applied approach). This method assumes that the total volume of concrete is completely compacted (i.e., the absolute volume). Trial mixtures are then prepared for testing and adjustments to ensure that the final mixture design meets both technical and economic requirements. However, most conventional mixture design methods are developed for conventional (natural) aggregates and are therefore not well-suited to SS aggregates, which differ significantly in physical properties, morphology, and surface texture. Consequently, the concrete mixture proportions in this study were designed based on the construction cost estimation norms specified in Official Dispatch No. 1776/BXD-VP (referred to as Dispatch No. 1776) [24] and the construction material norms outlined in Official Dispatch No. 1784/BXD-VP (referred to as Dispatch No. 1784) [25]. The prescribed mixture proportions for grade 400 concrete with a slump of 6–8 cm, corresponding to each coarse aggregate size (5–10 mm, 10–20 mm, and 20–40 mm), are presented in Table 4.

In Table 4, for each size of the coarse aggregate, the quantities of cement and aggregates (sand and stone) per 1 m^3 of concrete as specified in Dispatch No. 1776 include allowances for construction loss and are therefore higher than those specified in Dispatch No. 1784. The cement content per 1 m^3 of concrete according to the two dispatches ranges from 423–427 kg (for 20–40 mm aggregate) to 483–488 kg (for 5–10 mm aggregate). Although SS has a rough surface texture with numerous open pores that can increase binder and water demand [26, 27, 28], the initial mixture proportions were conservatively selected based on the lower values specified in Dispatch No. 1784 (as shown in Table 4), which would then serve as a basis for incremental adjustment if necessary. The calculated mixture proportions per cubic meter of BC510, BC1020, and BC2040 concrete are presented in Table 5.

Table 4. Mixture design of grade 400 concrete with a slump of 6–8 cm with different coarse aggregate sizes in accordance with the regulations of the Ministry of Construction [24, 25]

Size of coarse aggregate (mm)	**5–10**	**10–20**	**20–40**
According to dispatch No. 1776			
Cement (kg)	488	458	427
Sand (m^3)	0,410	0,424	0,441
Crushed stone (m^3)	0,854	0,861	0,861
Water (L)	193	181	169
According to dispatch No. 1784			
Cement (kg)	483	453	423
Sand (m^3)	0,402	0,416	0,432
Crushed stone (m^3)	0,813	0,828	0,840
Water (L)	193	181	169

Table 5. Mixture design proportions for 1 m³ of BC510, BC1020, and BC2040 concrete according to Dispatch No. 1784

Formosa SS mixtures	BC510	BC1020	BC2040
Cement (kg)	483	453	423
Fine aggregate (kg) (1)	577.3	597.4	620.4
Coarse aggregate (kg) (2)	1401.6	1421.7	1433.9
Water (L)	193	181	169
Sikacrete PP-1 (kg) (3)	24.2	22.7	21.2
Sikaplast-361 (mL) (3)	3864.0	3624.0	3384.0

Note: (1) Calculated based on the bulk density of Ha Tinh sand as shown in Table 2; (2) Calculated based on the bulk density of the Formosa SS mixtures BC510, BC1020, and BC2040 as presented in Table 3; (3) According to the manufacturer's recommendations: 5–10% of cement weight for Sikacrete PP-1, and 500–2000 mL per 100 kg of cement for Sikaplast-361.

2.4 Casting and curing of concrete specimens

The concrete components were mixed with a free-fall mixer, which is commonly used in construction projects in Vietnam, and the slump of the fresh concrete was tested in accordance with the TCVN 3106:2022 standard [29]. The concrete specimens were cast and cured following the TCVN 3105:2022 standard [30]. The water content specified in Table 5 corresponds to the mixtures without admixtures; meanwhile, Sikaplast-361, a high-range water-reducing (superplasticiser) admixture, was used to improve workability, prolong slump retention, and enhance flowability of the fresh concrete. Nonetheless, because of the rough surface texture of SS, which leads to higher water absorption, the fresh concrete mixtures achieved a slump of only about 5.5–6.0 cm (Fig. 3). Casting results indicate that a 10% increase in each component listed in Table 5 was necessary to ensure the actual required volume. Therefore, the adjusted mixture proportions for 1 m³ of BC510, BC1020, and BC2040 concrete, based on practical casting conditions, are summarised in Table 6.

