

Exploring the Potential of Iron Slag and Stone Ash as Aggregate Replacements for the Improvement of the Compressive Strength and Durability of Self-Compacting Concrete

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ABSTRACT

Industrial by-products, such as Iron Slag (IS) and Stone Ash (SA), can replace aggregates in concrete, but research on their mechanical performance and durability, particularly in Self-Compacting Concrete (SCC), is still limited. Using these materials supports sustainable construction principles while improving material efficiency. This study evaluates the effect of replacing coarse and fine aggregates with Iron Slag and SA, respectively, on the compressive strength, durability, and practical implementation of concrete in structural applications. The research was conducted experimentally with four SCC concrete mix variations: BSI-N (control), BSI-1 (0% SA), BSI-2 (50% SA), and BSI-3 (100% SA). Tests included compressive strength, slump flow, density, porosity, sorptivity, electrical resistivity, chloride penetration, and abrasion resistance, based on ASTM and SNI standards. The results show that BSI-3 (100% SA) had the highest compressive strength (50.40 MPa) and the lowest porosity and abrasion values, but failed to meet SCC criteria due to a slump flow below 550 mm. Conversely, BSI-2 met SCC specifications with a slump flow of 650 mm, showing the best chloride penetration resistance, while it maintained an adequate compressive strength of 44.38 MPa. It was concluded that an SCC mix with 50% SA and IS (BSI-2) is optimal for industrial building applications, particularly for floor slabs and supporting structures, as it balances strength, durability, and workability.

Keywords-SCC; iron slag; stone ash; compressive strength; durability

I. INTRODUCTION

Concrete, is one of the most widely used construction materials, showing strong mechanical properties, affordable price, and ease of use. As the construction sector rapidly develops, there is a need for building materials that offer broader advantages. Authors in [1] revealed that global concrete consumption exceeds 30 billion tons per year, with conventional concrete production significantly affecting the environment, primarily through carbon emissions from the cement industry and massive exploitation of natural aggregates. Data from the 2022 Global Cement Report demonstrate that the cement industry contributes approximately 8% to the total global carbon emissions, while in some areas, sand and stone mining causes the destruction of riverbanks and increases the risk of landslides. This situation has driven the need for using alternative resources, particularly underused waste materials. IS is a type of industrial waste that can be used in construction. In 2023, the World Steel Association noted that the global steel industry produces over 550 million tons of slag annually, with some Indonesian industries producing up to 1,400 tons of slag waste per month, making it possible to sustainably use this waste [2]. Additionally, SA- a byproduct of the rock-crushing process - can be utilized as a substitute for fine aggregates, such as sand. SCC is an advanced concrete that can flow without external vibration, depending on the composition of its constituent materials, especially the aggregates. The rigid characteristics of IS influence the fracture process zone. Authors in [3] observed that elongated particles in slag increase resistance to crack propagation, improving concrete's mechanical performance and overall durability. Authors in [4, 5] confirmed that partially replacing coarse aggregate with IS significantly improves concrete's mechanical properties, including its compressive, flexural, and tensile strengths. Optimal performance occurs at low replacement levels (20% in SCC). Furthermore, using IS increases concrete's resistance to chemical attack and reduces porosity. While a 30% replacement ratio can positively impact the workability of normal concrete, a major challenge is the potential decrease at

higher replacement levels, due to slag's high specific gravity and angular particle morphology, which interfere with concrete flow. This study used 100% IS replacement to create a worst-case scenario regarding workability, allowing the evaluation of the effectiveness of SA in mitigating these challenges and restoring the necessary self-compacting properties. Although previous research has extensively investigated the effects of IS or SA on concrete individually, there is a significant knowledge gap regarding their combined use as aggregate replacement materials. The present study examines the concurrent use of these two industrial by-products, focusing on the interaction of their combined chemical and physical properties. The experimental program extends beyond compressive strength to include water absorption and abrasion resistance. By evaluating the use of IS as a coarse aggregate substitute and SA as a fine aggregate replacement, this study provides essential technical information for using industrial waste.

