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TECHNICAL PAPER

Investigating the mechanical strength, durability and micro-structural properties of slag-based concrete

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Abstract
The use of ladle slag as a replacement for natural aggregates as coarse aggregate in concrete has gained attention in recent years due to its potential benefits in terms of sustainability and waste reduction. The paper aims to investigate the influence of ladle slag as a coarse aggregate replacement on various properties of concrete, including strength, durability, and microstructural changes. The paper may specifically investigate the strength improvement of concrete with ladle slag as coarse aggregate by varying the curing period, comparing the results at 7, 14, and 28 days of curing. In this study, experimental investigations are conducted using 100% Portland slag cement (PSC), 100% processed granulated blast furnace slag sand (PGBFS, iron slag) and partial or full replacement of natural coarse aggregates (NCA) with ladle slag coarse aggregate (LSA) with 0%, 20%, 40%, 60%, 80%, and 100% variations. Results showed the highest increase in compressive strength, flexure strength and high resistance to acid attack in concrete with 20% LSA replacement. Further, to optimize the ladle slag aggregate content, concrete mix with LSA content varying from 5 to 25% was tested, and maximum improvement with 20% LSA was observed. The moderate resistance against chloride permeation is exhibited by concrete mix with LSA, and microstructure shows increased porous structure compared to PSC, indicating the development of C–S–H and the link between C–S–H gels. The diffractograms show the presence of quartz aligned with alite and belite, which is known to result in a high amount of C–S–H gels and an increase in durability.

Keywords Portland slag cement · Ladle slag aggregate · Compressive strength · Acid resistance · Durability · Microstructure

Introduction

Concrete is known to be the second most used material in the world, and it also remains a ubiquitous material [1–3]. However, cement used to produce concrete accounts for at least 8% of all worldwide carbon emissions, giving concrete the largest carbon footprint of any building material [4]. In the process of converting limestone ($CaCO_3$) into Quicklime (CaO), which is used to produce clinker, a critical component of cement, carbon dioxide (CO_2) is generated as a byproduct. Additionally, CO_2 is released during the combustion of fossil fuels such as coal for producing cement. On the other hand, with the rising demand for this multi-phase composite material and the associated immense carbon footprint from the production and operation phase, significant concern is raised among researchers and practitioners for adopting sustainable alternatives [5].

River sand is used as the fine aggregate for the preparation of concrete mix and the durability of concrete is known to be dependent on its cleanness. The colossal consumption of river sand in the construction industry has alarmed the need to conserve the water bodies thus research in the direction to assess the efficacy of various products such as Robo sand or manufactured sand (M Sand), which is obtained by crushing hard stones is recognized [2]. Thus, characterizing by-products such as ladle slag to replace conventional river sand as fine aggregate has been extensively studied.

Ladle slag is a by-product generated during the steel-making process. The production of one ton of steel is expected to produce nearly 15–20% of slag [6], which are usually large aggregated clusters. The low-hydraulic reactivity of

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ladle slag makes it non-consumable hence, the opportunities to reuse ladle slag and reduce the stocking up of pile have gained attention in the recent past [7]. Studies in the recent past have shown that using ladle slag as fine aggregate is significant in improving the strength of cement mortar and concrete. An increase in the 28-day compressive strength of cement mortar with carbonated ladle slag as fine aggregate is found to be higher than mortar with river sand as fine aggregate [8]. The use of ladle slag powdered to fine-sized particles (i.e. 45 µm, 75 µm, and 150 µm) as a supplementary cementitious material or replacement to conventional cement has been studied in the works by [9, 10]. The findings evinced that the high calcium oxide content of the ladle slag as a cementitious material imparts expansiveness in concrete, and a majority of works in the past two decades have focussed on using ladle slag as an activated binder material in concrete [11–15].

The use of recycled aggregates and demolition wastes has been widely studied to eliminate the exploitation of natural aggregates in concrete structures. The use of ladle slag aggregate as a replacement for natural aggregate is studied as both coarse and fine aggregate for the preparation of concrete with ordinary Portland cement [16]. The findings of the study showed a reduction in slump value and an increase in compressive strength with increased replacement compared to concrete with conventional aggregates. The replacement of steel slag as coarse and fine aggregate in M20 grade concrete by Devi and Gnanavel [6] showed that up to 30% replacement of coarse aggregate increased in compressive and flexure strength. Though many studies have used ladle slag as a replacement for fine aggregate [10] and supplementary cementitious material [16, 17] in the concrete mix with Ordinary Portland Cement. There is a lack of substantial study in understanding the reactivity of ladle slag in Portland Slag Cement-based concrete mix.

In this study, the mechanical and micro-level modification of slag-based concrete with ladle slag as a coarse aggregate replacement will be assessed to address its efficacy for use in the concrete mix. The contribution of Portland slag cement as a replacement for Ordinary Portland cement, ladle slag replacement for natural coarse aggregate, and slag sand as fine aggregate in improvising the compressive strength, flexure strength, and durability against acid attack will be the primary objective of this work.

Materials and methodology

Cement

Portland slag cement (PSC), confirming to IS: 455 (1989), manufactured by JSW cement, is used in this work. In the interest of shielding the PSC from humidity exposure, it was stored in the laboratory facility. The initial properties of cement are listed in Table 1.

