Assessing the Effects of Libyan Iron Slag on Self-Compacting Concrete Characteristics

Nurdeen Mohamed Altwair
Department of Civil Engineering, Faculty of Engineering, Elmergib University, Khoms, Libya
nmaltwair@elmergib.edu.ly (corresponding author)

Ali Gomaa Abuzgaia
Department of Civil Engineering, Faculty of Engineering, Elmergib University, Khoms, Libya
abuzgaiaali@gmail.com

Abdualhamid Mohamed Alsharif
Department of Civil Engineering, Faculty of Engineering, Elmergib University, Khoms, Libya
amalsharif@elmergib.edu.ly

Lamen Saleh Sryh
Department of Civil Engineering, Faculty of Engineering, Elmergib University, Khoms, Libya
lssryh@elmergib.edu.ly

Saleh Elmahdi Ali Abdulsalam
Department of Civil Engineering, Faculty of Engineering, Elmergib University, Khoms, Libya
seabdulsalam@elmergib.edu.ly

Khalid Ashur Swalem
Civil Engineering Department, Faculty of Engineering, Gulf of Sidra University, Ben Jawwad, Libya
Khalidswalim@gsu.edu.ly

Received: 19 October 2024 | Revised: 10 November 2024 | Accepted: 21 November 2024

ABSTRACT

The current study addresses the growing environmental issue of waste from blast high furnaces, particularly iron and steel plants in Libya. It investigates the fresh and mechanical properties of Self-Compacting Concrete (SCC) by substituting conventional aggregate with slag aggregate. The fresh properties of SCC were assessed using slump flow diameter, T50 flow time, J-ring, and L-box tests. Its mechanical properties were also evaluated, including compressive strength, flexural strength, splitting tensile strength, and Ultrasonic Pulse Velocity (UPV). Various replacement ratios were tested, 30%, 60%, and 100% for coarse aggregate, 10%, 20%, and 30% for fine aggregate, and combinations of coarse and fine aggregate at specified ratios. The results indicated that higher slag powder content slightly increased the setting times. The coarse slag aggregate proportions negatively impacted the filling ability, while fine aggregate proportions enhanced it. The passing ability decreased when 60% of coarse slag was used as a replacement, but it improved with a 100% coarse slag replacement. Interestingly, replacing 60% of coarse aggregate with slag enhanced compressive strength. Meanwhile, the best flexural and splitting tensile strengths were observed with 20%-30% replacements of both coarse and fine aggregates with slag. All slag aggregate mixtures were classified as of excellent quality based on UPV assessments, highlighting their potential as sustainable construction materials.

Keywords-slag aggregate; self-compacting concrete; flowability; mechanical properties

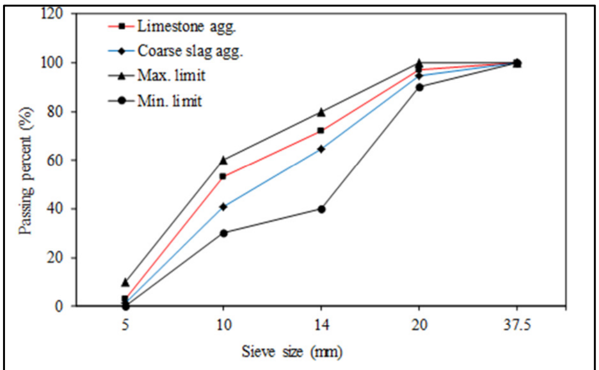
I. INTRODUCTION

In recent years, there has been a growing concern about the depletion of natural resources, coinciding with increased industrial waste production. This shift has led to a significant focus on sustainable development in civil engineering, with an emphasis on achieving this goal without compromising the properties of primary materials [1]. In the mid-twentieth century, research began to emerge regarding the use of economically viable alternative materials in the production and manufacturing of concrete. This includes the incorporation of industrial and agricultural waste into concrete components. Industrial byproducts, such as fly ash, blast furnace slag, and silica fume have replaced part of the cement used in concrete [2]. Additionally, agricultural waste products, such as rice husk ash, sugarcane bagasse ash, and date pit ash have also been utilized [3]. Another industry that has been impacted is the aggregate industry. Non-traditional sources are being explored as alternatives, including construction and demolition waste and industrial byproducts. The use of such materials not only alleviates the problem of fine aggregate scarcity in many industrialized nations, but also helps address environmental concerns associated with the accumulation of such waste [4]. Over the years, numerous concrete types have been developed to enhance the construction material industry and provide solutions to various challenges while considering environmental concerns. One such advancement is SCC, which is distinguished by its exceptional performance and ability to flow or compact under its weight without the need for vibration. These advantages are due to its unique properties, including high fluidity, stability, and excellent filling capacity, which set it apart from traditional concrete types. Additional benefits of SCC include reduced cost, shortened production time, ease of placement in confined spaces due to its flowability, and simplicity of pouring in complex reinforced areas [5]. However, like many other concrete types, SCC typically utilizes conventional aggregate and Portland cement, which are known to have an adverse environmental impact [6]. Therefore, it is crucial to develop new eco-friendly materials that can be used as alternatives to the traditional constituents of SCC. For instance, the use of Supplementary Cementitious Materials (SCMs) as partial replacements for Portland cement can contribute to mitigating the environmental impacts associated with cement production [7]. To address the critical issue of global warming, companies in the building materials and construction sectors have focused on using alternative cementitious materials, such as pozzolans.

