International Journal of GEOMATE, March., 2024 Vol.26, Issue 115, pp.61-72
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.115.4112
Geotechnique, Construction Materials and Environment

NATURAL AGGREGATE SUBSTITUTION BY STEEL SLAG WASTE FOR CONCRETE MANUFACTURING

*Lahcen Es-samlali[1], Yassine El Haloui[2], Fahd Oudrhiri-Hassani[3], Abdelmonaim Tlidi[4], Abderrahman Bekri[5]

[1,3] LMPEQ Laboratory, Cadi Ayad University of Marrakech, Morocco;
[2]Sci Engineer Lab Energy, Chouaib Doukkali University of El Jadida, Morocco;
[4]Faculty of Law, Economics and Social Sciences of Tetouan, Abdelmalek Essadi University, Morocco;
[5]Industrial Analysis Laboratory, Hassan I University of Settat, Morocco;

*Corresponding Author, Received: 02 Sep. 2023, Revised: 25 Jan. 2024, Accepted: 26 Jan. 2024

ABSTRACT: The release of steel slag into the environment has substantial repercussions, simultaneously affecting both the ecosystem and the economy. Therefore, the management and recovery of this waste demand careful consideration. In the context of the circular economy, this study aims to explore the feasibility of utilizing steel slag waste as a substitute aggregate for natural coarse and fine aggregates in the production of high-quality concrete. Throughout this research, concrete mixtures were developed by varying natural aggregate substitution rates with steel slag waste at 0, 25, 50, 75, and 100%. Comprehensive tests, encompassing physical, mineralogical, chemical, and mechanical analyses, were conducted on the steel slag waste to ascertain its primary technical properties. In all mixtures incorporating steel slag waste, compressive strength tests consistently revealed values surpassing those of the reference concrete. Notably, there were improvements of approximately 12% for coarse aggregate substitution and 32% for sand substitution. Assessments of flexural strength at 7 and 28 days underscored the substantial positive influence of fine and coarse aggregate substitution, especially at a 50% fine aggregate replacement, contributing significantly to enhanced flexural strength compared to conventional concrete. Furthermore, laboratory examinations indicated that the 28-day compressive and flexural strength, as well as water absorption of concrete, increased with slag content, albeit at the expense of reduced workability. Ultimately, the findings demonstrate the effective utilization of slag as a replacement for natural aggregates, maintaining the compressive and flexural strength of the concrete.

Keywords: Concrete, Valorization, Compressive strength, Water absorption, Steel slag.

1. INTRODUCTION

Steel slag waste is considered a by-product of the steelmaking process [1]. The annual global production of steel slag is estimated to be within the range of 180 to 270 million tons [2]. On a local scale, the steel industry generates approximately 115,000 tons of steel slag per year. Typically, this waste is stored in landfills or designated storage facilities situated at or near manufacturing sites. Unfortunately, such storage practices have detrimental effects on the environment and pose risks to human health. Furthermore, the restoration of these landfills and stockpiles incurs significant costs [3,4,5,6].

In the steel industry, two primary types of by-products are generated: basic oxygen furnace (BOF) slag and electric arc furnace (EAF) slag [7]. The steelmaking process, involving the removal of impurities like sand, ash, and limestone, leads to the formation of steel slag on the molten metal's surface [8]. This slag is produced in oxygen furnaces or open-hearth furnaces commonly employed in steelmaking [9]. In contrast, the electric arc furnace is utilized to melt steel scrap and other materials within an electric furnace [10]. As explained by Rees [11], the electric arc furnace incorporates cold recycled metal, pig iron, and directly reduced iron. It introduces an electric arc to generate sufficient heat for melting the scrap and adds additional minerals, such as ferrous alloys, during fusion to achieve the desired chemical composition for the steel.

Concrete is the most sought-after material in the world and contributes to the growing consumption of natural resources [12]. Annually, approximately 40 billion tons of aggregates are produced globally to meet the demands of concrete production, as noted by Li [13]. According to Adesina, the demand for concrete is expected to surge significantly, leading to increased exploitation of natural aggregate deposits, considering aggregates constitute about 80% of the volume of concrete [14]. To mitigate environmental impact and safeguard natural resources, this study explored the feasibility of substituting conventional natural aggregates in concrete with aggregates derived from steel slag—an approach that aligns with scientific principles and promotes ecological sustainability.

The literature review highlights various applications for steel slag in concrete. According to Lai [15], replacing 50% of coarse aggregates and 30% of fine aggregates in conventional concrete with steel slag, an industrial by-product of steel manufacturing, resulted to substantial improvements in compressive strength and microstructure. This improvement not only contributed to environmental preservation and material durability but also offers an eco-friendly alternative for utilizing steel slag, representing 70% of the total steel slag production in mainland China. According to the findings of Cristina Barbosa [16], the incorporation of steel slag as an aggregate and mineral powder in concrete, while replacing conventional aggregates and commercial mineral additions, improved the durability of the material against chloride attack. This improvement is evidenced by reduced chloride penetration depth, decreased water absorption, and increased compressive and tensile strengths. These results underlined the technical viability of using steel slag concretes as promising options in the construction sector.

Singh [17] suggested that replacing 75% of coarse aggregates with LD slag in ordinary and high-performance concrete leads to enhanced mechanical properties and durability. This substitution resulted in a 7-9% increase in compressive strength, a 19-29% improvement in tensile strength, a 6-11% boost in flexural strength, a 7-16% rise in modulus of elasticity, along with reduced water absorption, abrasion, drying shrinkage, and captivity coefficient. This approach has made it possible not only to recycle steel waste currently destined for the landfill site, but also to prevent soil contamination. Andrade [18] advocated for the complete replacement of conventional aggregates with steel slag aggregates in ecological structural concretes, spanning three compressive strength classes. This substitution was carried out without chemical admixtures or with a PCE-based superplasticizer, resulting in superior mechanical performance, reflected in higher compressive strengths and better resistance to carbonation, with carbonation depths reduced by up to 60% compared with conventional concretes. These findings affirmed the technical feasibility of utilizing steel slag as an aggregate in cement-based composites.

Masilamani [19] has highlighted the superior performance of energy-optimized furnace steel slag when characterized by particle size, mechanical, physical, chemical, and microstructural analyses using scanning electron microscopy and X-ray diffraction. Additionally, the study of its shape through image treatment reveals improved performance compared to natural aggregates, validating its sustainable use as a substitute for coarse aggregates in concrete [19].

Olofinnade [20] demonstrated that substituting up to 40% of natural sand with steel slag in the production of interlocking concrete paving blocks enhances compressive and tensile strengths by 15% and 10%, respectively. This has demonstrated the potential for ecological and sustainable road infrastructure by recovering steel waste.