Table 1 Properties of PSC

Property	Value
Fineness	370 m^2/kg
Initial Setting Time	30 min
Final Setting Time	600 min
Compressive Strength	
3 days	24 MPa
7 days	30 MPa
28 days	58 MPa

Fig. 1 Slag Sand

Fine Aggregate

Processed Granulated Blast Furnace Slag (PGBFS) manufactured by JSW Cement Ltd, conforming to IS 16714: 2018 [18], is used for the preparation of concrete mix shown in Fig. 1. The sieve analysis of PGBFS is classified as Grading Zone III as per IS:383(2016) [19]. The sieve analysis values are shown in Table 2. The comparison of the grain size distribution of river sand with slag sand is shown in Fig. 2. The water absorption of river sand and slag sand was determined as 0.8% and 0.92% as per IS 383–2016.

Coarse aggregate

The coarse aggregates utilized for the concrete mix are ladle slag aggregates collected from Jindal Steel Plant in Bellary District, Karnataka, India shown in Fig. 3. All observable impurities were eliminated during the initiation

Table 2 Sieve Analysis of Slag Sand

IS Sieve Designation	Percentage Passing
10 mm	100
4.75 mm	99.8
2.36 mm	99.6
1.18 mm	85.45
600 µm	34.5
300 µm	17
150 µm	4.6

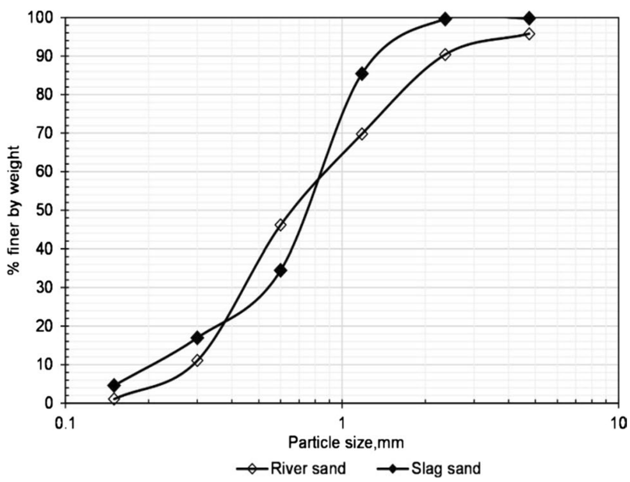

Fig. 2 Grain size distribution of fine aggregates

Fig. 3 Ladle Slag Aggregate

phase of material processing. The sieve size gradation of the ladle slag particles determined as per IS 2386—1963 Part–1(2016) [20] is shown in Fig. 4. The chemical composition of ladle slag is listed in Table 3. The physical properties of ladle slag determined as per IS 2386–1963 are listed in Table 4.

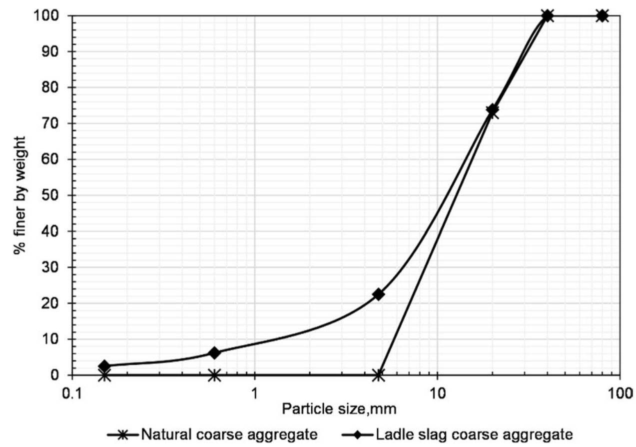

Fig. 4 Grain size distribution of coarse aggregates

Table 3 Chemical Composition of Ladle Slag

Composition	Value (%)
Silica (SiO_2)	14.72
Calcium Oxide (CaO)	42.06
Magnesium Oxide (MgO)	8.06
Total Iron (FeO)	12.93
Total Sulphur (S)	0.034

Table 4 Physical properties of Ladle Slag

Property	Value	Reference
Crushing Value (%)	19	IS 2386—1963 Part—4 (2016)
Los Angeles Abrasion Value (%)	17	
Impact Value (%)	15	
Water Absorption (%)	3.24	IS 2386—1963 Part—3 (2016)
Specific Gravity	3.12	
Bulk Density (kg/l) Loose	1.96	
Bulk Density (kg/l) Rodded	2.15	

Concrete Mixtures

Apart from the aggregate components, all concrete mixtures were prepared whilst keeping all mix design parameters constant (Table 5).

The concrete mixes were prepared as two groups, and the coarser aggregate composition used in these groups is as follows:

- Group 1: This is a standard concrete mix without replacing the natural coarse aggregate with ladle slag steel.

Table 5 Proposed slag-based concrete composition

Material	Composition
Portland slag cement (PSC)	400 kg/m^3
Processed Granulated Blast Furnace Slag Sand (PGBFS)	665 kg/m^3
Ladle Slag Coarse Aggregate (LSA)	1261 kg/m^3
Water	161 kg/m^3
Admixture	1%

- Group 2: In this proposed group, ladle slag replaces natural coarse aggregate in proportions of 20%, 40%, 60%, 80% and 100%.