Table 6. Mixture proportions for 1 m³ of BC510, BC1020, and BC2040 concrete after adjustment based on actual casting conditions

Formosa SS mixtures	BC510	BC1020	BC2040
Cement (kg)	531.3	498.3	465.3
Fine aggregate (kg)	635.0	657.1	682.4
Coarse aggregate (kg)	1541.8	1563.9	1577.3
Water (L)	212.3	199.1	185.9
Sikacrete PP-1 (kg)	26.6	25.0	23.3
Sikaplast-361 (mL)	4250.4	3986.4	3722.4

After the curing period, a set of three specimens for each type of concrete was tested to determine compressive strength on the 3rd, 7th, and 28th day after fabrication. The compressive strength tests were conducted in accordance with the TCVN 3118:2022 standard [31] by using the TSY-2000 TYPE compression testing apparatus. Additionally, in order to assess the deformation of the specimens at the point of failure based on concrete type (i.e., the type of coarse aggregate derived from Formosa SS mixtures) and curing duration, compressive strength tests were accompanied by strain measurements. The situation of the concrete specimens in the testing apparatus and their photos after the compression test are shown in Fig. 4 and Fig. 5, respectively.

pISSN 1859-1388
eISSN 2615-9678

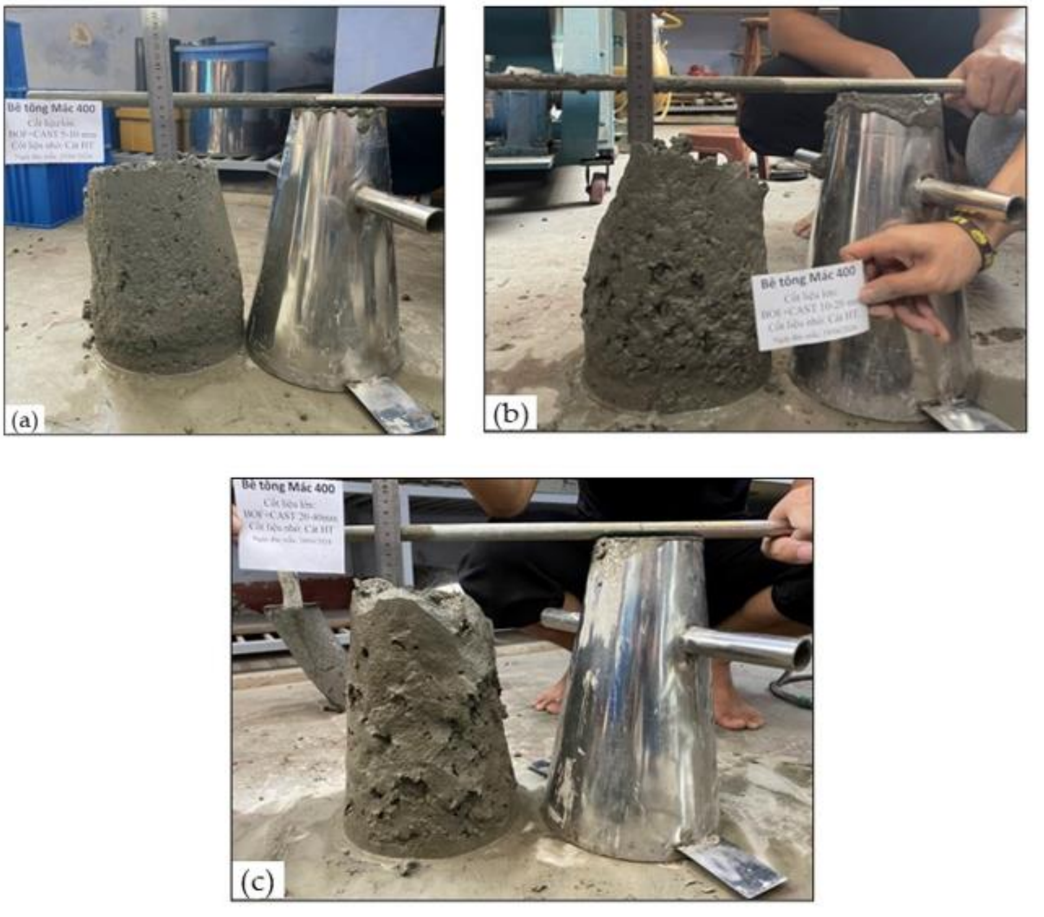

Fig. 3. Slump test of fresh concrete

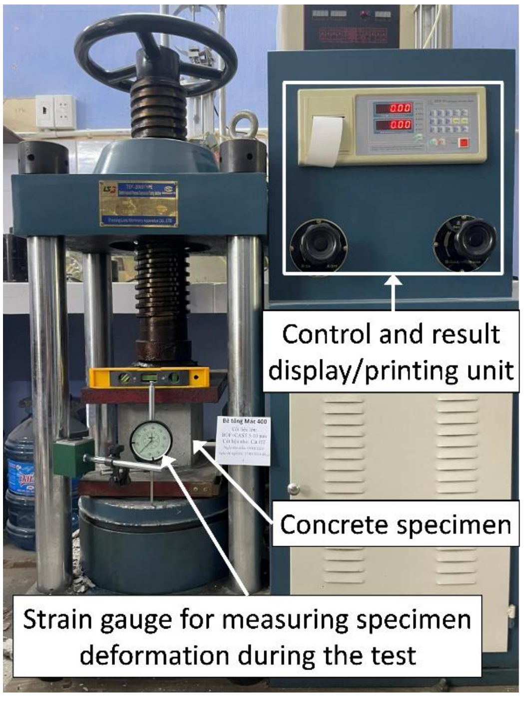

Fig. 4. Situation of the concrete specimen in the compression test apparatus

DOI: 10.26459/hueunijns.v134i1S-1.7855

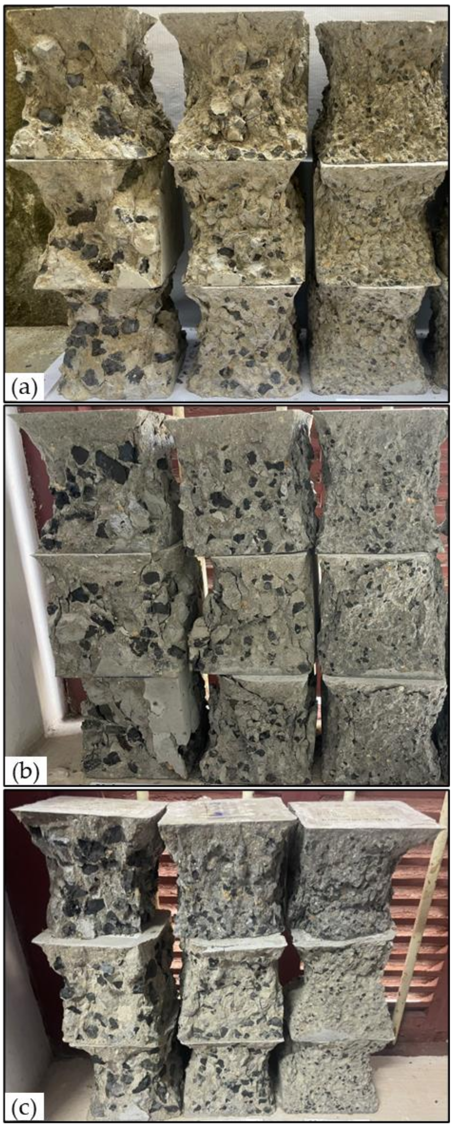

Fig. 5. Concrete specimens after compression test after (a) 3 days; (b) 7 days; (c) 28 days of curing (from left to right: BC2040, BC1020, and BC510 concrete, respectively)