Shen [21] presented the concept of permeable concrete made from carbonated steel slag, which reduced material costs by 75.8%, used 100% solid waste, and absorbed around 100 kg/m^3 of CO_2. This environmentally friendly approach presented a promising alternative in the construction industry.

Abd El-Hakim's research [22] demonstrated that high-performance concrete mixtures containing different percentages of electric arc furnace steel slag coarse aggregate, coupled with steel slag powder (SSP) and silica fume (SF) as mineral filler, outperform natural aggregate mixtures. Optimal mechanical properties and performance are achieved with a concrete mixture featuring 50% EAFS.

Mohamad [23] supported the use of waste materials such as plastics, steel slag, and crushed rubber as partial replacements for aggregates in the manufacturing of concrete paving blocks. Studies indicate that paving blocks with up to 50% steel slag exhibit superior compressive strength compared to conventional paving blocks.

Pham [24] explored the addition of 20% and 40% autoclaved aerated concrete grains to recycled concrete and crushed clay bricks. The results show a decrease in gas diffusivity and air permeability, with previous models effectively predicting these properties for the tested mixes.

This literature review showed a global trend towards studying the use of steel slag in concrete, supported by research demonstrating improved properties over conventional concrete. However, there is a lack of in-depth local research on this subject. These studies reviewed support the use of steel slag, an industrial waste product, as a partial or total replacement for natural aggregates in standard structural concretes not requiring high performance. This could significantly reduce the environmental impact of natural resource extraction and improve concrete properties. However, further local research is essential to confirm the technical feasibility of sustainably replacing natural aggregates with steel slag in the typical concretes used in this region.

This research has enabled an in-depth study to be undertaken to assess the possibility of recycling steel slag waste for fine concrete production. Fine concrete has a variety of applications in the construction industry, including architectural cladding, floor slabs, prefabricated facades, thin floors and high-performance structures, providing both aesthetic and functional enhancements for modern building projects. The steel slag was carefully prepared and graded into fine (0-5 mm) and coarse (5-15 mm) aggregates. These recycled aggregates then replaced natural sand (0-5 mm) and coarse aggregate (5-15 mm) respectively in the composition of concrete. Four levels of substitution were selected to study the progressive impact of this substitution: 25%, 50%, 75%, and 100%. All concrete mixes were prepared according to Moroccan standards using ordinary Portland cement to ensure compliance with local construction practices. Our study aims is to compare the mechanical strengths between conventional concrete mixes with those incorporating steel slag, providing local evidence of the feasibility and effectiveness of this sustainable substitution.

2. RESEARCH SIGNIFICANCE

This research project evaluated the potential of using aggregates from Moroccan-produced steel slag in concrete to identify ecological and economic benefits. By promoting the circular economy and green construction, it offers a sustainable alternative to natural aggregates, reducing the carbon footprint and preserving natural resources. Promising results could mark a significant innovation in local construction by promoting more sustainable practices and offering builders a wider perspective on the innovative use of steelworks slag. This approach not only aims to protect the environment but also seeks to deliver significant economic benefits to the industry.

3. MATERIALS AND METHODS

3.1 Raw Materials

The quality and behavior of a concrete mix are mainly determined by its constituents, namely cement, aggregates, water and air voids. As the Moroccan Concrete Industry Association [25] points out, the typical composition of concrete is made up of a solid phase representing 70 to 90% of the mass of a cubic meter. The variation in water content is generally between 5.5 and 9%, with hydraulic cement accounting for 6 to 18% of the total mass of dry constituent.

In this study, a Portland cement called CPJ 45 was used as a hydraulic binder of the concrete mixtures. The technical properties of the selected cement include a 32.5 MPa compressive strength at 28 days, an initial setting time of 205 minutes, a final setting time of 301 minutes, and a SO_3 content of 2.5%. As for the water source, a drinking water tap was utilized to ensure water quality. Consistency was maintained across all mixtures by keeping the water-to-cement (W/C) ratio constant, and the aggregates were utilized in a dry hydrous state.

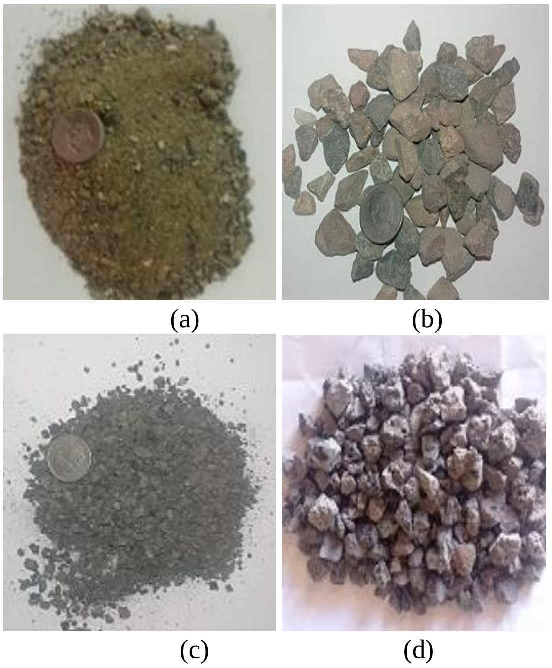

Fig.1 a) Natural sand (NS), b) natural crushed aggregate (NCA), c) Steel slag fine sand (SSf), d) Steel Slag aggregate (SSA).

Natural sand (NS) with a fraction of 0-5 mm and natural crushed limestone (NCA) aggregates with a fraction of 5-15 mm were used as aggregates for conventional concrete (reference concrete). These aggregates were supplied by a local distributor. Fig.1-a and 1-b illustrate the natural aggregates used in our study.

The steel slag (SS) aggregates were collected from the landfills of EL JORF SFAR EL JADIDA city, Morocco. Various samples of SS waste were taken from different positions of the SS landfills (top, middle, and bottom positions). The collected SS samples were then mixed, homogenized, and reduced to smaller samples. It should be mentioned that the particle size curve of the SS aggregates (of the prepared SS sample) indicated that 45% of its fraction consists of sizes smaller than 5 mm, and 35% of its fraction includes sizes between 5-15 mm. Therefore, no crushing process was conducted on SS aggregates. 5- and 15-mm sieves were used to separate 0-5 mm and 5-15 mm fractions to obtain SS sand and coarse aggregates (see Fig. 1-c and Fig. 1-d) that will be used for SS concrete manufacturing.

3.2 Research Methodology

This article explores the feasibility of substituting natural aggregates with steel slag waste in concrete production. To achieve this objective, a thorough characterization of all raw materials was carried out.