Experimental methods

The concrete mix prepared using ladle slag as coarse aggregate with the Portland slag cement at varying proportions is shown in the flow chart (Fig. 5).

The methodology for laboratory analysis of fresh and hardened concrete properties to assess the influence of natural coarse aggregate replacement with ladle slag along with detailed micro-level examination is mentioned as a flow chart (Fig. 6).

The designation of concrete mix with proportions and variation in LSA proportion is listed in Table 6.

Fresh concrete property

Slump test

The sampling of materials to test the fresh property of concrete mix was performed as per IS: 1199–1959 and IS 456–2000 [21, 22].

Properties of hardened concrete

Compressive and flexure strength

The compressive strength and flexure strength of cured concrete samples were measured following the guidelines of IS 516–1959 [23]. Predetermined quantities of cement, fine aggregates coarse aggregates and water were used according to the mix design specifications. Mixing them thoroughly using a concrete mixture until a uniform consistency is achieved. The cube moulds were cleaned thoroughly and applied a thin layer of oil to facilitate the easy removal of cubes once they have hardened. The cubes are filled with freshly mixed concrete the filling process is done carefully to avoid segregation and the entrapping of air bubbles. After filling the cube moulds excess concrete is struck off by using a trowel to achieve a level and smooth surface. Three samples were used to calculate the average compressive and flexure strength of each concrete mix. The specimens are cured in the curing tank in water for 48 h ensuring a temperature of 24°C to 30°C. The cube specimens of size 15 cm × 15 cm × 15 cm were prepared as per standard to