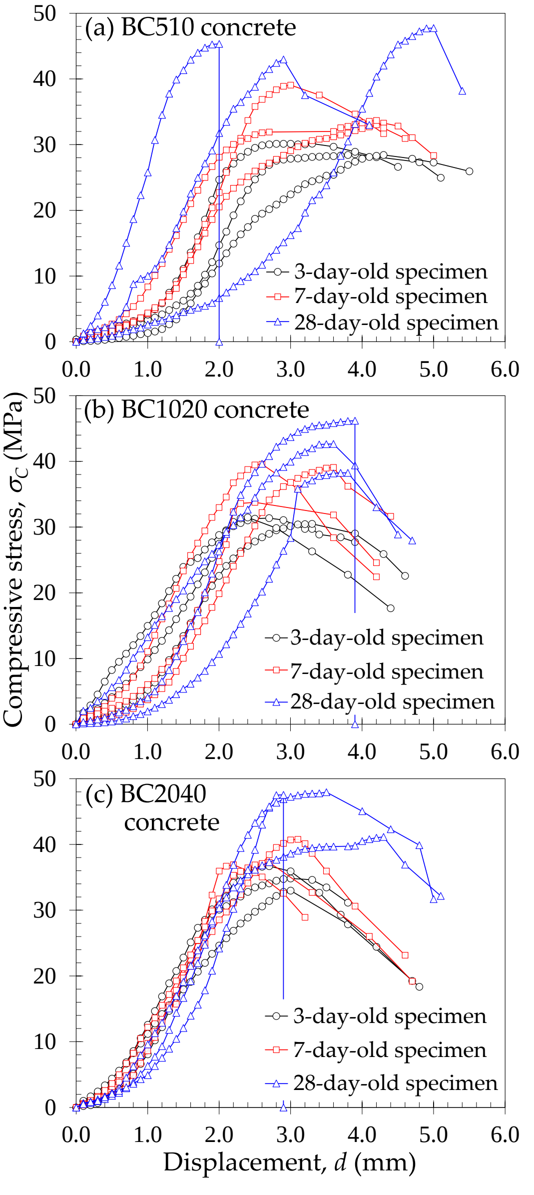

Fig. 6. Relationships between compressive stress and deformation of all concrete specimens during compression test

2.5 Properties of concrete incorporating Formosa SS mixtures as coarse aggregate

Since the deformation of concrete specimen under compression was continuously measured (at an increment of 0.1 mm) from the beginning of the test until the specimen reached its maximum strength and failure, the test results for each specimen are presented as the relationship between compressive stress (σ_C, MPa) and deformation (*d*, mm), as shown in Fig. 6.

The experimental results indicate a general increasing tendency of compressive strength (*R*, MPa), i.e., the maximum compressive stress at the point of failure, with curing duration. The deformation at the point of failure (d_{Rmax}, mm) is shown in Fig. 7 with the curing duration for each specimen. It can be observed that the d_{Rmax} of the BC510 concrete is greater and varies over a wider range (from 2 to 5 mm) compared with that of the BC1020 and BC2040 concretes. The fracture

Hue University Journal of Science: Natural Science
Vol. 134, No. 1S-1, 27–41, 2025 (Special Issue: IFGTM 2025) pISSN 1859-1388
eISSN 2615-9678

characteristics captured in Fig. 5 show that the extent of coarse aggregate failure, i.e., BC510, BC1020, and BC2040 mixtures, increases with curing duration. After 3 days of curing, failure predominantly occurred within the cementitious matrix and at the aggregate-matrix interface, leading to relatively consistent values of R and d_{Rmax} across all specimens. As the strength of the concrete increased (after 7 and 28 days), failure occurred both within the cementitious matrix and the aggregates, leading to greater differences in R and d_{Rmax}.