Various concrete mixes were then formulated, including the reference concrete (C0, with 0% steel slag aggregates), as well as concretes with progressive replacements of natural coarse aggregates and natural sand by steel slag equivalents. Concrete mix formulations are as follows:

- Reference concrete: C0 (0% SSA) ;
- Replacement of coarse natural aggregates by coarse steel slag aggregates: C1 (25% SSA), C2 (50% SSA), C3 (75% SSA), and C4 (100% SSA);
- Replacement of natural sand by steel slag sand: CS1 (25% SSf), CS2 (50% SSf), CS3 (75% SSf), and CS4 (100% SSf).

To assess the recovery potential of steel slag waste, various laboratory tests were carried out, including measurements of density, slump, water absorption and mechanical properties.

3.3 Concrete Formulation

The concrete mix design was determined using the DREUX-GORISSE method [26]. This method is used to guarantee the mechanical strength of the material during construction, as well as the workability and durability of the concrete. It maximizes the compactness of the granular skeleton in order to improve the workability of the concrete, reduce the amount of cement paste to be used, and minimize the cost of the concrete.

In this study, we worked with C25 concrete. It is worth mentioning that C25 means that the compressive strength is at least 25 MPa after 28 days of manufacture. To apply the DREUX-GORISSE method, the first step is to calculate the desired compressive strength of the concrete using Eq. (1), then determine the cement/water ratio (C/w) using Eq. (2). The cement dosage C is then estimated on the basis of the concrete workability curves.

$$f_{cm} = 1.15\, f_{c28} \quad (1)$$

$$C/w = \frac{f_{cm}}{GF_{CE}} + 0.5 \quad (2)$$

Where, f_{cm} is the desired compressive strength of the concrete, f_{c28} is the theoretical compressive strength (25 MPa) of the concrete, F_{CE} is the average compressive strength of the cement at 28 days, and G is a coefficient related to the quality and maximum size of the aggregates. Table 1 shows the various assumptions used to apply the DREUX GORISSE method.

Table 1 Assumptions of concrete formulation.

Concrete data	
$fc28$ (MPa)	25
Consistence	plastic
Vibration	Normal vibration
Cement data:	
Compressive strength at 28 days (MPa)	32.5
Real density (g/cm3)	3.1
Aggregate data	
Quality of aggregate	Current (G=0.55)
Moisture	Dry
Aggregate form	Crushed
Maximum size	15 mm

3.4 Tests Method

The chemical structure of the aggregates was determined using X-ray fluorescence (XRF) analysis, while microstructural analysis was conducted through scanning electron microscopy (SEM). The structure and composition of the materials were further analyzed using X-ray diffraction (XRD).

Additionally, the raw materials underwent a series of tests to determine their physical and mechanical properties. Particle size distribution for each material was determined in accordance with NF P18-560 standard. The modulus of fineness was calculated following NF P 18-540 standard. Relative density (specific weight) was determined according to NF EN 1097-3 standard. Aggregates' hardness was assessed through LOS ANGELES and MDE tests, complying with NF P 18-572 and NF P18-573 standards, respectively. Sand cleanliness was measured following the NF P 18-597 standard. Fresh concrete mixes were prepared, and slump (workability) measurements were taken in accordance with NF EN 206-1 standard.

The fresh density of all mixes was measured following NF EN 12350-6 standard. These fresh concrete mixes were then poured into normalized cubic molds (150 × 150 × 150 mm and 150 × 150 × 560 mm) for subsequent mechanical testing. After 24 hours, demolding was conducted, and specimens were cured in a humid chamber at controlled humidity and temperature (> 95% and 20 ± 2 ◦C) to the required age.

Following curing (7 and 28 days), concrete samples were subjected to mechanical tests to assess compressive and flexural strengths, adhering to NF EN 12390-2 and NF EN 12390-5 standards, respectively.

Water absorption by immersion was determined in accordance with NF EN 1097-6 standard, using 100 mm cubic test specimens prepared for each concrete mix at the age of 28 days. These specimens were oven-dried at 105 ◦C for 72 h, then weighed (Wd) and immersed in a tank of water for 24 h. Additionally, the weight of the samples after immersion (Ww) was measured, and the water absorption rate was calculated as a progression of the dry sample mass, as shown in Eq. (3).

$$W_A(\%) = \frac{Ww-Wd}{Wd} \times 100 \quad (3)$$

Where, (W_A) is the water absorption rate, (W_w) is the weight of the wet specimen, and (W_d) is the weight of the dry.

4. RESULTS AND DISCUSSION

4.1 Chemical, Mineralogical, and Morphological Properties of Steel Slag

X-ray diffraction was used to carry out a mineralogical analysis of the steel slag powder, as described in our previous study [27]. The diffraction patterns show a highly crystalline nature, the predominant metallic phases in the steel slag are: $CaSiO_3$, $CaCO_3$, MgO, Ca_2FeAlO_5, $Ca_2Al(AlSi)O_7$, $Ca_3Mg(SiO_4)_2$, Ca_2SiO_4. Regarding the mineralogical composition.

Table 2 showed that the principal crystalline mineral phases contained in the metallic slag are calcium carbonate ($CaCO_3$) and silicate (Ca_2SiO_4) (% by weight = 62.7%). In addition, Iron Silicon Oxide and Calcium Aluminum Silicate represent for about 20%. The mineralogical compositions of these samples showed significant similarities with those of the Barra study [28].

Table 2 Mineralogical composition of steal slag.

Mineralogical element	Chemical formula	wt.%
Calcium Carbonate	$CaCO_3$	41.2
Calcium Silicate (Larnite)	Ca_2SiO_4	21.5
Iron Silicon Oxide	$Fe_{2.95}Si_{0.05}O_4$	10.8
Calcium Aluminum Silicate (Gehlenite)	$Ca_2(Al(AlSi) O_7)$	9.4
Calcium Silicate (Wollastonite)	$CaSiO_3$	6.2
Calcium Magnesium Silicate (Merwinite)	$Ca_3Mg(SiO_4)_2$	4.5
Calcium Iron Aluminum Oxide (Brownmillerite)	Ca_2FeAlO_5	4.5
Magnesium Oxide (Periclase)	MgO	2

X-ray fluorescence spectrometry was used to carry out the chemical analysis of the steel slag. As shown in Table 3, the main chemical constituents of steel slag are the oxides CaO, SiO_2, Fe_2O_3, Al_2O_3, MgO and FeO.

Numerous studies confirm that the above-mentioned oxides make up the bulk of the oxides present in steel slag [29]. Also, the proportion of these oxides can vary depending on the type of furnace used and the raw materials used in steelmaking.

Table 3 Chemical composition of steel slag.