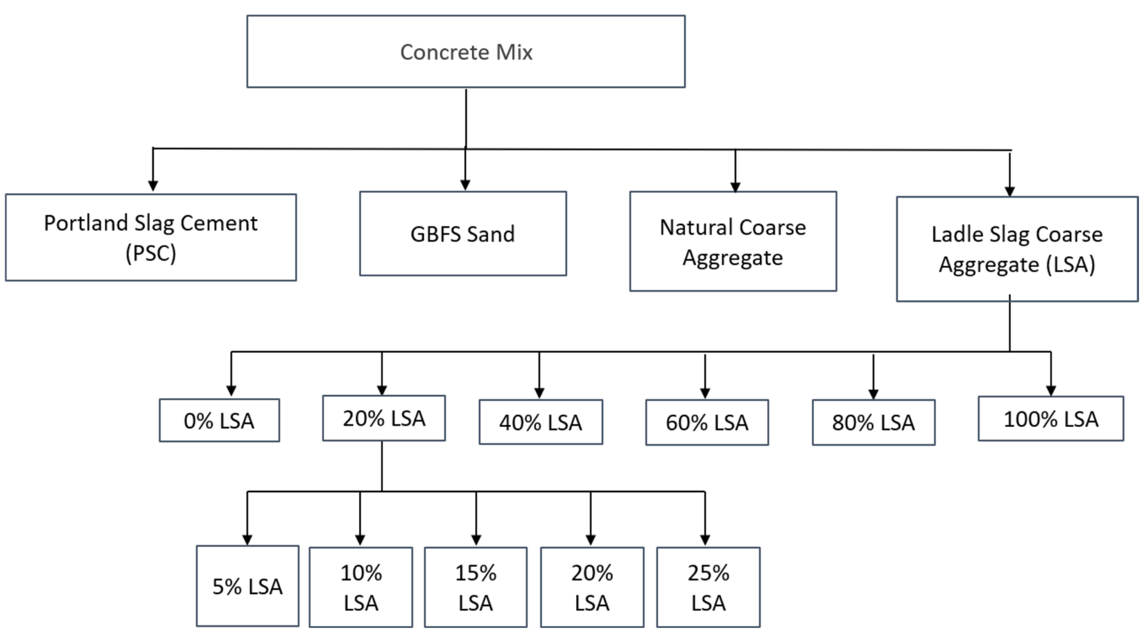

Fig. 5 Framework showing the materials used in this study

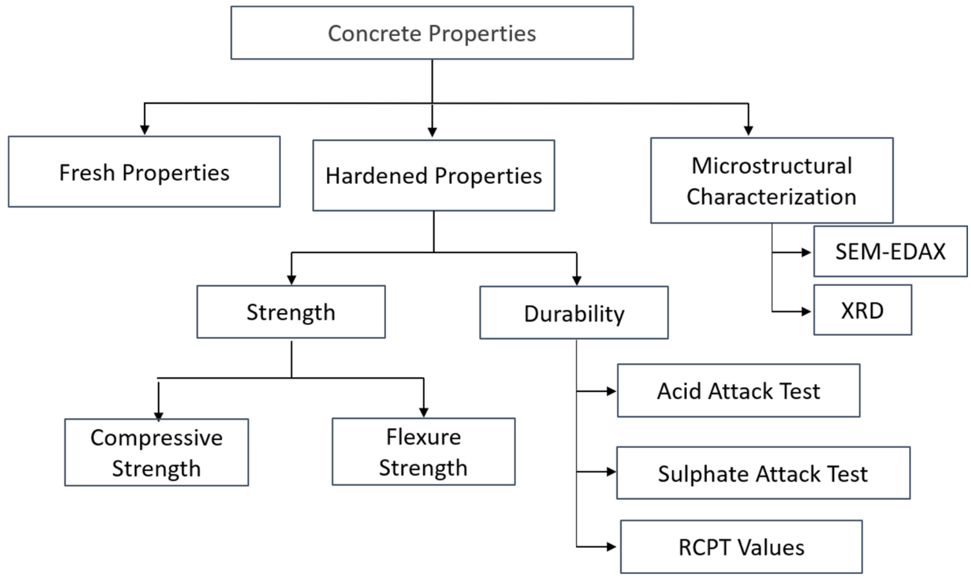

Fig. 6 Methodology representing the experimental phases used in the study

Table 6 Designation of concrete mixes used in the study

S. No	Mix proportion	Designation
1	1:1.66:3.15 (100%NCA)	LA0
2	1:1.66:2.52:0.63 (80%NCA + 20% LSA)	LA20
3	1:1.66:1.89:1.26 (60%NCA + 40% LSA)	LA40
4	1:1.66:1.26:1.89 (40%NCA + 60% LSA)	LA60
5	1:1.66:0.63:2.52 (20%NCA + 80% LSA)	LA80
6	1:1.66:3.15 (100% ladle slag aggregate)	LA100

Table 7 Category of concrete based on chloride ion permeability

Charge passed (Coulombs)	Chloride ion permeability
> 4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
< 100	Negligible

determine the compressive strength. The flexure test specimens of size 15 cm × 15 cm × 70 cm.

Durability

Rapid chloride permeability test (RCPT)

Whiting first introduced this approach in 1981, and it has now been standardized by AASHTO T 277–07 (2008) and ASTM C1202-12 [24, 25]. The test includes applying a 60-V voltage to a cylindrical, vacuum-saturated concrete specimen. The specimen is exposed to a 0.3 M sodium hydroxide solution on one side and a 3% sodium chloride solution on the other. For a total of 6 h, the resulting current is measured every 30 min. Using Eq. (1), which is based on the trapezoidal rule, the total charge passed (in Coulombs) is determined from the current data. Using this "charge passed", the concrete is categorized for its resistance to chloride attack into many classes. The classification of concrete based on resistance to chloride ion permeability is shown in Table 7.

$$Q = 900\left(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{330} + I_{360}\right) \quad (1)$$

where,

Q = charge passed (Coulombs).

I_0 = current measured at the time (t_0), Amperes.

I_1 = current measured at the time (t_i), Amperes.

Acid attack

ASTM C1898-20 [26] was referred to determine the resistance of concrete to hydrochloric acid attack in addition to an assessment of concrete resistance to magnesium sulphate attack to address the durability aspect.

The 15 cm × 15 cm × 15 cm oven-dried concrete cubes were weighed before being fully immersed in the sulfuric acid and sulphate solutions for durability assessment. Triplicate specimens were subjected to the compression strength test and the compressive strength of samples after water immersion were compared to quantify the impact of acid attack.

Micro-level characterization

Scanning Electron Microscope (SEM) and X-ray diffractogram (XRD) analysis were used to analyse the change in the morphology and chemical composition of cured concrete samples. The concrete mix samples after the compressive strength test were carefully extracted and used immediately for performing SEM and XRD analysis.

Results and discussion

Slump test

The slump value of concrete with slag sand replacement is shown in Fig. 7. The slump value of concrete decreased with an increase in slag sand replacement (i.e. 10%, 20%, 30%). The 30% replacement of fine aggregate with slag sand resulted in an 80% reduction in slump value. The higher water absorbing capacity of slag sand leaves less water for the hydration of mortar. Thus, lesser workability of concrete and a similar observation has been reported in concrete with steel slag as fine and coarse aggregate [6, 16].

Strength tests

Compressive strength

The compressive strength value which indicates resistance offered by the concrete mix to the applied maximum axial stress is compared for samples prepared with varying water/cement ratios. The results are plotted in Fig. 8. The results show that compressive strength decreased by nearly 14% and 22% with an increase in water/cement ratio from 0.50 to 0.51 and 0.53. The increase in the fluidity of the concrete mix leads to an increase in the porosity with an increase in the water-cement ratio. Thus, the bonding between the particles is less, attributing to a reduction in compressive strength.