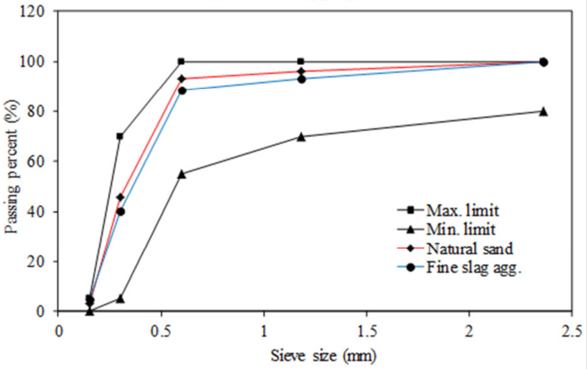
The global demand for iron has been increasing, leading to an annual surge in iron production and the generation of vast amounts of iron slag as a byproduct. Iron slag occupies significant land areas and releases pollutants into the atmosphere during production. The disposal of iron slag is costly, and its removal requires substantial natural resources, contributing to air and water pollution through various waste treatment processes [8]. Iron slag is produced during the steel-making process. Large quantities of carbon powder and limestone are introduced during the reduction phase in the electric arc furnace. These materials react with oxides to remove excess oxygen from the molten iron, leaving behind the slag as a secondary product. The resources consumed in managing iron slag waste and its adverse environmental impact necessitate the exploration of alternative methods for its disposal [9]. Despite the potential environmental issues associated with iron slag disposal, large quantities of this material remain in industrial areas, such as the iron and steel plant in Misrata, Libya. Although a small portion of iron slag is used in limited applications, such as road paving, it is still considered industrial waste. The accumulation of solidified iron slag in large blocks can cause significant environmental problems when discarded in nearby landfills. These issues include decreased soil permeability and reduced water infiltration, leading to increased surface water accumulation, waterlogging, and related health issues in nearby communities. Groundwater contamination and negative impacts on the region's natural appearance are a subject of concern [9]. Furthermore, environmental concerns are not the only challenges associated with iron slag disposal; economic factors also play a role. Increased demand, scarcity of raw materials, and rising energy prices contribute to the escalating costs of construction materials. Therefore, the search for energy-efficient and environmentally friendly alternatives for building materials has gained global attention. The current research aims to investigate the potential of utilizing locally sourced Libyan iron slag as a replacement for fine and coarse aggregate in SCC. This approach addresses the environmental and economic concerns associated with traditional materials. Furthermore, the present study examines the mechanical properties of SCC produced with this Libyan iron slag substitute. The findings are expected to provide valuable insights into the development of sustainable and eco-friendly building materials, while also minimizing the environmental and economic impacts related to the disposal of iron slag. By leveraging local resources, this research not only promotes sustainability, but also supports local economies.

II. EXPERIMENTAL WORK

In this study, ordinary Portland cement produced by Al-Burj Cement Factory, a subsidiary of the Arab Union Contracting Company, was utilized. This cement conforms to the British Standard Specification for Portland cement (BS 12:1996). Natural sand free from impurities was employed, with its physical properties meeting British Standards BS 812:1995. The specific gravity of the sand was found to be 2.64, and its water absorption was approximately 0.8%, with silica content exceeding 98%. Figure 1(a) illustrates the results of the sieve analysis for the sand used. The coarse aggregate employed in the reference mix was limestone aggregate sourced from quarries in the city of Tarhuna, Libya. The largest nominal size of this aggregate is 19 mm, and its physical properties also comply with the British Standards BS 812:1995. The specific gravity of the coarse aggregate was measured at 2.72, with a water absorption rate of 1.2%, a unit weight of 1530 kg/m³, a crushing value of 19.5%, and a wear value of 21.3%. Figure 1(b) presents the results of the sieve analysis for the coarse aggregate. The slag was supplied by the iron and steel plant in Misrata Libya. It arrived in large blocks and chunks, which were manually crushed into smaller pieces using hammers, followed by initial crushing using a stone-crushing machine to achieve the desired size ranges. The material was sieved using standardized sieves to obtain the desired grading. The slag was divided into three parts. The first part was ground to a high degree of fineness using a ring mill to conduct a chemical composition analysis and assess the physical properties of the Ground Slag (GS) powder. The second part represented the fine aggregate, which was obtained by passing the pre-crushed slag through the reference sieves for fine aggregate. The third part represented the coarse aggregate, which was extracted by passing the crushed slag through the reference sieves for coarse aggregate according to the British Standards BS 882-1992. Figure 2 portrays the three distinct parts of the studied slag.