Oxides	Chemical composition (%)
Al_2O_3	7.59
MgO	4.15
SiO_2	15.31
P_2O_5	0.45
Na_2O	1.05
KO_2	0.05
CaO	29.31
TiO_2	0.60
SO_3	1.76
MnO	3.78
Fe_2O_3	31.23
LOI	2.70

In terms of morphology and texture, Fig. 2 showed that the steel slag aggregates are irregular in shape, with pronounced angles and reduced sphericity, ranging from sub-rounded to sub-angular. Scanning electron microscope (SEM) analysis of the slag particles revealed a very coarse surface texture and a porous structure [27].

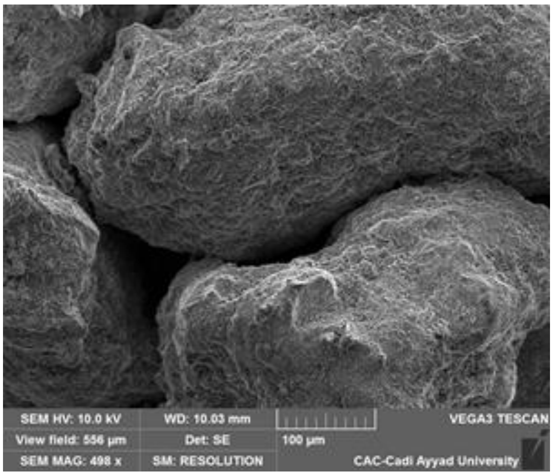

Fig.2 SEM analysis of steel slag.

4.2 Physical and Mechanical Proprieties of Materials

Fig. 3 illustrated the grading curves of the raw materials (NS: natural sand, NCA: natural coarse aggregate, SSf: steel slag sand, and SSA: steel slag coarse aggregate). Natural sand (NS) contains more fines than steel slag sand (SSf). In addition, NCA and SSA have practically the same trend of the particle size curve.

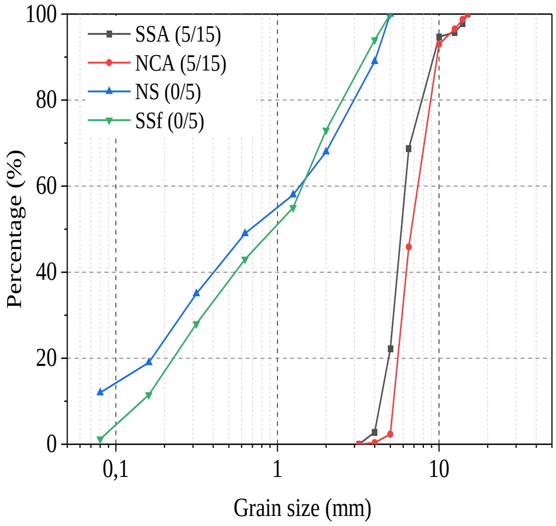

Fig.3 Particle size distribution of the materials used.

Table 4 Mechanical and physical properties of the aggregates used.

Materials	NS	SSf	NCA	SSA	Requirement
Specific density (t/m^3)	2.64	3.26	2.66	3.40	--
Bulk density (t/m^3)	1.61	2.05	1.44	1.90	--
Sand Equivalent (%)	67	84	--	--	> 60 %
Sand fineness modulus	2.71	2.89	--	--	1.8 < FM < 3.2
Water absorption (%)	1.5	2.3	1.1	1.2	< 2.5 %
Los-Angelos (%)	--	--	28	14	< 30 %
Micro-Deval (%)	--	--	21	9	< 30 %

Table 4 showed the physical and mechanical behavior characteristics of the aggregates used. It can be revealed that the density (specific and bulk) of steel slag aggregates is higher than that of natural aggregates, which can be explained by the presence of iron oxides [30]. Also, the mechanical properties, obtained from Los-ANGELOS and MDE tests, showed that the steel slag aggregates present higher hardness in comparison to that of natural aggregate, which corresponds to Hussain study [31].

Moreover, the sand equivalent results indicated that steel slag sand (SSf) is very clean in comparison with natural sand. In addition, both sands SSf and NS present normal sand fineness modulus (ranging between 1.8 -3.2). It was revealed also that the water absorption rate of steel slag aggregates is higher than that of natural aggregate. So, it will consume higher quantity of water during the formulation.

4.3 Mix Design

For the mix design, the DREUX-GORISSE method was used. In addition, the data in Table 1 were used as a basis for the theoretical concrete mix design. The C/E ratio was calculated using Eq. (2) (C/E = 1.70).

With regard to the desired consistency of the concrete, the latter is plastic in nature. Consequently, the cement dosage was 350 kg/m^3 and the water dosage 208 l/m^3. Finally, using the DREUX-GORISSE graphical method, aggregate quantities were calculated and presented in Table 5.

Table 5 Concrete design results of all mixtures in kg/m^3.

Sample	NS (0/5)	SSf (0/5)	NCA (5/15)	SSA (5/15)
C0	801.3		986.9	0
C1	801.3		740.2	315.6
C2	801.3	--	493.4	631.2
C3	801.3		246.7	946.8
C4	801.3		0	1262.4
CS1	601.0	213.3	986.9	
CS2	400.7	426.6	986.9	--
CS3	200.3	639.9	986.9	
CS4	0	853.1	986.9	

4.4 Mechanical and Physical Properties of Concrete

4.4.1 Density

It was observed that the density of conventional concrete was equal to 2271 kg/m^3 and that of concrete containing a total replacement of coarse aggregate SSA and sand SSf was 2698 and 2564 kg/m^3, respectively. Thus, the high density of steel slag compared to natural aggregates results in high-density concrete, as shown in Fig. 4.

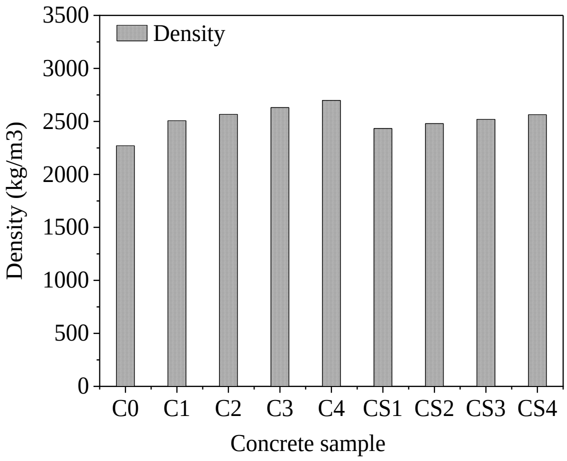

Fig. 4 Density values of concrete samples.