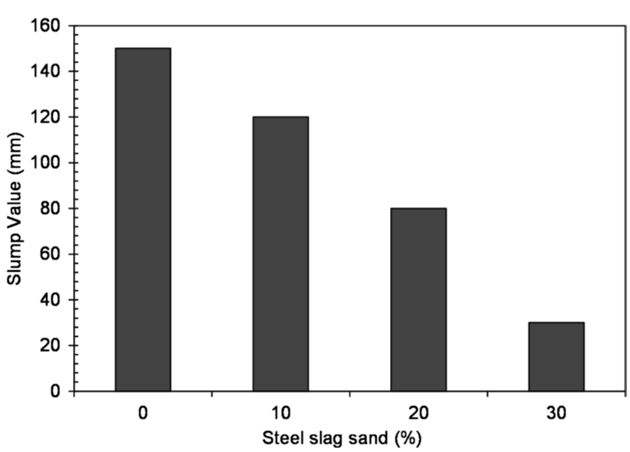

Fig. 7 Variation in slump value with increase in NCA replacement with LSA

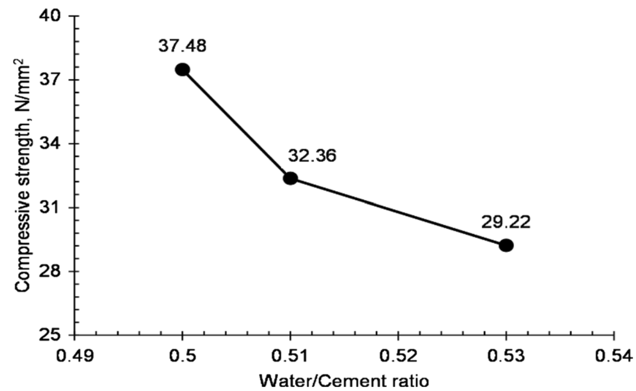

Fig. 8 Target compressive strength with variation in water/cement ratio

Figure 9 displays the compressive strength values of concrete after 7, 14, and 28 days and the increase in ladle slag content. The compressive strength of concrete with 20% LSA replaced for NCA increased by 14%, 12% and 5%, with an increase in the curing period by 7, 14 and 28 days, respectively. The further increase in LSA content did not significantly contribute to an increase in compressive but showed improved strength with an increase in the curing period.

Figure 10 displays the compressive strength values of concrete after 7, 14, and 28 days, with a 5% variation in ladle slag coarse aggregate, with the greatest compressive strength at 20% ladle slag coarse aggregate. The debris of the materials are shown in Fig. 11a and b.

Flexural strength

The maximum bending stress that the specimen can withstand before failure is measured by the flexural strength test.

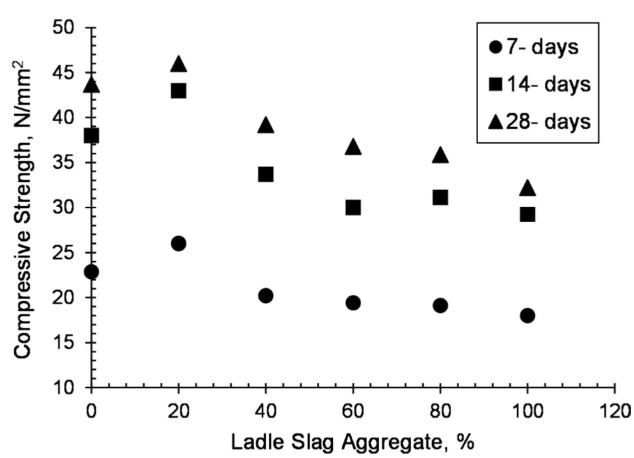

Fig. 9 Compressive strength of concrete with varying LSA content

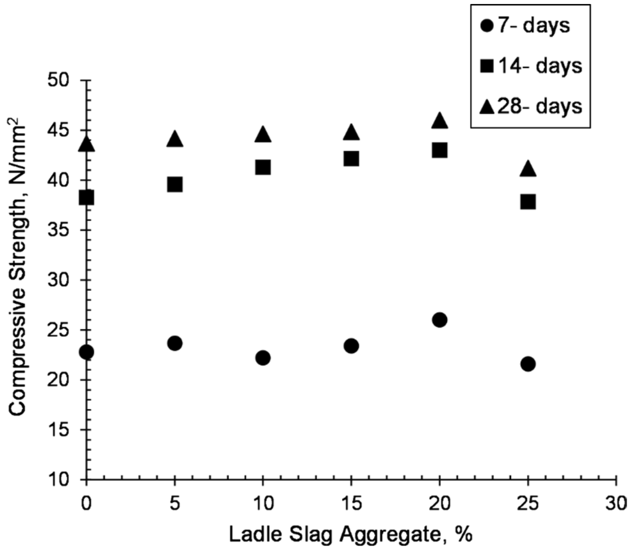

Fig. 10 Compressive strength of concrete with redefined LSA contents

In this study, three specimens from each group were tested to flexure to failure using a single-point load. Figure 12 displays the flexural strength values of concrete after 7, 14, and 28 days, with a 20% variation in ladle slag coarse aggregate, with the greatest flexural strength at 20% ladle slag coarse aggregate. Further, the variation in flexure strength is confirmed by redefining the LSA content in increments of 5%, and the results are shown in Fig. 13. A similar response of flexure test results as that of compression test is observed in this study and a similar observation is reported by [17].

Figure 13 shows the flexural strength values of concrete after 7, 14, and 28 days, with a 5% variation in ladle Slag coarse aggregate, with the greatest flexural strength at 20% ladle slag coarse aggregate.

Acid Attack Test

When subjected to harsh environments and aggressive chemical attacks, concrete loses some of its durability. Acid durability variables are needed to be addressed to increase