II. EXPERIMENTAL PROCEDURE

A. Materials Characteristics

The current study used IS as a substitute for coarse aggregate and SA as a replacement for fine aggregate. The coarse aggregate consisted of 10-20 mm crushed stone and 5-20 mm IS. The IS was obtained from waste produced by the steel smelting process in Makassar City, South Sulawesi, Indonesia. The fine aggregate consisted of river sand and SA obtained from crushed stone waste around the Bili-Bili River in the Gowa Regency of Indonesia. Table I presents the aggregate characteristics, and Figure 1 shows the aggregates used. Portland Composite Cement (PCC) that meets the Indonesian cement production standard SNI 15-7064-2004 and is available on the market was used as a binding material. Table II depicts the compound elements of PCC cement and IS based on Energy Dispersive X-ray Spectroscopy (EDS) testing. Viscocrete 3115N was added as a superplasticizer at around 1.6-2% of the binder weight. To achieve specific workability targets, the usage of the superplasticizer is adjusted for each mix without exceeding the proposed dosage of 2.0% by binder

weight for SCC. In general, the compounds in IS are similar to those in PCC cement. This suggests that slag aggregate and cement paste can bond with each other, strengthening the bond between the mortar matrix and slag aggregate.

TABLE I. CHARACTERISTICS OF AGGREGATES

Characteristics	Crushed stone	IS	Sand river	SA
Specific gravity (SSD)	2.62	3.20	2.54	2.60
Water absorption, %	2.28	2.32	2.40	4.64
Fineness modulus (FM)	7.45	6.96	2.85	3.10
Abrasion, %	20.25	24.37	-	-

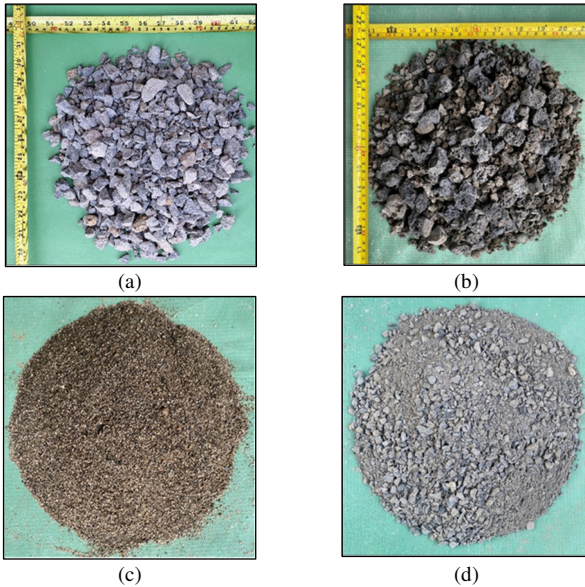


Fig. 1. Aggregates: (a) crushed stone, (b) IS, (c) river sand, (d) SA.

TABLE II. COMPOUND ELEMENTS OF PCC AND IS

Materials	Compound elements (%)									
	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	MnO	FeO
PCC	0.34	0.93	8.11	17.84	2.05	0.76	66.92	0.24	0.08	2.60
IS	0.15	5.25	12.94	14.32	0.39	0.11	35.53	0.83	5.33	24.48

B. Research Design

Four SCC mix variations were designed based on the guidelines of the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC) [6] and the Interim Specification Standards SKh-1.7.23 and SKh-1.10.14 [7]. IS was used as a 100% replacement for crushed stone, while SA was utilized as a replacement for river sand at 0%, 50%, and 100% levels. The specimen variations are displayed in Table III, and the SCC composition is portrayed in Table IV. All concrete variations used a water-to-cement ratio of 0.31. The BSI-N variation served as a control mix using 100% river sand and 100% crushed stone. A fixed w/c ratio and a standardized IS gradation were maintained throughout the experimental program to isolate the influence of the mineral admixtures. Eliminating variables related to moisture content and particle distribution ensures that the observed changes in mechanical and durability performance can be directly attributed to the replacement levels of IS and SA, allowing for a controlled and rigorous comparative analysis.