In addition, it should be noted that the high density of concrete with SSA (and SSf) is advantageous for retaining structures where the high weight of the concrete can increase stability, as well as for basements or offshore structures where the weight can improve buoyancy resistance [15]. As Baalamurugan's study of slag-containing concrete showed, a high-strength, high-density composite material attenuates gamma rays better than conventional concrete, helping to reduce radiation [32].

4.4.2 Workability

The workability of the mixes was calculated using the slump test. Fig. 5 and Fig. 6 show the results of the slump test on concrete mixtures, depending on the percentage of steelworks slag used as aggregate or sand.

Fig.5 Illustration of slump measurement.

Despite a very high cement/water ratio of 1.70, the workability of the concrete is poor if we replace natural aggregates with steelworks slag. Conventional concrete is plastic, then depending on the slag content, the concrete becomes firmer. The slump decreases from 79 to 51 mm for concrete containing coarse steel slag and to 58 mm for concrete containing fine slag. In addition, the steel slag aggregates with higher specific gravity, relative density and absorption properties than natural aggregates, reduce workability performance [33]. This can be explained by the angular, rough surface of steel slag aggregates compared with natural aggregates [34]. Replacing sand with slag leads to a reduction in fine grains, which in turn results in poor workability of the concrete used. For this reason, researchers generally introduce water reducers into concrete to improve workability, due to the high water absorption of steel slag aggregates [35].

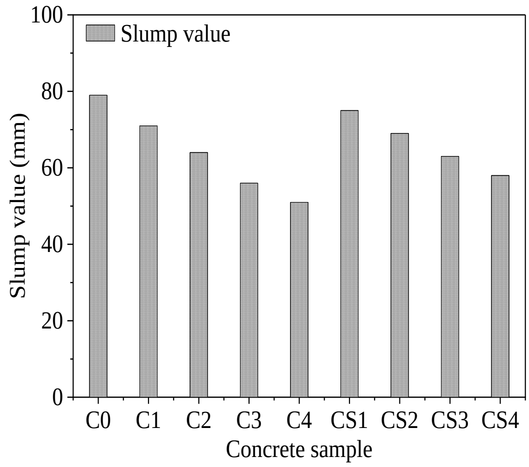

Fig.6 Slump values of concrete samples.

Fig.7 Rupture pattern of concrete specimens under compression.

4.4.3 Compressive strength Test

The compressive strength test was carried out on all the mixes designed as shown in Fig. 7. The results obtained are shown in Fig. 8 and the relative difference between the reference mixes and the waste mixes is shown in Fig. 9.

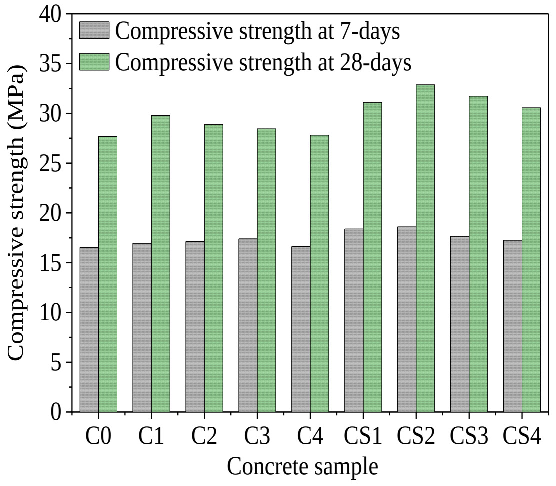

Fig.8 Compressive strength of concrete mixes at 7 and 28 days.

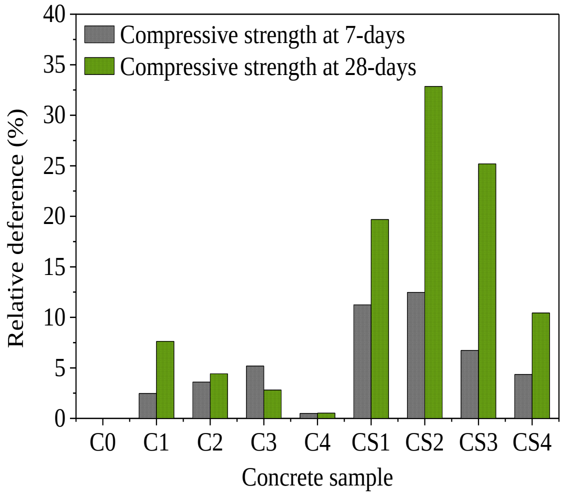

Fig.9 Relative deference of compressive strength at 7 and 28 days.

It was found that, irrespective of the substitution rate and the age of the test, the compressive strength of all the mixes containing steel slag waste is higher than that of the reference concrete. The latter has compressive strengths of 18 and 27.5 MPa at 7 and 28 days, respectively.

In the case of natural coarse aggregate substitution, the highest strength value (29 MPa) was detected at 28 days for a steel slag content of 25%. This strength value decreased as the steel slag content increases, reaching 28 MPa for total coarse aggregate substitution. In fact, the improvement in compressive strength is around 12 for 25% replacement of coarse aggregate.

The substitution of natural sand significantly improved compressive strength compared with the substitution of coarse aggregate. The highest strength value (36 MPa) was obtained for a steel slag content of 50%. The improvement in compressive strength in this case is around 32%.

These results are consistent with previous studies which showed that the higher unit weight and crushing strength of steel slag improves the compressive strength and durability of concrete, while the porous and tough outer texture of steel slag promotes cohesion between the mortar phase and coarse aggregates, justifying the enhanced results obtained with steel slag concrete compared to conventional concrete [36]. The inclusion of fine slag aggregate improved the cleanliness of the sand and is a fundamental factor influencing the mechanical performance of the concrete. This study showed that an artificial neural network model based on various parameters such as cement dosage and curing time could accurately determine the increase in compressive strength of concrete incorporating steel slag as a partial replacement for aggregate recycling of steel slag aggregate in Portland cement concrete [37].

4.4.4 Flexural strength test

The flexural strength of conventional concrete at 7 and 28 days is an important indicator of the durability and strength of concrete. As shown in Fig. 10 and Fig. 11, the flexural strength of conventional concrete at 7 and 28 days is 1.8 and 2.9 MPa, respectively. The use of fine aggregates in concrete mixtures can significantly increase flexural strength at 7 and 28 days. For example, mixtures containing 25 and 50% fine aggregate can increase the 28-day flexural strength to 3.2 and 3.4 MPa, respectively.

In addition, the use of coarse aggregate in concrete mixtures also improves flexural strength. Mixtures containing 75% coarse aggregate can achieve higher flexural strength than conventional concrete, up to 3.1 MPa. Thus, the use of both fine and coarse aggregates can improve the flexural strength of concrete mixtures. This study justifies the results obtained, namely that replacing 75% of the natural aggregates with LD slag as aggregate in normal and high performance Metakaolin concrete improves its flexural strength by 6 to 11% compared with control concrete [17].