Fig. 11 **a** and **b** Debris of material

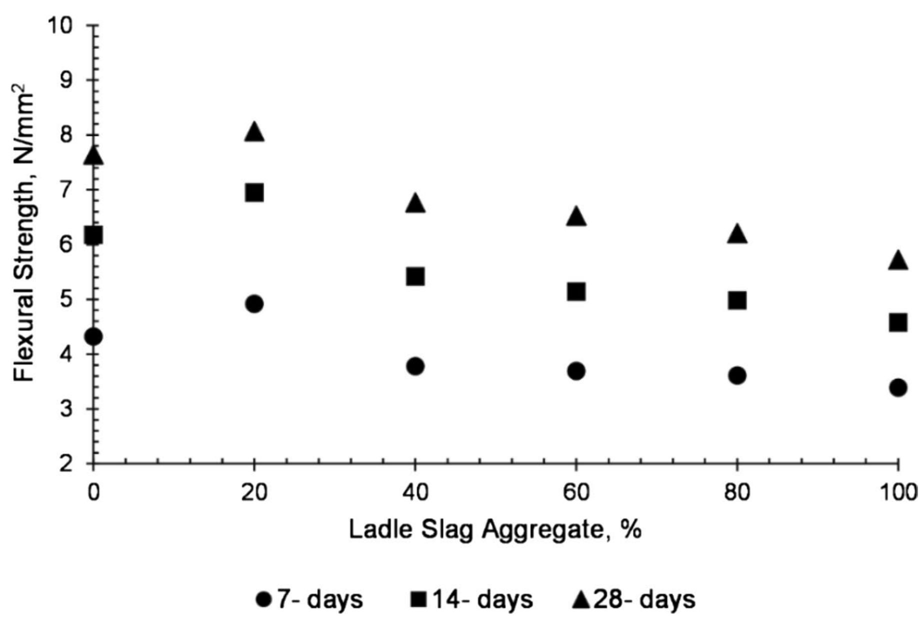

Fig. 12 Flexure strength variation with varying LSA content

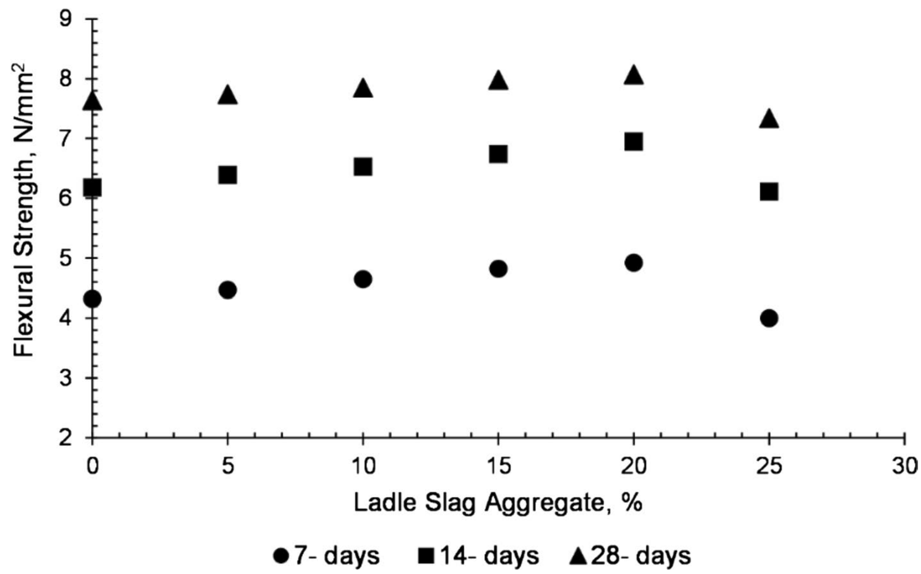

Fig. 13 Flexure strength variation with redefined LSA contents

the longevity of concrete. The compressive strength of M40 with varying percentages of ladle slag replacement as coarse aggregate before and after the acid attack procedure, along with a comparison of weight variation, is listed in Table 8. The comparison of compressive strength is shown in Fig. 14. The loss of compressive strength was reduced with the replacement of coarse aggregate using 20% LSA from 3.61% to 2.6%, whereas, with a further increase in LSA content, the rate of strength loss increased.

Sulphate attack test

The compressive strength and weight loss of samples subjected to sulphate attack is compared with that of concrete without sulphate attack. The weight loss observed in different concrete mixes is listed in Table 9.

The compressive strength variation before and after sulphate attack of concrete mixes with varying percentages of LSA replacement is shown in Fig. 15. The compressive strength was reduced by a maximum of about 7% for concrete with 40% LSA replacement, whereas minimum loss of strength was observed in the concrete mix with 20% LSA. The loss of compressive strength is in the range of 5% to 6% for remaining concrete mixes, indicating the stabilization in strength loss.

Durability test

The resistance to chloride penetration is influenced by changes in temperature, humidity, and chemical reactivity of concrete during the curing period. RCPT test results of concrete with 20% ladle slag as a replacement to coarse aggregate after 28 and 56 days of controlled curing are compared in Fig. 16. The reduction in electrical conductivity with an increase in the curing period is observed. The resistance of ladle slag replaced as coarse aggregate in M40 concrete with Portland slag cement falls under the category of moderate resistance, and a similar observation has been reported by [6]. The faster rate of pozzolanic reaction and increased homogeneity of the concrete mix with an increase in the curing period are known to contribute to the reduction of chloride permeation.