(a) Coarse aggregate



(b) Fine aggregate

Fig. 1. Particle size distribution of used aggregate according to BS 882.

The chemical analysis of the slag powder revealed that it primarily consists of silicon oxide, aluminum oxide, calcium oxide, iron oxide, and loss on ignition, with respective percentages of 31.3%, 119%, 40.6%, 3.7%, and 1.6%. Additionally, the pozzolanic activity index, measured by compressive strength by ASTM C311/C311M-17 after 7 and 28 days for mortar containing the GS, was approximately 83.8% and 96.23%, respectively. The surface area of the slag powder (Blaine number) was recorded at approximately 3012 cm²/g, which is higher than that of the cement, measured at 2970 cm²/g. The specific gravities of the coarse and fine slag aggregate were found to be 3.05 and 2.91, respectively.

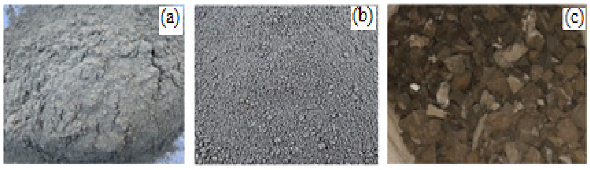


Fig. 2. Slag aggregate based on particle size: (a) Slag powder, (b) fine slag aggregate, and (c) coarse slag aggregate.

The data presented in Table I exhibit the percentage replacement proportions of slag aggregate (fine aggregate: coarse aggregate) by conventional aggregate in the reference mix. The latter, denoted as Mix A, was prepared with specific quantities of the main components: 450 kg/m³ of cement, 898 kg/m³ of sand, 910 kg/m³ of coarse aggregate, 180 liters/m³ of water, and 6.3 liters/m³ of superplasticizing admixture. Additionally, cement paste mixes containing GS were formulated at varying replacement levels of (A1) 0%, (A2) 10%, and (A3) 20% to investigate the effect of GS on the setting time characteristics of the cementitious systems.

TABLE I. REPLACEMENT PROPORTIONS OF SLAG AGGREGATE

Mix	A	B	C	D	E	F	G	H	I	J
Fine	0	0	0	0	10	20	30	10	20	30
Coarse	0	30	60	100	0	0	0	20	30	40

The fresh properties of SCC, including slump flow diameter and T50 flow time, J-ring test, and L-box test, were determined by the specifications outlined in BS EN 12350-8, BS EN 12350-12, and BS EN 12350-10, respectively. The slump flow diameter was measured by filling a slump cone with fresh concrete and compacting it with a tamping rod. After lifting the cone, the SCC flowed freely, and the diameter of the spread was recorded with a ruler. The T50 flow test utilized a truncated cone mold with a base diameter of 20 cm and a height of 30 cm. After filling the mold with SCC and lifting it, the spread diameter was recorded. The J-ring test assessed workability by placing the slump cone in the center of a J-ring, filling it, and lifting it to measure the concrete's flow. The L-box test featured two vertical arms and a horizontal plate. Fresh SCC was poured into one side, and upon lifting the plate, the flow distance on the horizontal surface was measured, indicating the concrete's passing ability and segregation resistance. The mechanical properties of SCC, specifically compressive strength, flexural strength, splitting tensile strength, and UPV, were evaluated based on the specifications established in British Standards BS EN 12390-3, BS EN 12390-5, BS EN 12390-6, and BS EN 12504-4, respectively. Cubes measuring 150 mm × 150 mm × 150 mm were cast to assess both the compressive strength and UPV. Cylinders with dimensions of 150 mm × 300 mm were prepared to measure the splitting tensile strength. Additionally, beams measuring 100 mm × 100 mm × 400 mm were cast to determine the flexural strength. The compressive strength, flexural strength, and splitting tensile strength of the SCC specimens were tested at 7, 28, and 56 days, while the UPV was measured at 28 and 56 days.

III. RESULTS AND DISCUSSION

Figure 3 shows the impact of incorporating GS on the initial and final setting times of cement paste samples.

Both initial and final setting times vary with the proportion of slag added to the mix. The findings reveal that the initial and final setting times of the reference mix (without GS addition) are the shortest compared to the other mixes containing GS. It was observed that as the GS content increases, the initial and final setting times of the samples increase moderately. The increased surface area of the GS compared to cement affects the reaction rate due to the interaction between cement particles and smaller GS particles, resulting in a prolonged setting time. Notably, the effect of GS on hydration becomes more pronounced at later ages. The observed increase in setting time could be attributed to the dilution effect, where the addition of GS reduces the concentration of cement particles [10]. The increased surface area with higher GS content may lead to greater water absorption by the paste, potentially reducing the setting time of the cement paste [11].