In the same context, this study shows that the use of steel slag in the total replacement of natural aggregates in high-strength concretes reinforced with steel fibers resulted in a flexural strength of 7.9 MPa at 20°C, decreasing to 4.5 MPa at 800°C, as well as an increase in fracture energy and displacement at fracture when subjected to elevated temperatures [38].

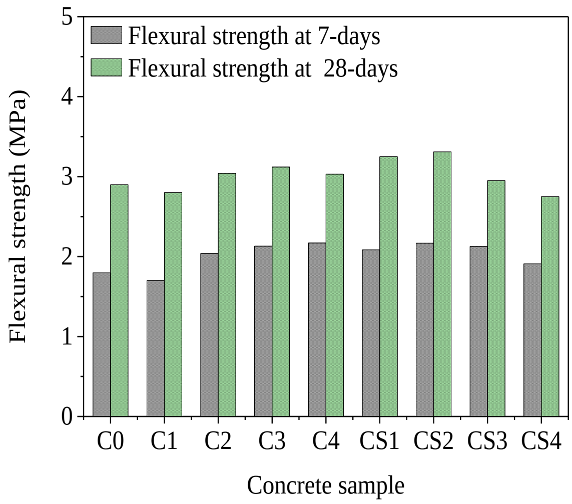

Fig.10 Flexure strength of concrete mixes types at 7 and 28 days.

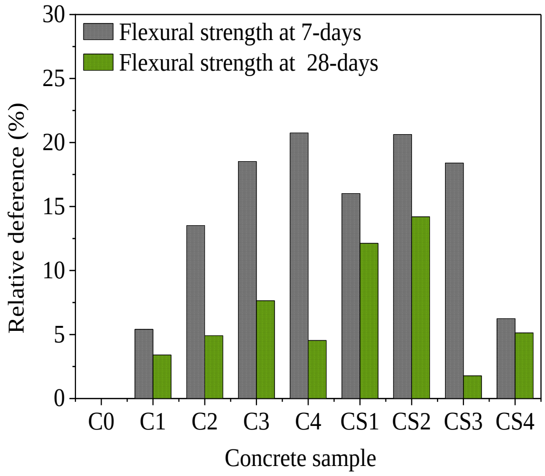

Fig.11 Relative deference of flexure strength at 7 and 28 days.

4.4.5 Water absorption

The long-term performance of concrete depends on interactions with the environment in which it is used, where the penetration of harmful substances has an impact on concrete quality, which can only be controlled by the permeability properties of concrete near the surface [39]. Specifically, the transport capacities of water and dissolved chloride ions in unsaturated concrete are largely related to the amount of water in the pores of the concrete, in combination with the convective action caused by water absorption [40]. Water absorption (WA), both of which depend on the number and size of pores [41]. the surface of steel slag aggregate (SSA) is porous and rough, explaining the high level of water absorption by SSA at the micro level [42].

It is observed in Fig. 12 that the 28-day water absorption rate of the concretes increases with the steel slag content. Thus, the absorption rate of the conventional concrete is 1.17 and the concretes CS4 (100% replacement of fine aggregates) and C4 (100% replacement of coarse aggregates) are 2.63 and 3.81%, respectively. It can be concluded that the addition of coarse slag aggregates has a significant influence on water absorption compared to fine aggregates and this can be explained by the porous texture of steel slag.

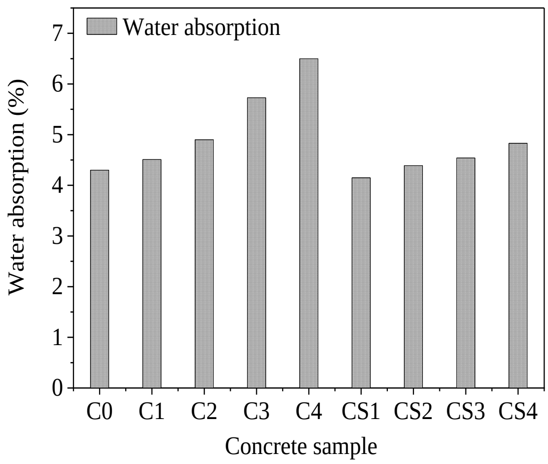

Fig.12 Water absorption of concrete samples.

4.4.6 Microstructural characterization of mixes

In this section, the microstructural characterization of the mix's microstructure, both for natural and steel slag mixes, was investigated to examine the interfacial transition zone (ITZ) between cement paste and aggregate. Reference concrete (C0) and steel slag concrete (CS4) were evaluated using an SEM device after 90 days of curing.

The microstructure and ITZ of C0 and CS4 are depicted in Fig. 13. As observed in Fig. 14, the appearance of micro-cracks and pores formed around the interfacial transition zone is different, suggesting a difference in mechanical performance between steel slag concrete and conventional concrete. This aligns with the results showing that the mechanical performance of concrete with steel slag is significantly higher than that of natural concrete.

The presence of aggregated steel slag indicates that the improvement in the interface transition zone (ITZ) is the main reason for the improved performance [43]. It is clear that the interfacial transition zone of steel slag concrete is more homogeneous than the interfacial transition zone of conventional concrete. Indeed, the dense interfacial transition zone with fewer micro-cracks and more hydration products in steel slag concrete is attributed to the low heat of hydration and release of water from the slag, leading to beneficial secondary hydration [44,45].

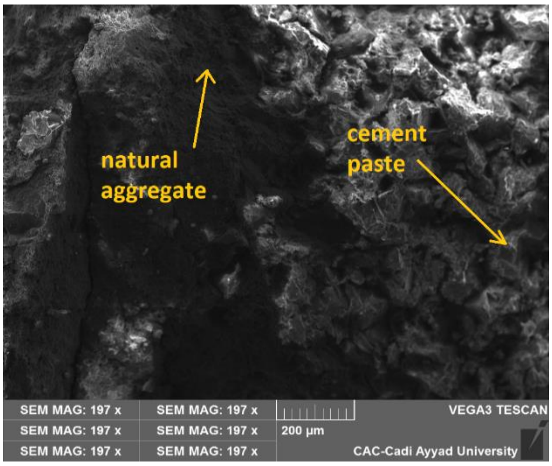

Fig.13 SEM images of the two types of concrete after 28 days of curing of the conventional concrete.