TABLE III. SPECIMEN VARIATION

Mix ID	W/C	Fine aggregate (%)		Coarse aggregate (%)		FM
		River sand (S)	SA (Ash)	Crushed stone (G)	IS (Gs)	
BSI-N	0.31	100	0	100	0	5.20
BSI-1	0.31	100	0	0	100	4.95
BSI-2	0.31	50	50	0	100	5.01
BSI-3	0.31	0	100	0	100	5.08

TABLE IV. THE COMPOSITION OF SCC

Mix ID	Materials (Kg/m ³)								Weight of fresh concrete (kg/m ³)
	W	C	Fine Agg.		Coarse Agg. G	IS		Sp.	
			S	Ash		Gs-1 (5-10 mm)	Gs-2 (10-20 mm)		
BSI-N	170	550	747	0	802	0	0	8.8	2385
BSI-1	170	550	747	0	0	493	493	9.9	2501
BSI-2	170	550	374	382	0	493	493	11	2614
BSI-3	170	550	0	765	0	493	493	11	2635

SA plays a dual role as a fine aggregate replacement and microfiller, effectively filling voids within the IS matrix, and enhancing packing density and aggregate interlocking. This combination is essential for SCC performance because the SA improves cohesion and density, which optimizes flow and self-consolidation. This approach ultimately achieves target strength and workability while minimizing cement content, reducing costs, and aligning with sustainable construction principles.

C. Testing Methods

The performance of fresh concrete was tested using an SCC test with a slump flow test and a V-funnel test to measure flowability and viscosity, based on EFNARC guidelines. Then, cylindrical specimens measuring 100 mm x 200 mm and beams measuring 100 mm x 100 mm x 400 mm were prepared. Each type of test consisted of three specimens. After demolding, the specimens were cured in fresh water for 28 days. Conducting tests included strength and durability tests. Strength tests included density, compressive strength, and flexural strength. Durability tests included porosity, sorptivity, chloride penetration depth, and abrasion resistance, as presented in Table V.

III. RESULTS AND DISCUSSION

A. Fresh Concrete Properties

The workability of SCC was evaluated using slump flow tests to measure filling ability and V-funnel tests to assess viscosity and passing ability, as shown in Table VI. The BSI-N, BSI-1, and BSI-2 variations met the standard specifications for slump flow 550 mm to 850 mm and time 2 s to 5 s. BSI-N exhibited the highest fluidity; however, BSI-1 and BSI-2 showed a marginal decrease in workability when river sand was replaced with up to 50% SA in the presence of IS coarse aggregate. Notably, replacing all of the river sand with SA (BSI-3) led to a drastic reduction in workability, causing the mixture to fall outside the SCC classification. This decline is likely due to SA's angular morphology, rougher texture, and higher specific surface area, which increases the demand for water and superplasticizers.

TABLE V. SUMMARY OF TEST METHOD

Testing	Test method	Specimen size	Important aspects of test method
Hardened density	ASTM C642 [8]	100 dia. mm× 200 mm ht. (cylinder)	The weight of each specimen was measured in saturated dry conditions
Porosity	ASTM C642 [8]	50 × 100 × 150 mm (prism)	Specimen weight was measured in oven-dry (A), surface-dry conditions after soaking for 48 h (B) and boiling for 5 h (C), and weight in water (D)
Compressive strength	ASTM C39 [9]	100 dia. mm × 200 mm ht. (cylinder)	Load rate = 0.5 N/mm ² /min
Flexural strength	ASTM C78 [10]	100 × 100 × 400 mm (prism)	Load rate = 0.25 N/mm ² /min
Water absorption rate (sorptivity)	ASTM C1585 [11]	50 × 100 × 150 mm (prism)	The specimen was placed in an oven at 50 ± 2°C for 3 days, then stored in an environmental chamber for 15 days at 23 ± 2°C. Epoxy was applied to each side of the specimen and the top side of the specimen was covered with plastic.
Chloride penetration depth	[12]	50 × 100 × 150 mm (prism)	The specimens were oven-dried at 50 ± 2°C for 3 days, then stored in an environmental chamber for 15 days at 23 ± 2°C. Epoxy was applied to all sides of the specimen except the bottom. The specimens were exposed to a 5% NaCl solution to a depth of 2 ± 1 mm on the bottom surface of the specimen for 28 days. The specimens were split and sprayed with 0.1 N AgNO ₃ solution.
Abrasion resistance	EN 1097 - 2: 2007 [13]	50 mm (cube)	Weigh the specimen before and after the abrasion test with the Los Angeles Machine every 100 revolutions up to 1000 revolutions.