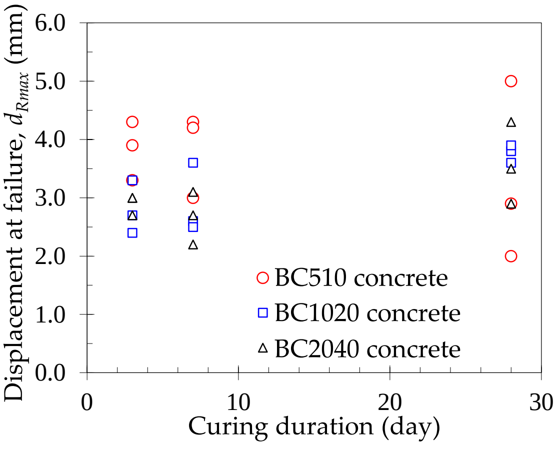

Fig. 7. Displacement at the point of failure of tested specimens

The results of compressive strength of all the concrete specimens over curing duration are shown in Fig. 8. In this figure, the dashed line indicates the expected compressive strength of grade 400 concrete after 3, 7, and 28 days based on empirical data, corresponding to approximately 40, 65, and 99% of the maximum strength (38.5 MPa), respectively. The average compressive strength after 3, 7, and 28 days (shown as solid lines in Fig. 8 and denoted as R_3, R_7, and R_{28}) for the BC510, BC1020, and BC2040 concrete sample are as follows: R_3 = 29.0, 31.1, and 34.8 MPa; R_7 = 35.3, 37.5, and 38.3 MPa; R_{28} = 45.4, 42.4, and 45.6 MPa, respectively. It can be observed that the compressive strength of all the concrete specimens exceeds the required strength for grade 400 concrete. After 28 days of curing, the average compressive strength of the three types of concrete in this study is between 110 and 118% of the required strength for grade 400 concrete. Furthermore, the variation in compressive strength between individual specimens and the average value ranges from 0 to 10.5%, thereby satisfying the accuracy requirement by TCVN 3118:2022.

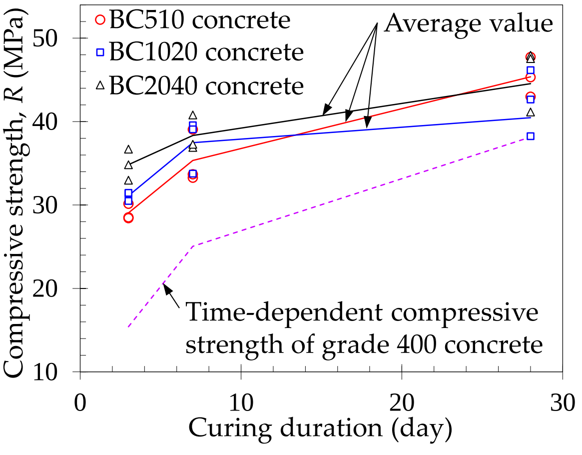

Fig. 8. Compressive strength over curing duration of all concrete specimens

Figure 9 illustrates the bulk density (ρ_C, t/m^3) of all the concrete specimens over the curing period. Conventional heavy-weight concrete typically has a bulk density in the range of 2.2–2.5 t/m^3, whereas the concretes incorporating coarse aggregates made from Formosa SS mixtures in this study exhibit ρ_C values ranging from 2.61 to 2.74 t/m^3. As such, they meet the requirements for special heavy-weight concrete ($\rho_C \geq 2.6$ t/m^3) [32]. According to Hudson's formula for the design and construction of seawave-breaking blocks, when the bulk density of concrete exceeds 1.13 times that of conventional concrete (i.e., 2.6/2.3), the required design weight of the wave-breaking block can decrease by half (a 0.53-fold decrease). Moreover, when the block dimensions remain constant, the wave-breaking safety factor of the block can be doubled (Uemura et al. 2015). With this advantage, SS has been used as aggregate in concrete for constructing coastal and seabed protection structures in developed countries, such as Tetrapod blocks and artificial blocks (e.g., Ferrform blocks, Artificial stones, Marine stones) in Japan [32, 33, 34, 35]. Therefore, the preliminary findings of this study highlight the potential for using Formosa SS in particular, and SS in Vietnam in general, as a concrete aggregate for the fabrication of seawave-breaking structures. This application is especially meaningful in the context of increasing SS production and associated environmental concerns, exhausting the natural construction materials, and the intensifying coastal and seabed erosion and damage to shoreline structures in Vietnam in the context of climate change and rising sea level conditions.