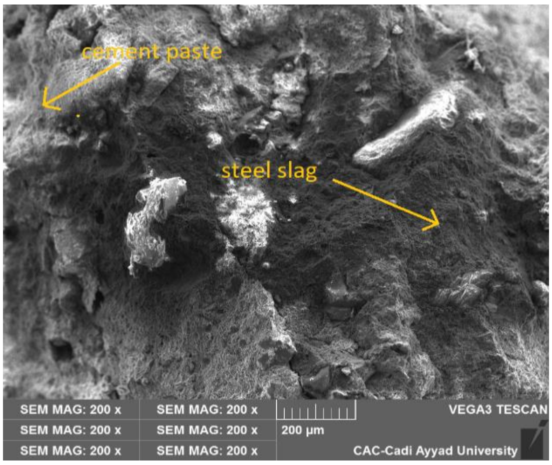

Fig.14 SEM images of the two types of concrete after 28 days of curing of concrete made of steel slag.

5. CONCLUSIONS

Despite the superior physical and geotechnical properties of steel slag as an aggregate for concrete, its utilization remains restricted, primarily due to its LOS ANGELOS coefficients and remarkably high sand equivalent value in comparison to natural aggregates. Our approach, therefore, endeavors to integrate slag aggregates into concrete to substitute natural aggregates. In this study, concrete mixtures were developed, incorporating steel slag aggregates at varying proportions of 0, 25, 50, 75, and 100%, and subjected to thorough testing. The primary outcomes of this investigation are outlined as follows:

- The integration of steel slag aggregates into concrete production proves to be highly successful. Utilizing steel slag aggregates in concrete yields superior mechanical performance.
- The optimal steel slag content is advised to be 50%. This recommendation of incorporating 50% steel slag results in maximum strength with a marginal reduction in workability, approximately around 11%.
- Concrete mixes incorporating steel slag aggregates exhibit slightly lower workability compared to the reference concrete. If maintaining workability is a priority, it is recommended to use cementitious admixtures, such as superplasticizers.
- Substituting natural sand with steel slag sand is deemed potentially more cost-effective than replacing natural coarse aggregates with steel slag aggregates. This is attributed to the higher manufacturing costs associated with natural sand in comparison to gravel.

6. ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest: The authors declare no conflict of interest.

7. REFERENCES

[1] Shi C., Steel Slag—Its Production, Processing, Characteristics, and Cementitious Properties. Journal of materials in civil engineering vol. 16, Issue 3, 2004, pp.230-236.

[2] Survey U. S. G., Iron and steel slag statitics, Miner. Commod. Summ. Slag-Iron Steel Washington, vol. 703, Issue 14, 2021, pp.86–87.

[3] Chaiyasarn K., Poovarodom N., Ejaz A., Ng A. W., Hussain Q., Saingam P., and Joyklad P., Influence of natural fiber rope wrapping techniques on the compressive response of recycled aggregate concrete circular columns. Results in Engineering, vol. 19, 2023 pp.101-291.

[4] Yooprasertchai E., Bahrami A., Saingam P., Hussain Q., Ejaz A., and Joyklad P., Incorporation of Steel Fibers to Enhance Performance of Sustainable Concrete Made with Waste Brick Aggregates: Experimental and Regression-Based Approaches. Buildings, vol. 13, Issue 11, 2023, pp.1311-2820.

[5] Joyklad P., Saingam P., Ali N., Ejaz A., Hussain Q., Khan K., and Chaiyasarn K., Low-Cost Fiber Chopped Strand Mat Composites for Compressive Stress and Strain Enhancement of Concrete Made with Brick Waste Aggregates. Polymers (Basel), vol. 14, Issue 21, 2022, pp. 1421-4714.

[6] Saingam P., Ejaz A., Ali N., Nawaz A., Hussain Q., and Joyklad P., Prediction of Stress–Strain Curves for HFRP Composite Confined Brick Aggregate Concrete under Axial Load. Polymers

(Basel), vol. 15, Issue 4, 2023, pp.844-868.

[7] Motz G. J. H., Products of steel slags an opportunity to save natural resources. Waste management. vol. 21, Issue 3, 2001, pp.285-293.

[8] Eisele T. C., Kawatra S. K., and Ripke S. J., Water chemistry effects in iron ore concentrate agglomeration feed. Mineral Processing and Extractive Metallurgy Review, vol. 26, Issue 3-4, 2005, pp.295-305.

[9] Lepadatu A. M., Stoica T., Stavarache I., Teodorescu V. S., Buca D., and Ciurea M. L., Dense Ge nanocrystal layers embedded in oxide obtained by controlling the diffusion-crystallization process. Journal of nanoparticle research, vol. 15, 2013, pp.1-12.

[10] Rey O., L'Idolâtrie de la vie. A Book: Gallimard, vol. 15, 2020, pp.1-56.

[11] Rees F., Mobilité des métaux dans les systèmes sol-plante-biochar. Université de Lorraine, 2014, pp.1-316.

[12] Mohamad N., Muthusamy K., Embong R., Kusbiantoro A., and Hashim M. H., Environmental impact of cement production and Solutions: A review Materials Today: Proceedings, vol. 48, 2022, pp.741-746.

[13] Li N. and Unluer C., A comparative study of ethylenediamine tetraacetic acid induced gas-solid and liquid-solid accelerated carbonation for enhancement of steel slag aggregates. Construction and Building Materials, 2023, vol. 400, pp.132-539.

[14] Adesina A., Properties of alkali activated slag concrete incorporating waste materials as aggregate: A review. Materials Science Forum, vol. 967, 2019, pp.214–220.

[15] Lai M. H., Zou J., Yao B., Ho J. C. M., Zhuang X., and Wang Q., Improving mechanical behavior and microstructure of concrete by using BOF steel slag aggregate. Construction and Building Materials, vol. 277, 2021, pp.122-269.

[16] Costa L. C. B., Nogueira M. A., Andrade H. D., de Carvalho J. M. F., da Fonseca F. P., Brigolini G. J., and Peixoto R. A. F. , Mechanical and durability performance of concretes produced with steel slag aggregate and mineral admixtures. Construction and Building Materials, vol. 318, 2021, pp.126-152.

[17] Singh P., Roy A. B. D., and Singh H., Mechanical and durability properties of concrete incorporating weathered coarse Linz-Donawitz (LD) steel slag. J Journal of Building Engineering, vol. 61, 2022, pp.105-301.

[18] Andrade H. D., de Carvalho J. M. F., Costa L. C. B., Elói F. P. da F., Silva K. D. do C., and Peixoto R. A. F., Mechanical performance and resistance to carbonation of steel slag reinforced concrete. Construction and Building Materials, vol. 298, 2021, pp.123-910.

[19] Masilamani A., Ramalingam M., Kathirvel P., Murali G., and Vatin N. I., Mechanical, Physico-Chemical and Morphological Characterization of Energy Optimised Furnace (EOF) Steel Slag as Coarse Aggregate in Concrete. Materials (Basel), vol. 15, Issue 9, 2022, pp.1509-3390.