Authors in [5, 14] observed a decrease in slump flow when natural coarse aggregate was replaced with IS. This reduction was attributed to the high angularity and irregular morphology of the slag particles, which increase internal friction and diminish the flowability of the concrete mixture. The experimental results demonstrated a direct correlation between SA content and V-funnel flow time, indicating an increase in plastic viscosity. The increase in V-funnel values from BSI-1 to BSI-2 confirms that SA increases the thickness of the concrete matrix, which reduces its flowability through the constricted outlet. Therefore, the replacement of fine aggregate with SA is limited to 50% to comply with the SCC criteria defined by the EFNARC guidelines [6].

TABLE VI. FRESH PROPERTIES OF SCC

Mix ID	Testing method		
	Slump flow (mm)	T ₅₀₀ mm (s)	V-funnel (s)
Specification	550 – 850	2 - 5	7 - 27
BSI-N	730	3.15	8.69
BSI-1	660	2.94	22.41
BSI-2	650	3.61	36.32
BSI-3	460	30.06	N/A

B. Density and Strength

Overall, concrete density increased consistently with the addition of replacement materials (IS and SA), as shown in Table VII. The significant increase in hardened density of BSI-1, BSI-2, and BSI-3, driven by IS's higher specific gravity and SA's filling effect, suggests high potential for applications requiring superior strength and durability. Replacing natural coarse aggregate with IS (BSI-1) increased density by 211 kg/m³, rising from 2,227 kg/m³ to 2,438 kg/m³. This densification is further enhanced by the rough texture and angularity of the slag particles, which improve mechanical interlocking with the cement matrix. Additionally, the fine SA particles optimize packing density by filling interstitial voids between aggregates, as observed when concrete is made with industrial by-products [14, 15]. Consequently, these mixtures

are highly suitable for heavy-load structures or applications in aggressive environments where a dense, impermeable matrix is essential [16].

TABLE VII. DENSITY AND STRENGTH OF SCC

Mix ID	Density (kg/m ³)	Compressive strength (MPa)	Flexural strength (MPa)
BSI-N	2227	39.79	4.91
BSI-1	2438	35.04	6.50
BSI-2	2460	44.38	6.70
BSI-3	2646	50.40	7.52

The increase in density is positively correlated with the increase in compressive strength, except for BSI-1. This may be due to the angular shape and texture of the IS, which results in less dense packing around the coarse aggregate. Adding SA as a substitute for fine aggregate can significantly increase compressive strength. An increase in compressive strength of 11.53% occurred in BSI-2 (50% SA), and the largest increase, 26.66%, occurred in BSI-3 (100% SA). This increase is due to SA's finer particle size and sharper shape compared to natural sand. SA is made of rock fragments, which increases the density and bond between particles in the concrete mixture. These fine, angular particles improve the density of the particle arrangement and fill the voids between the IS more effectively. Authors in [17] showed that using SA as a substitute for up to 35% of the fine aggregate can significantly increase concrete's compressive strength. Authors in [18] reported that increasing the aggregate substitution ratio (coarse or fine) with IS also increases compressive strength. This enhancement may be due to improved Interfacial Transition Zone (ITZ) quality and increased aggregate strength. The increase in strength is likely due to IS's high calcium and iron oxide content, which accelerates the hydration process. Unlike compressive strength, flexural strength increased consistently across all replacement aggregate variations compared to control concrete (BSI-N). Flexural strength increased by 32.4% when coarse aggregate was replaced entirely with IS (BSI-1). This indicates IS's better ability to withstand tensile strains that occur during bending.