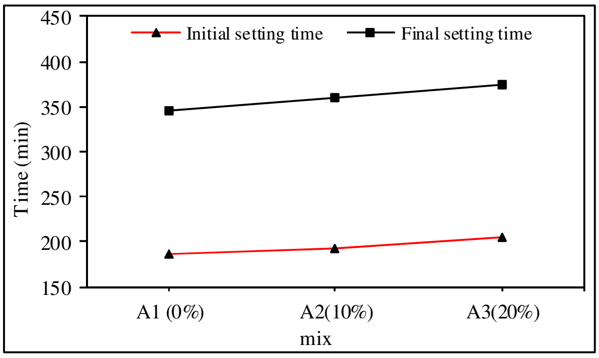


Fig. 3. Effect of GS on setting times of cement paste.

The investigation of three crucial properties of SCC, namely filling ability, passing ability through obstacles and molds of various dimensions, and self-leveling ability, has been conducted. As observed in Table II, all mixtures conformed to the specifications outlined by the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC). When the proportion of coarse slag aggregate was altered, it was found that an increase in the coarse slag aggregate content resulted in a decrease in filling ability, accompanied by a reduction in flowability and an increase in T50. This trend was reversed when the proportion of fine slag aggregate was altered. When both coarse and fine slag aggregate proportions were varied, the increase and decrease in flowability differed according to the quantity of coarse slag aggregate in the mixture. It was observed that the passing ability of the concrete, indicated by the J-ring test value, decreased as the coarse slag aggregate replacement ratio increased up to 60%. However, at a 100% replacement ratio (mixture D), the passing ability improved compared to the reference mixture. This effect was reversed when the proportion of fine slag aggregate was increased, and the remaining components remained constant. The highest J-ring value was recorded for mixture J (9 mm). This indicates that the highest replacement ratio of coarse and fine slag aggregate (mixtures D and J) yielded the highest values for this test. Regarding passing capacity, as represented by the L-Box test value, it was found that when the coarse slag aggregate replacement ratio exceeded 30% (mixtures B and C), it was accompanied by a decrease in the L-Box value. This trend was reversed when the fine slag aggregate replacement ratio was increased (mixtures F and G). It was also found that this value was lowest for mixtures D and J, which had the highest coarse and fine slag aggregate contents. Based on the above findings, it can be concluded that an increase in the coarse slag aggregate content leads to a decrease in workability, while an increase in the fine slag aggregate content enhances workability. The rough texture of the coarse slag aggregate and its ability to absorb water resulted in a decrease in workability, despite the higher density of this type of aggregate compared to the limestone aggregate used in the reference mixture. In contrast, the fine slag aggregate's reduced ability to absorb water due to the reduction of voids and pores after grinding led to an increase in workability [11].

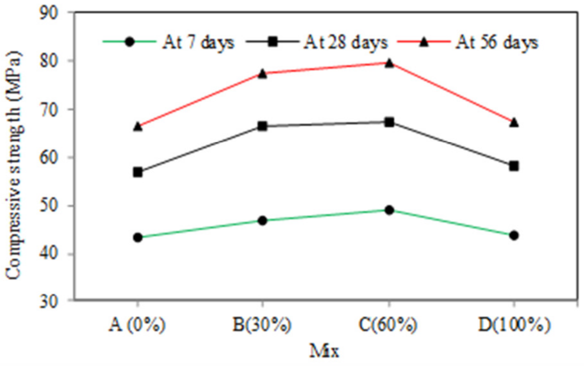
TABLE II. TEST RESULTS FOR FRESH PROPERTIES OF SCC BY EFNARC SPECIFICATION

Mix	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Limits as per EFNARC guidelines**
Flow (mm)	760	773	743	697	778	783	798	753	741	651	650 - 800
T50 (sec.)	3.11	2.86	3.23	4.18	2.79	2.47	2.13	3.68	4.05	4.92	2 - 5
J-ring (mm)	4	3	3	8	3	2	2	4	5	9	0 - 10
L-Box (%)	98	100	98	86	99	100	100	94	91	84	80 - 100