Table 8 Weight Loss Due to Acid Attack Test Results

Concrete Mix	Weight before acid attack (kg)	Weight after the acid attack (kg)	Reduction in Weight (%)	Reduction in Compressive Strength (%)
LA0	8.56	8.12	5.4	3.61
LA20	8.62	8.18	5.11	2.60
LA40	8.64	7.89	8.63	3.30
LA60	8.70	7.90	9.10	5.40
LA80	8.80	7.86	10.68	6.70
LA100	8.90	8.10	8.90	6.11

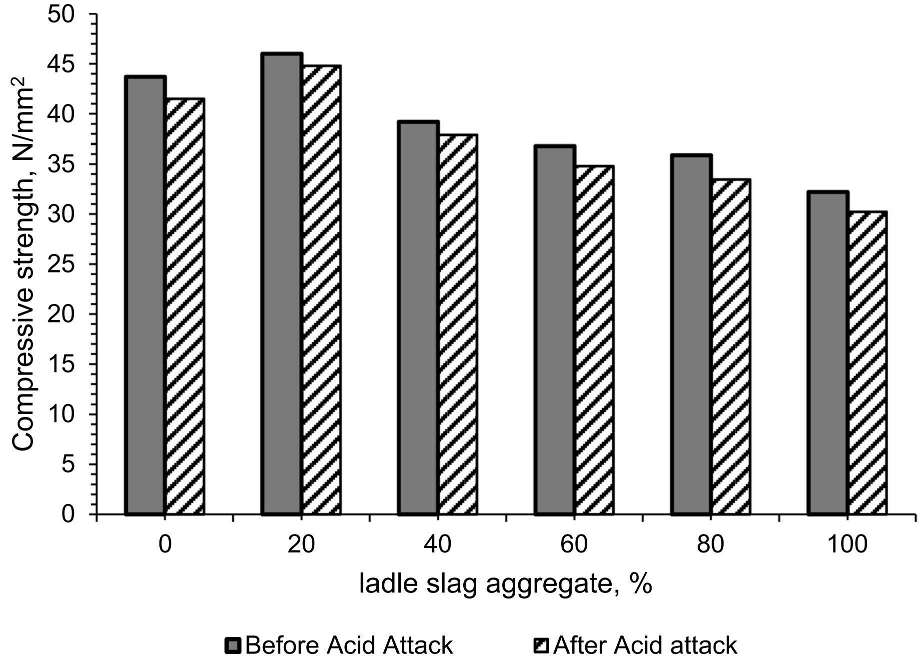

Fig. 14 Compressive strength before and after an acid attack

Table 9 Weight loss due to sulphate attack test results

Type of Concrete	Weight before Exposure (kg)	Weight after Exposure (kg)	Reduction in Weight (%)	Reduction in Compressive Strength (%)
LA0	8.56	8.23	3.85	6.17
LA20	8.62	8.22	4.60	2.21
LA40	8.64	8.58	6.90	6.93
LA60	8.70	8.26	5.05	6.08
LA80	8.80	8.21	6.70	6.10
LA100	8.90	8.54	7.17	5.18

X-ray diffractogram analysis

The presence of Quartz (SiO_2), Alite (C_3S), and Belite (C_2S) was observed for the control concrete mix (Fig. 17), and this can be attributed to the possibility of the formation of a high proportion of calcium silicate hydrate gels and increased durability [27, 28]. The interface bonding between the hardened aggregate and cementitious paste consisting mostly of silicates with high crystallinity is also observed.

The XRD diffractogram of concrete with PSC (Fig. 18) shows the reduction in the intensity of Quartz, Alite and Belite, confirming the intrinsic reactivity occurrence and formation of cementation products. The reduction in base width of reactive alite and belite in Fig. 18 compared to that observed in Fig. 17 at Bragg angles 26°, 55°, and 68° also confirms the participation of C_3S and C_2S in hydration to form hydrate compounds.

Scanning electron microscopic analysis

The change in the morphology and the surface texture due to the formation of cementation bonding with an increase in curing time in the concrete mix with 20% ladle slag replacement is compared with that of the control sample using SEM images, as shown in Figs. 19, 20 and 21.

The concrete mix appears more porous than the PSC, indicating the slow pozzolanic reaction rate at the earlier stages of curing. The comparison of scanning electron micrographs obtained for the control concrete mix (Fig. 19) and PSC concrete mix after 28 and 56 days (Figs. 20 and 21) of curing shows a clear morphological change indicating the densification of the concrete mix. Thus, increased strength is evinced as discussed in an earlier section.

The increase in the curing period exhibits the porous structure of the concrete mix, indicative of the weak