Flexural strength was the highest in BSI-3 (7.52 MPa), which is a 53.2% increase over BSI-N. This increase is the cumulative result of increased density and pore filling. These findings align with those in [19], where an increase in flexural strength of up to 100% slag replacement was observed, indicating an improved microstructure and better bonding within the concrete matrix.

C. Durability Performance

This study assessed the durability performance based on the results of porosity, sorptivity, chloride penetration depth, and abrasion resistance tests.

1) Porosity

Porosity is the percentage of pores in concrete. The more numerous and interconnected the pores are, the easier it is for aggressive substances, such as water, chloride ions, and carbon dioxide, to penetrate the concrete and reach the reinforcement, triggering corrosion and premature deterioration, as displayed in Figure 2. Compared to normal concrete (BSI-N), which has a porosity of 11.62%, BSI-1 and BSI-2 have increased porosity values by 2.08% and 0.77%, respectively. Meanwhile, BSI-3 has decreased in porosity by 1.09% compared to BSI-N. The high porosity values in BSI-1 and BSI-2 suggest that using IS as a coarse aggregate without SA creates a weaker ITZ and increases voids in the concrete structure. Conversely, the decrease in porosity values in BSI-3 indicates that using SA entirely as a fine aggregate increases concrete density and reduces total pore volume. Lower porosity values indicate better durability and resistance in concrete.

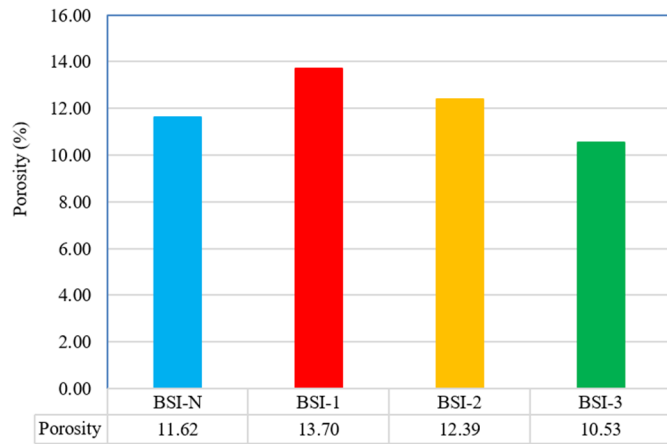


Fig. 2. Porosity of SCC.

2) Sorptivity

Sorptivity testing measures the ability of concrete to absorb water through capillary pores. This property plays an important role in determining concrete durability. Figure 3 presents the results of the IS concrete sorptivity test. This test measures the change in mass of the specimen during the first 6 h after placing it in a container filled with water to determine initial absorption (Si). Then, daily testing is carried out for 8 days to determine secondary absorption (Ss). The BSI-3 mixture had 31.7% lower sorptivity than the control (BSI-N), indicating that

the combination of IS and SA effectively lowers the concrete's water absorption capacity. Conversely, BSI-1 showed a 17.07% increase in sorptivity relative to BSI-N, which correlates with its higher porosity. These findings align with previous research, which established that the use of industrial waste as an alternative aggregate can significantly influence porosity and permeability, depending on its physical characteristics. Specifically, combining IS with a high-performance fine aggregate, such as SA, mitigates the adverse effects of increased porosity on sorptivity values. Authors in [20] found that using industrial waste, such as slag, as an alternative aggregate affects the porosity and permeability of concrete, depending on its physical characteristics.