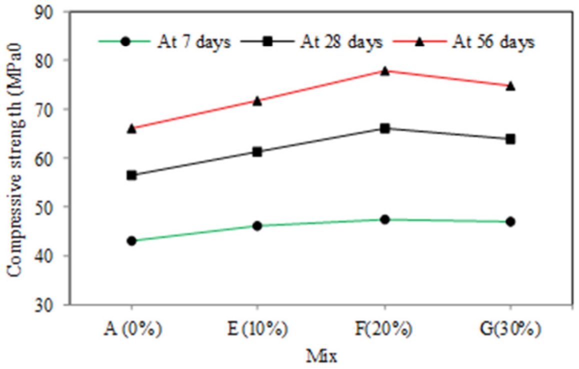
Figure 4(a) illustrates the effect of coarse slag aggregate replacement on compressive strength. The results indicate that compressive strength increases up to a 60% replacement ratio, after which it begins to decrease, reaching values comparable to the reference mixture at a 100% replacement ratio. The highest compressive strength values were achieved at a 60% replacement ratio (Mix C), followed by a 30% replacement ratio (Mix B). Figure 4(b) demonstrates the effect of fine slag aggregate replacement on the compressive strength of SCC. The data suggests that the partial replacement of natural aggregate with fine slag aggregate can enhance the compressive strength of SCC. All mixtures containing fine slag aggregate exhibited higher compressive strengths than the reference mixture at all ages. The highest compressive strength values were observed for Mix F (20% replacement ratio), reaching approximately 47.5 MPa, 66.02 MPa, and 78.12 MPa at 7, 28, and 56 days, respectively. This was followed by Mix G (30% replacement ratio) and Mix E (10% replacement ratio). The positive influence of fine slag aggregate on compressive strength has been reported in previous studies. Authors in [12] found that partial replacement of natural aggregate with 10% and 25% slag aggregate in fine SCC resulted in compressive strength increases of 4% and 13%, respectively. Figure 4(c) demonstrates the effect of coarse and fine slag aggregate ratios (mixed aggregate) on compressive strength. This positive impact on compressive strength is evident in mix H (20% coarse aggregate and 10 % fine aggregate), which showed the highest strength values compared to other mixes. Mix I (30% coarse aggregate and 20% fine aggregate) also showed a higher compressive strength, while mix J (40% coarse aggregate and 30% fine aggregate) had similar strength values to the reference mix. This result agrees with authors in [13], who indicated that higher replacement ratios of slag aggregate for conventional aggregate result in increased compressive strength for both coarse and fine aggregate. This enhancement could be attributed to improved Interfacial Transition Zone (ITZ) quality and increased aggregate strength. Authors in [14] concluded that replacing natural aggregate with 40% slag aggregate provided higher compressive strength compared to conventional concrete. They also mentioned that more than 40% replacement of slag aggregate resulted in satisfactory results. The improvement in strength with slag aggregate replacement may be due to the rough and porous surface of slag aggregate enhancing bonding with the cementitious matrix, leading to increased strength. The higher specific gravity of slag aggregate (3.05) compared to limestone aggregate (2.72) may also contribute to this improvement [15]. However, a decrease in strength is observed at high replacement ratios, which may be attributed to increased porosity caused by the high slag aggregate ratio, negatively affecting mechanical properties.

The results are presented in Figure 5, which depicts the flexural strength of SCC specimens at different ages (7, 28, and 56 days) for various replacement ratios of coarse slag aggregate, fine slag aggregate, and a combination of both. Figure 5(a) illustrates the effect of coarse slag aggregate replacement on flexural strength. A slight improvement in flexural strength is observed for Mix B (30% replacement ratio) compared to the reference mixture at all ages. However, beyond a 30 % replacement ratio, a decline in flexural strength is observed. Figure 5(b) demonstrates the effect of fine slag aggregate replacement on flexural strength. A slight increase in flexural strength is observed for Mix F (20% replacement ratio) at 28 and 56 days compared to the reference mixture. This increase corresponds to a 2.6% and 0.7% improvement at 28 and 56 days, respectively. No significant improvement in flexural strength is observed for other mixtures. Figure 5(c) shows the effect of mixed coarse and fine slag aggregate replacement on flexural strength. While a slight improvement in flexural strength is observed for Mix H (20% coarse slag aggregate and 10% fine slag aggregate) at 28 and 56 days, no significant effect is observed for other mixtures. The other mixes exhibit a negative yet acceptable effect, where an increase in the replacement ratio of the mixed slag aggregate correlates with a decrease in flexural strength across all ages. The findings of this study are consistent with those of authors in [16], who investigated the flexural strength of SCC containing 10% to 100% iron slag as a replacement for fine aggregate. Was found that replacing fine aggregate with 10% to 40% iron slag resulted in improved flexural strength. The improved flexural strength observed in mixtures with lower replacement ratios (less than 30% coarse slag aggregate and less than 10% fine slag aggregate) can be attributed to enhanced mechanical bonding at the ITZ due to the rough surface of the slag aggregate [17]. The decrease in flexural strength at higher replacement ratios could be attributed to increased porosity within the concrete microstructure due to the increased slag aggregate content [15].