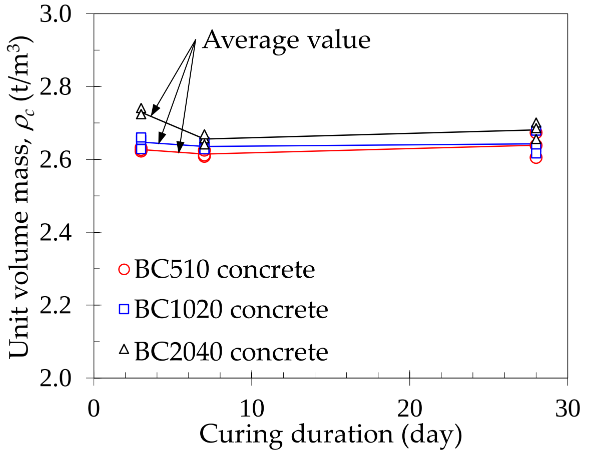

Fig. 9. Unit volume mass of all concrete specimens

3 Conclusions and remarks

Based on the experimental results of the grain size and the physico-mechanical properties of Formosa SSs and their mixtures, we designed three types of concrete incorporating coarse aggregates made from Formosa SS mixture, and they met the specifications for grade 400 concrete. The study yields the following main conclusions.

Since each type of Formosa SSs is divided into two different particle sizes, 0–10 mm and 0–40 mm, the grain size distribution of Formosa SSs (including BOF 040, BOF 010, CAST 040, and CAST 010) does not comply with the gradation requirements for fine and coarse aggregates for concrete according to TCVN 7570:2006. However, the physico-mechanical properties, such as bulk specific gravity, water absorption, crushing value, and Los Angeles abrasion value, meet the standards for recycled coarse aggregates of type I for concrete as specified in TCVN 11969:2018, and the crushed stone grade ranges from 120 to 140 according to TCVN 7570:2006. Therefore, these types of Formosa SS can be used as coarse aggregates for grade 400 concrete.

The BC510, BC1020, and BC2040 mixtures, consisting of particle-size ranges of 5–10 mm, 10–20 mm, and 20–40 mm, were obtained from the mixtures of the original Formosa SSs in proportions corresponding to the discharge ratios from the steel plant. These mixtures exhibit physico-mechanical properties that adapt the requirements for coarse aggregates in grade 400 concrete. The three types of concrete, incorporating BC510, BC1020, and BC2040 mixtures as coarse aggregates and Ha Tinh sand as fine aggregate, were proportioned at 1.1 times the dosage outlined in the Dispatch No. 1784. The average compressive strength of 28-day-old specimens ranges from 42.4 to 45.6 MPa, exceeding 110 to 118% of the required strength for grade 400 concrete.

With a bulk density of approximately 2.61–2.74 t/m^3, the concretes developed in this study satisfy the criteria for heavy-weight concrete, offering advantages when used for the construction of seawave-breaking structures. This application approach offers dual benefits, not only enhancing the functionality of coastal and seabed protection structures but also contributing to environmental sustainability by reducing SS disposal and decreasing the exploitation of increasingly scarce natural construction materials.

pISSN 1859-1388
eISSN 2615-9678

This approach has already demonstrated effectiveness in coastal protection applications in developed countries, such as Japan, and is therefore both relevant and urgently needed in the context of escalating coastal erosion and the deterioration of shoreline infrastructure in Vietnam.

This study remains exploratory and serves as an initial orientation, given that SS differs significantly in composition and properties from the natural aggregates. Moreover, the construction field typically involves the use of large volumes of materials, which are subject to various environmental factors and long service lifespans. Therefore, further research is necessary to evaluate the long-term properties of SS and concrete incorporated SS as aggregates under different environmental conditions and over extended periods of time.