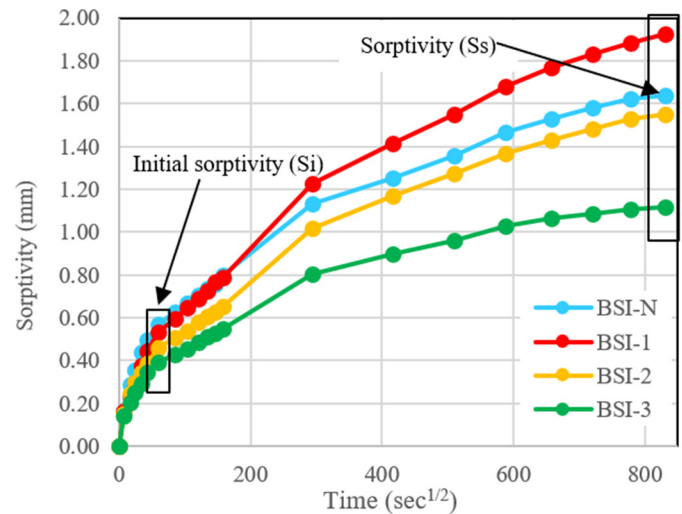


Fig. 3. Sorptivity of SCC.

3) Chloride Penetration Depth

Figure 4 depicts the method for measuring the chloride penetration depth, and Table VIII presents the results. This test was performed on SCC concrete that was exposed to a 5% NaCl solution for 28 days, measuring the extent to which chloride ions can penetrate concrete and potentially cause reinforcement corrosion. The experimental results reveal a nuanced relationship between chloride resistance and internal morphology. Although BSI-2 demonstrated the greatest resistance (12.23 mm), BSI-3's performance suggests that total porosity is not the sole factor in durability. Despite having the lowest total pore volume, BSI-3's higher chloride penetration compared to BSI-2 can be attributed to pore connectivity and tortuosity of the diffusion path.

In BSI-1, the absence of fine SA failed to offset the angular geometry of the IS, resulting in "wall effects" and macro-cavities in the cement paste. Conversely, BSI-2's superior performance suggests an optimal filling effect, wherein SA particles refined the ITZ. The discrepancy in BSI-3, where lower porosity did not result in lower penetration, indicates that, although the matrix is dense, the remaining pores may be more interconnected, providing a more direct route for chloride ion migration. These results confirm that pore size distribution and connectivity play a more critical role in ion transport than

total porosity alone [21]. Authors in [22] found that concretes produced with slag aggregates and powder exhibit lower chloride penetration depths than conventional mixtures. The reduced chloride ingress in the BSI-2 and BSI-3 mixes confirms that using industrial by-products refines the pore structure, restricting the diffusion of aggressive ions into the concrete matrix. Additionally, IS concrete has a denser ITZ and reduced microcracking compared to concrete made without slag due to pozzolanic reactions resulting in a denser microstructure and improved durability [23].

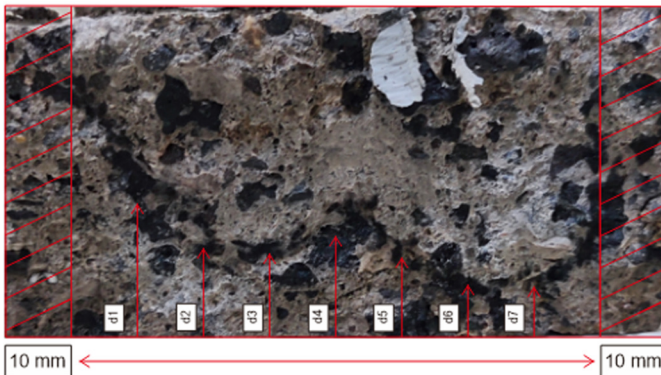


Fig. 4. Measuring penetration depth.

TABLE VIII. CHLORIDE PENETRATION DEPTH

Mix ID	Penetration depth (mm)
BSI-N	21.93
BSI-1	22.54
BSI-2	12.23
BSI-3	17.98

4) Abrasion Resistance

Abrasion testing measures a concrete's resistance to wear due to repeated frictional forces, which is particularly important for concrete used in road and industrial flooring applications. This test uses eight cube specimens with different amounts of IS and SA added. Figure 5 portrays the percentage weight loss (abrasion) versus the number of revolutions. The wear values of BSI-N, BSI-1, BSI-2, and BSI-3 are 43.13%, 29.18%, 27.88%, and 25.08%, respectively. Based on these results, it is evident that the wear value of IS concrete decreases as the percentage of IS and SA increases. Using IS and SA as aggregates in concrete has been shown to increase abrasion resistance and concrete strength. This is thought to be/possibly due to the mechanical properties of IS, which is harder and denser than crushed stone. Additionally, SA is finer and able to fill the pores in concrete more effectively, thus producing a wear-resistant concrete structure.