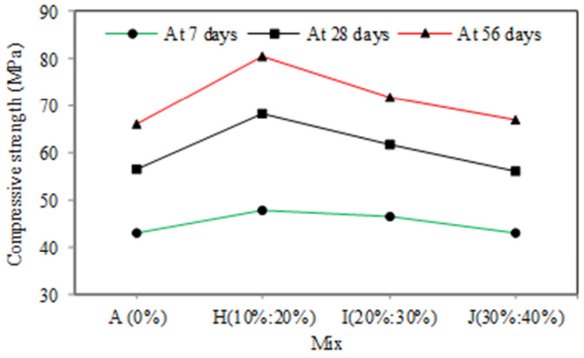
The results indicate that replacing up to 30% of the natural aggregate with coarse slag aggregate resulted in an improvement in splitting tensile strength compared to the reference concrete as shown in Figure 6(a). However, increasing the replacement ratio beyond 30% led to a decrease in tensile strength. Regarding the effect of fine slag aggregate, the mix containing 20% fine slag aggregate (Mix F) exhibited the highest splitting tensile strength compared to the reference mix as illustrated in Figure 6(b). The results also indicated that the replacement of a combination of 20% coarse slag aggregate and 10% fine slag aggregate (Mix H) resulted in an improvement in the splitting tensile strength for all ages as depicted in Figure 6(c). The pattern of the splitting tensile strength results aligns with those observed for flexural strength. The enhancement in strength at lower replacement ratios of less than 30% for coarse slag and 10% for fine slag can be attributed to the increased mechanical bonding in the ITZ due to the rough surface texture of the slag aggregate. The reduction in strength observed at higher replacement ratios is likely due to an increase in porosity within the concrete matrix as the quantity of slag aggregate increases.



(a) Coarse slag aggregate

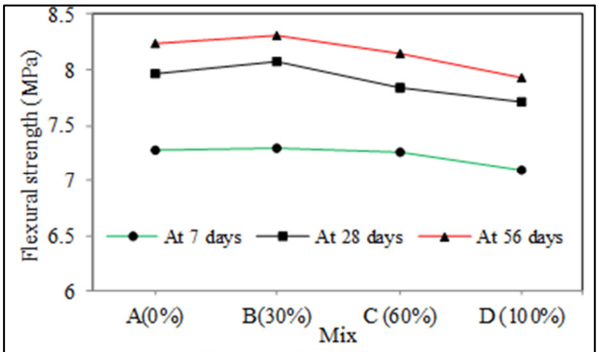


(b) Fine slag aggregate

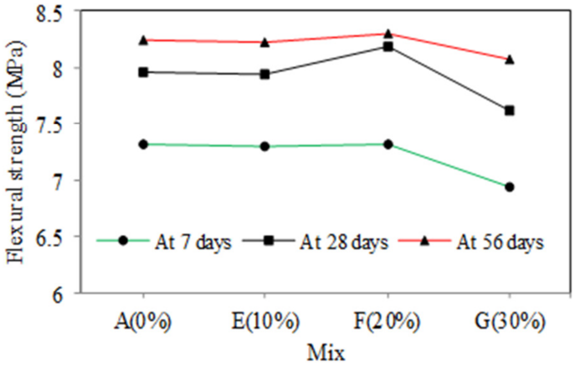


(c) Mixed aggregate

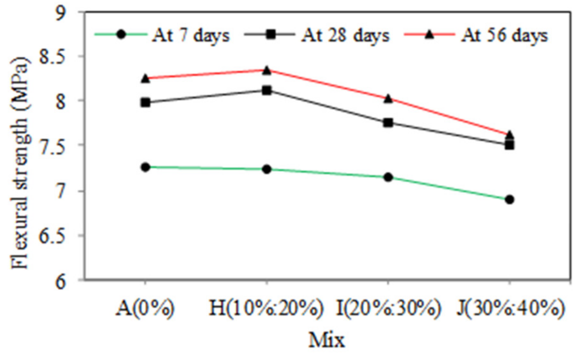
Fig. 4. Effect of slag aggregate replacement on compressive strength.