Acknowledgement

This research was financially supported by the 2023 Provincial Research, Application, and Technology Development Program of Ha Tinh Province (Contract No. 563/QĐ-SKHCN). The authors would like to express their sincere gratitude for this support.

References

1. Nhan TT, Hai NLP, Thien DQ, Nhan NTT, Thuy NT, Thanh HT, et al. Study on the changes in the physico-mechanical properties with time and curing conditions for effective utilisations of granulated blast furnace slag in Ha Tinh. Ha Tinh: Report of Ha Tinh province level research project; 2022. 102 p.
2. U.S. Geological Survey (USGS). Mineral Commodity Summaries 2024. 2024; 216 p.
3. Gao J, Sha A, Wang Z, Tong Z, Liu Z. Utilisation of steel slag as aggregate in asphalt mixtures for micro wave deicing. Journal of Cleaner Production. 2017; 152:429-442.
4. Hasita S. Suddeepong A, Horpibulsuk S, Samingthong W, Arulrajah A, Chinkulkijniwat A. Properties of asphalt concrete using aggregates composed of limestone and steel slag blends. Journal of Materials in Civil Engineering. 2020; 32:6020007.
5. Yildirim I Z, Prezzi M. Geotechnical properties of fresh and aged basic oxygen furnace steel slag. Journal of Materials in Civil Engineering. 2015; 27(12):4015046.
6. Euroslag. Statistics 2018 [internet]. 2018 [cited 2025 May]. Duisburg-Rheinhausen: Euroslag. Available from: https://www.euroslag.com/products/statistics/statistics-2018/.
7. Liu J, Xu J, Liu Q, Wang S, Yu B. Steel Slag for Roadway Construction: A Review of Material Characteristics and Application Mechanisms. Journal of Materials in Civil Engineering. 2022; 34(6):03122001.
8. Vietnam Steel Association (VSA). Ho Chi Minh: VSA; 2001 [cited 2023 June]. Available from: http://vsa.com.vn/gioi-thieu/chuc-nang-nhiem-vu.
9. Nhan TT, Matsuda H, Thach TX, Vien ND, Thanh HT. Strength of granulated blast furnace slag during hydration reaction process. Lecture Notes in Civil Engineering. 2019;54:427-432.
10. The Ministry of Natural Resources and Environment (MONRE). Circular No. 02/2022/TT-BTNMT: Circular specifying the detailed implementation of certain provisions of the Environmental Protection Law. Ha Noi: The Ministry of Natural Resources and Environment (MONRE); 2022. 76 p.
11. The Ministry of Construction (MOC). Decision No. 430/QĐ-BXD: Technical guidelines on iron slag and steel slag for use as building materials. Ha Noi: Institute of Construction Materials; 2017. 25 pages.
12. The Ministry of Science and Technology (MOST). National Standard TCVN 13906:2024 – Steel slag using as backfill material. Ha Noi: The Ministry of Science and Technology (MOST); 2024. 15 p.
13. The Ministry of Science and Technology (MOST). National Standard TCVN 13908–2:2024 – Slag aggregate for concrete, Part 2: Electric arc furnace oxidizing slag aggregate. Ha Noi: The Ministry of Science and Technology (MOST); 2024. 21 p.
14. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-1:2006 –Aggregates for concrete and mortar - Test methods - Part 1:

Sampling. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 6 p.

15. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-2:2006 –Aggregates for concrete and mortar - Test methods - Part 2: Determination of partical size distribution. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 5 p.
16. The Ministry of Science and Technology (MOST). National Standard TCVN 7570:2006 –Aggregates for concrete and mortar - Specifications. Ha Noi: The Ministry of Science and Technology (MOST); 2006; 11 p.
17. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-4:2006 –Aggregates for concrete and mortar - Test methods - Part 4: Determination of apparent specific gravity, bulk specific gravity and water absorption. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 5 p.
18. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-6:2006 –Aggregates for concrete and mortar - Test methods - Part 6: Determination of bulk density and voids. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 4 p.
19. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-7:2006 –Aggregates for concrete and mortar - Test methods - Part 7: Determination of moisture. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 2 p.
20. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-11:2006 – Aggregates for concrete and mortar - Test methods - Part 11: Determination of crushing value (ACV) and softening coefficient of coarse aggregate. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 5 p.
21. The Ministry of Science and Technology (MOST). National Standard TCVN 7572-12:2006 – Aggregates for concrete and mortar - Test methods - Part 12: Determination of resistance to degradation of coarse aggregate by abration and impact in the Los Angeles machine. Ha Noi: The Ministry of Science and Technology (MOST); 2006. 3 p.
22. Gökalp İ, Uz VE, Saltan M, Tutumluer E. Technical and environmental evaluation of metallurgical slags as aggregate for sustainable pavement layer applications. Transportation Geotechnics. 2018;14:61-9.
23. The Ministry of Science and Technology (MOST). National Standard TCVN 11969:2018 –Recycled coarse aggregates for concrete. Ha Noi: The Ministry of Science and Technology (MOST); 2018. 14 p.
24. The Ministry of Construction (MOC). Official Dispatch No. 1776/BXD-VP: Publication of Construction Work Cost Estimation Norms – Construction Section. Ha Noi: The Ministry of Construction (MOC); 2007. 578 p.
25. The Ministry of Construction (MOC). Official Dispatch No. 1784/BXD-VP: Publication of Material Norms in Construction – Construction Section. Ha Noi: The Ministry of Construction (MOC); 2007. 205 p.
26. Pathak S, Choudhary R, Kumar A, Shukla SK. Evaluation of benefits of open-graded friction courses with basic oxygen furnace steel-slag aggregates for hilly and high-rainfall regions in India. Journal of Materials in Civil Engineering. 2020;32(12):4020356.
27. Yang C, Xie J, Wu S, Amirkhanian S, Wang Z, Song J, et al. Enhancement mechanism of induction heating on blending efficiency of RAP - virgin asphalt in steel slag recycled asphalt mixtures. Construction and Building Materials. 2021;269:121318.
28. Ameri M, Hesami S, Goli H. Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag. Construction and Building Materials. 2013;49;611-617.
29. The Ministry of Science and Technology (MOST). National Standard TCVN 3106:2022 – Fresh concrete - Test method for slump. Ha Noi: The Ministry of Science and Technology (MOST); 2022. 9 p.
30. The Ministry of Science and Technology (MOST). National Standard TCVN 3105:2022 – Fresh and hardened concrete - Sampling, making and curing of test specimens. Ha Noi: The Ministry of Science and Technology (MOST); 2022. 20 p.
31. The Ministry of Science and Technology (MOST). National Standard TCVN 3118:2022 – Hardened concrete - Test method for compressive strength. Ha Noi: The Ministry of Science and Technology (MOST); 2022. 13 p.

32. Uemura R, Akahane K, Maruyama M, Yokoo M, Sanazawa M, Tasaki T, et al. Overview of slag usage technology development at various works. Tokyo: Nippon Steel & Sumitomo Metal Technical Report; 2015. Report No.: 109/UDC669.1.054.82.

33. Toshiaki K, Chika K, Eiji K, Koichi T. Application of steelmaking slag to marine forest restoration. Tokyo: Nippon Steel & Sumitomo Metal Technical Report; 2015. Report No.: 109/UDC669.184.28:639. 64;79-84.

34. Toshiaki K, Chika K, Eiji K. Study on Environmental impact evaluation of steelmaking slag using in coastal sea area. Tokyo: Nippon Steel & Sumitomo Metal Technical Report; 2015. Report No.: 109/UDC669.054.82:639.25;85-89.

35. Kazuhiro H, Naoto T, Yoshiyuki K, Keisuke S. Overview of iron/steel slag application and development of new utilisation technologies. Tokyo: Nippon Steel & Sumitomo Metal Technical Report; 2015. Report No.: 109/UDC669.1.054.82;5-11.