[20] Olofinnade O., Morawo A., Okedairo O., and Kim B., Solid waste management in developing countries: Reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production. Case Studies in Construction Materials, vol. 14, 2021, pp.100-532.

[21] Shen W., Liu Y., Wu M., Zhang D., Du X., Zhao D., and Xiong X., Ecological carbonated steel slag pervious concrete prepared as a key material of sponge city. Journal of cleaner production, vol. 256, 2020, pp. 120-244.

[22] Abd El-Hakim R. T., Elgendy G. M., El-Badawy S. M., and Amin M., Performance evaluation of steel slag high performance concrete for sustainable pavements. International Journal of Pavement Engineering, vol. 23, Issue 11, 2022, pp. 3819-3837.

[23] Mohamad H. M., Bolong N., Saad I., Gungat L., Tioon J., Pileh R., and Delton M., Manufacture of Concrete Paver Block Using Waste Materials and By-Products: a Review. GEOMATE Journal, vol. 22, Issue 93, 2022, pp.9-19.

[24] Pham V. N., Kato A., Nguyen H. G., Nguyen V. T., Phan Q. M., and Kawamoto K., Gas transport parameters of recycled concrete and clay brick aggregate blended with autoclaved aerated concrete grains. GEOMATE Journal, vol. 20, Issue 82, 2021, pp. 93-100.

[25] Moroccan Association of the Concrete Industry, Concrete in Morocco: Processes and Applications. Casablanca: Moroccan Technical Editions, 2019, pp.1-358.

[26] Dreux G. and Festa J., New guide of concrete and its constituents. Paris: Edition Eyrolles, 1998, pp.1-416.

[27] Es-Samlali L., EL Haloui Y., Amrani M., Oudrhiri H. F., Tlidi A., and Bekri A., Potential valorisation of steel slag waste as an alternative material for pavement layers. GRAĐEVINAR, vol. 75, 2023, pp.163–176.

[28] Barra M., Ramonich E. V, and Munoz M. A., Stabilization of soils with steel slag and cement for application in rural and low traffic roads. Beneficial Use of Recycled Materials in Transportation Applications, vol. 51, 2001, pp.423–432.

[29] Herbelinc M., Bascou J., Lavastre V., Guillaume D., Benbakkar M., Peuble S., and Baron J. P., Steel Slag Characterisation—Benefit of Coupling Chemical, Mineralogical and Magnetic Techniques. Minerals, vol. 10, Issue 8, 2020, pp.080-705.

[30] Chen Z., Huang L., Yan L., Cai H., Luo X., and Li Y., Autoclaved steel slag coarse aggregate : A

potential solution for sustainable concrete production Autoclaved steel slag coarse aggregate : A potential solution for sustainable concrete production. Construction and Building Materials, vol. 400, 2023, pp. 132-627.
[31] Hussain A., Khaja S., and Hussaini K., Use of steel slag as railway ballast: A review. Transportation Geotechnics, vol. 35, 2022, pp. 100-779.
[32] Baalamurugan J., Kumar V. G., Chandrasekaran S., Balasundar S., Venkatraman B., Padmapriya R., and Raja V. B., Recycling of steel slag aggregates for the development of high density concrete: Alternative & environment-friendly radiation shielding composite. Composites Part B: Engineering, vol. 216, 2021, pp.108-885.
[33] Kvočka D., Šušteršič J., Mauko P. A., and Mladenović A., Mass Concrete with EAF Steel Slag Aggregate: Workability, Strength, Temperature Rise, and Environmental Performance. Sustainability, vol. 14, Issue 23, 2022, pp.015-502.
[34] Miah J., Ali K., Lo Monte F., Paul C., Babafemi A. J., and Brankoˇbrankošavija B., The effect of furnace steel slag powder on the performance of cementitious mortar at ambient temperature and after exposure to elevated temperatures. Structures. Elsevier, Vol. 33, 2021, pp.2811-2823.
[35] Xue G., Fu Q., Xu S., and Li J., The dense interfacial transition zone with fewer microcracks and more hydration products in steel slag concrete is attributed to the low heat of hydration and the release of water from the slag leading to beneficial secondary hydration. Journal of Building Engineering, vol. 56, Issue. 04, 2022, pp.104-742.
[36] Dong Q., Wang G., Chen X., Tan J., and Gu X., Recycling of steel slag aggregate in portland cement concrete: An overview. Journal of cleaner production, 2021, vol. 282, pp.124-447.
[37] Piro N. S., Mohammed A. S., Hamad S. M., Kurda R., and Qader B. S., Multifunctional computational models to predict the long-term compressive strength of concrete incorporated with waste steel slag. Structural Concrete, vol. 24, Issue 2, 2023, p. 2093-2112.
[38] Hajiaghamemar M., Mostofinejad D., and Bahmani H., A high-strength concrete resistant to elevated temperatures using steel slag aggregates. Structural Concrete, vol. 24, Issue 3, 2023, pp.3162-3177.
[39] Makul N., Fediuk R., and Szelag M., Advanced interactions of cement-based materials with microorganisms: A review and future perspective. Journal of Building Engineering, vol. 45, Issue 10, 2022, pp.103-458.
[40] Bao J., Li S., Zhang P., Ding X., Xue S., Cui Y., and Zhao T., Influence of the incorporation of recycled coarse aggregate on water absorption and chloride penetration into concrete. Construction and Building Materials, 2020, vol. 239, pp.117-845.
[41] Kurda R. and De Brito J., Water absorption and electrical resistivity of concrete with recycled concrete aggregates and fly ash. Cement and Concrete Composites, vol. 95, 2019, pp.169-182.
[42] Qasrawi H., Fresh properties of green SCC made with recycled steel slag coarse aggregate under normal and hot weather. Journal of Cleaner Production, vol. 204, 2018, pp.980-991.
[43] Wang G., Chen X., Dong Q., Yuan J., and Hong Q., “Mechanical performance study of pervious concrete using steel slag aggregate through laboratory tests and numerical simulation. Journal of Cleaner Production, 2020, vol. 262, pp.121-208.
[44] Sun J., Zhang Z., Zhuang S., and He W., Hydration properties and microstructure characteristics of alkali-activated steel slag. Construction and Building Materials, vol. 241, 2020, pp.118-141.
[45] Mo L., Zhang F., Deng M., Jin F., Al-Tabbaa A., and Wang A., Accelerated carbonation and performance of concrete made with steel slag as binding materials and aggregates. Cement and Concrete Composites, vol. 83, 2017, pp. 138-145.