(a) Coarse slag aggregate



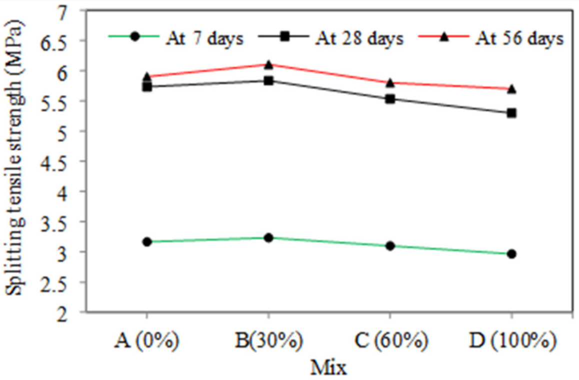
(b) Fine slag aggregate



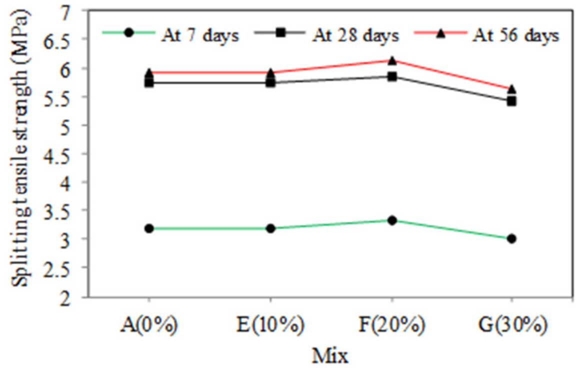
(c) Mixed aggregate

Fig. 5. Effect of slag aggregate replacement on flexural strength.

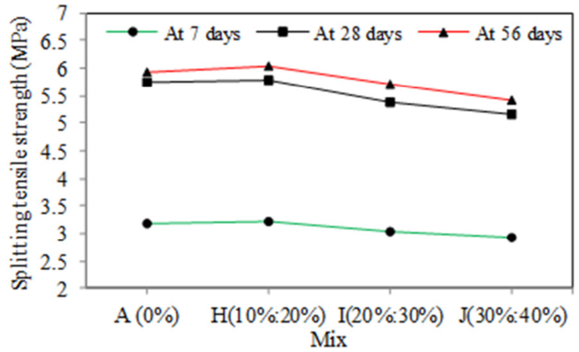
The results illustrated in Figure 7 indicate that UPV Values are nearly uniform across all SCC mixtures at both 28 and 56 days. It is also noted that the UPV tends to decrease slightly with an increase in the replacement ratio of either fine or coarse slag aggregate. This gradual reduction in UPV can be attributed to the increased pore volume within the SCC matrixes as the replacement ratios of slag aggregate rise. The findings that are presented lend support to the previously discussed explanations for the observed diminishment in mechanical strength at elevated replacement percentages. Overall, the UPV exceeded 4 km/s for all mixtures, indicating that all tested mixtures exhibit excellent quality.



(a) Coarse slag aggregate



(b) Fine slag aggregate



(c) Mixed aggregate

Fig. 6. Effect of slag aggregate replacement on splitting tensile strength.

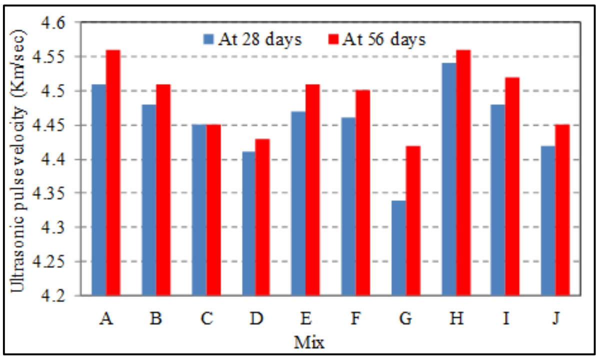


Fig. 7. UPV test results for SCC mixtures containing slag aggregate.

IV. CONCLUSIONS

Based on the experimental results, the following conclusions can be drawn:

- The initial and final setting times exhibit a slight increase with the addition of GS to the cement paste.
- All mixtures complied with the specifications for SCC. An increase in the coarse slag aggregate reduced the filling ability, while an increase in the fine aggregate enhanced it. When the combined aggregate ratio (coarse and fine) was increased within the same mixture, the effect on flowability varied depending on the amount of coarse aggregate present. Conversely, the passing ability values decreased up to a 60% replacement ratio of coarse slag aggregate, then increased at a 100% replacement ratio.
- Compared to the reference mixture, a 60% replacement of coarse slag aggregate (Mix C) demonstrated an increase in compressive strength. As the proportion of fine slag aggregate increased, the strength continued to rise, peaking at a 20% replacement level. The best compressive strength performance was observed in mixtures containing a mix of coarse and fine slag aggregate, specifically mix H (20% coarse aggregate and 10% fine aggregate).
- The mixtures that exhibited the most significant improvements in flexural and splitting tensile strengths were mix B (30% coarse slag replacement) for coarse slag aggregate, mix F (20% fine slag replacement) for fine slag aggregate, and mix H (20% coarse and 10% fine slag) for the mixed slag aggregate.
- UPV values are nearly uniform among all SCC mixtures. The UPV values exceed 4 km/s for all mixtures, indicating that all tested mixtures possess excellent quality.

REFERENCES

[1] M. Khan and C. McNally, "A holistic review on the contribution of civil engineers for driving sustainable concrete construction in the built environment," *Developments in the Built Environment*, vol. 16, Dec. 2023, Art. no. 100273, https://doi.org/10.1016/j.dibe.2023.100273.