Overall, this research successfully demonstrates that IS and SA can be used as alternative materials to replace natural aggregates. These materials meet concrete strength standards and improve durability. The current research supports the adoption of environmentally friendly, efficient concrete technology in modern construction.

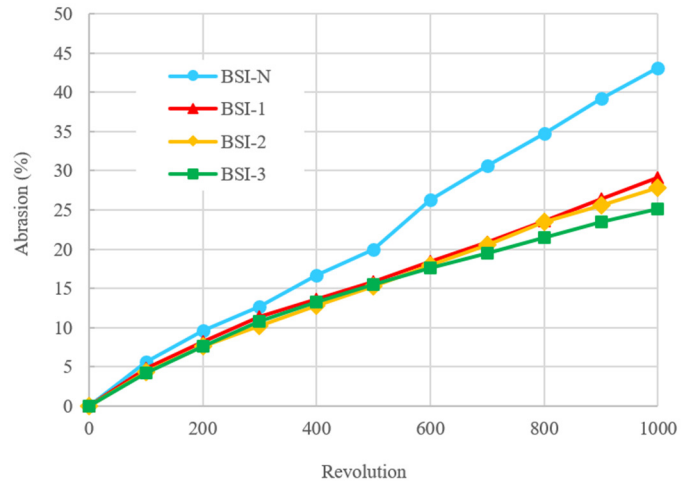


Fig. 5. The number of revolutions to percentage of abrasion.

IV. CONCLUSIONS

The following conclusions can be drawn based on the analysis of Self-Compacting Concrete (SCC) using IS and SA as aggregate substitutes:

- Replacing aggregates with Stone Ash (SA) and Iron Slag (IS) significantly increased the compressive strength of concrete after 28 days. The BSI-3 mix (100% SA + IS) had the highest compressive strength, reaching 50.40 MPa (26.66% higher than normal concrete). This is because industrial waste improves density, particle bonding, and load distribution. The BSI-2 mix (50% SA and IS) showed an increase in compressive strength to 44.38 MPa. However, the BSI-1 mix (0% SA), which used only IS, experienced a decrease in strength due to the lack of a microfine aggregate to fill the voids.
- The combination of IS and SA significantly improves concrete durability, as indicated by decreased porosity, sorptivity, chloride penetration depth, and abrasion. The BSI-2 mixture (50% SA and IS) exhibited the greatest resistance to aggressive ions and had the lowest chloride penetration value (12.23 mm). The BSI-3 mixture (100% SA + IS) had the lowest porosity (10.53%) and lowest abrasion (25.08%), indicating a denser structure and superior long-term durability.
- Based on the EFNARC guidelines, only the BSI-2 mix (50% SA) met the SCC criteria, achieving a slump flow of 650 mm and a T500 time of 3.61 s. Conversely, the BSI-3 mix (100% SA), despite having the best durability, failed to meet the SCC specifications because its slump flow was less than 550 mm. Thus, the proportions must be modified or admixtures must be added to improve its flowability.
- The BSI-2 mix (50% SA + IS) is proposed for industrial buildings, particularly for floor slabs and ancillary structures. It exhibits an optimal balance of compressive strength, durability, and workability, which is essential for structures bearing heavy loads or exposed to aggressive environmental conditions. This composition also supports

sustainable construction practices by utilizing industrial waste as a high-performance construction material.

- Further research will focus on optimizing the BSI-3 mix by adjusting the dosage of the superplasticizer or using a different type to achieve the required workability. This will unlock the mix's superior mechanical and durability properties for SCC applications.

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