[2] V. J. Patel, J. Juremalani, H. R. Kumavat, and J. Patel, "Flexural and Abrasion Performance of High Volume GGBS Concrete Pavements," *Engineering, Technology & Applied Science Research*, vol. 14, no. 5, pp. 17055–17059, Oct. 2024, https://doi.org/10.48084/etasr.8534.

[3] N. Altwair and H. Elghwaria, "Influence of Incorporating PVC Waste on the Mechanical Properties of Cement Mortar," *Journal of Pure & Applied Sciences*, vol. 22, no. 3, pp. 138–144, Oct. 2023, https://doi.org/10.51984/jopas.v22i3.2761.

[4] M. Behera, S. K. Bhattacharyya, A. K. Minocha, R. Deoliya, and S. Maiti, "Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review," *Construction and Building Materials*, vol. 68, pp. 501–516, Oct. 2014, https://doi.org/10.1016/j.conbuildmat.2014.07.003.

[5] K. Boakye and M. Khorami, "Properties of Self-Compacting Concrete (SCC) Prepared with Binary and Ternary Blended Calcined Clay and Steel Slag," *Infrastructures*, vol. 9, no. 3, Mar. 2024, Art. no. 46, https://doi.org/10.3390/infrastructures9030046.

[6] N. J. Mim *et al.*, "Eco-friendly and cost-effective self-compacting concrete using waste banana leaf ash," *Journal of Building Engineering*, vol. 64, Apr. 2023, Art. no. 105581, https://doi.org/10.1016/j.jobe.2022.105581.

[7] J.-H. Wee, "A review on carbon dioxide capture and storage technology using coal fly ash," *Applied Energy*, vol. 106, pp. 143–151, Jun. 2013, https://doi.org/10.1016/j.apenergy.2013.01.062.

[8] O. Bouchenafa, R. Hamzaoui, A. Bennabi, and J. Colin, "PCA effect on structure of fly ashes and slag obtained by mechanosynthesis. Applications: Mechanical performance of substituted paste CEMI + 50% slag /or fly ashes," *Construction and Building Materials*, vol. 203, pp. 120–133, Apr. 2019, https://doi.org/10.1016/j.conbuildmat.2019.01.063.

[9] M. Xue, W. Hu, L. Huanyu, and Y. Fu, "Beneficial Reuse of Municipal Solid Waste Incineration Bottom Slag in Civil Engineering," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8306–8310, Apr. 2022, https://doi.org/10.48084/etasr.4693.

[10] N. Altwair and F. Al-Mazoughi, “The effect of blast furnace slag grinding time on the properties of cement paste and mortar,” *International Science and Technology Journal*, , vol. 2, no. 33, Jan. 2024, http://www.doi.org/10.62341/ISTJ.

[11] S. Haruna, B. Mohammed, and M. M. A. Wahab, "Effect of GGBS Slag on Setting Time and Compressive Strength of One-Part Geopolymer Binders," *Journal of Infrastructure and Facility Asset Management*, vol. 2, no. 2, pp. 149–160, Sep. 2020, https://doi.org/10.12962/jifam.v2i2.7640.

[12] G. Singh and R. Siddique, "Effect of iron slag as partial replacement of fine aggregates on the durability characteristics of self-compacting concrete," *Construction and Building Materials*, vol. 128, pp. 88–95, Dec. 2016, https://doi.org/10.1016/j.conbuildmat.2016.10.074.

[13] I. Arribas, I. Vegas, J. T. San-José, and J. M. Manso, "Durability studies on steelmaking slag concretes," *Materials & Design*, vol. 63, pp. 168–176, Nov. 2014, https://doi.org/10.1016/j.matdes.2014.06.002.

[14] R. Malathy and L. Kothei, “Mechanical properties of self-compacting concrete with partial replacement of natural sand by steel slag,” *International Journal of Earth Sciences and Engineering*, vol. 5, no. 03, pp. 635–639, 2012.

[15] K. P. P. Bharathi, S. K. Adari, and U. Pallepamula, "Mechanical properties of self-compacting concrete using steel slag and glass powder," *Journal of Building Pathology and Rehabilitation*, vol. 7, no. 1, Apr. 2022, Art. no. 46, https://doi.org/10.1007/s41024-022-00184-z.

[16] G. Singh and R. Siddique, "Strength properties and micro-structural analysis of self-compacting concrete made with iron slag as partial replacement of fine aggregates," *Construction and Building Materials*, vol. 127, pp. 144–152, Nov. 2016, https://doi.org/10.1016/j.conbuildmat.2016.09.154.

[17] I. M. Nikbin *et al.*, "A comprehensive investigation into the effect of aging and coarse aggregate size and volume on mechanical properties of self-compacting concrete," *Materials & Design*, vol. 59, pp. 199–210, Jul. 2014, https://doi.org/10.1016/j.matdes.2014.02.054.