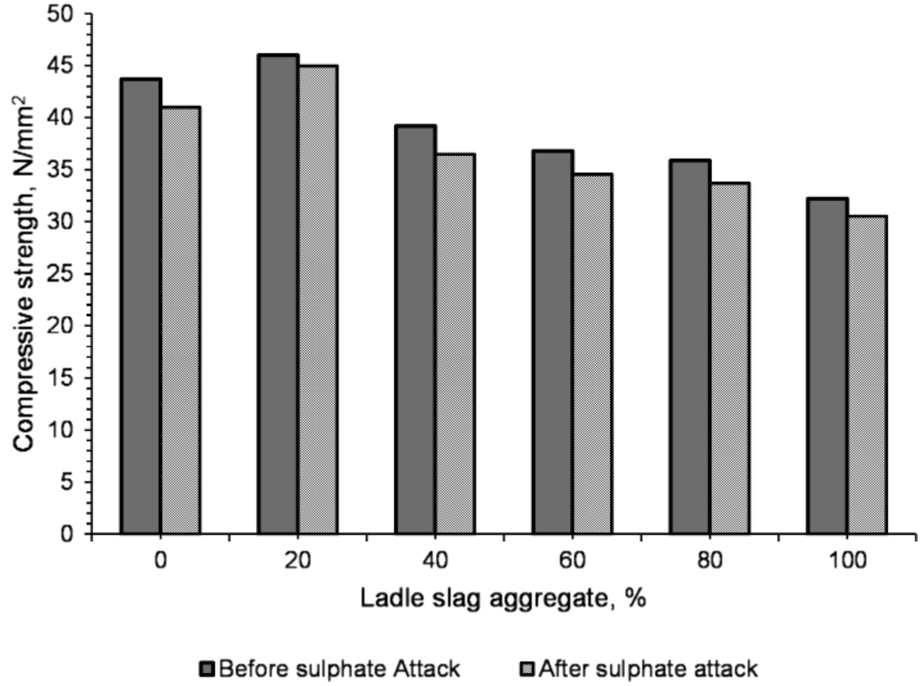

Fig. 15 Compressive strength before and after sulphate attack

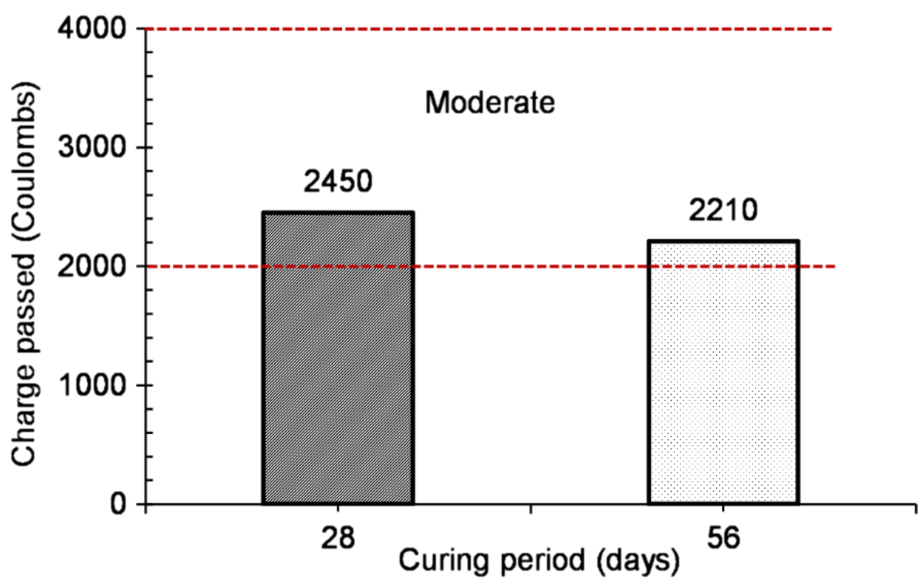

Fig. 16 Variation of chloride permeability with variation in the curing period

development of C-S-H and their link with C-S-H gel. The calcium hydroxide generated during cement hydration might be the consequence of interaction with the active amorphous silica present in slag and cement to create C-S-H gel, which contributes to the mechanical and durability aspects of concrete [29–31].

Conclusion

Ladle slag is an industrial byproduct that is known to impact the environment. Thus, a competent way of reusing steel slag is necessary to balance sustainable development and environmental preservation. Ladle slag has shown enhancement in strength and durability

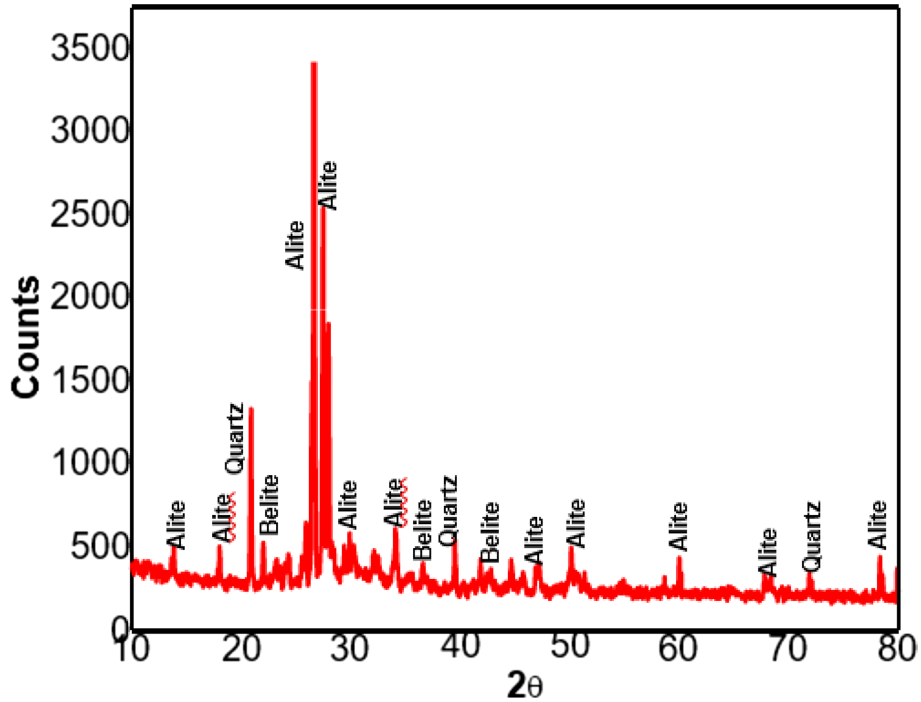

Fig. 17 X-ray diffractogram of control concrete mix used in the study

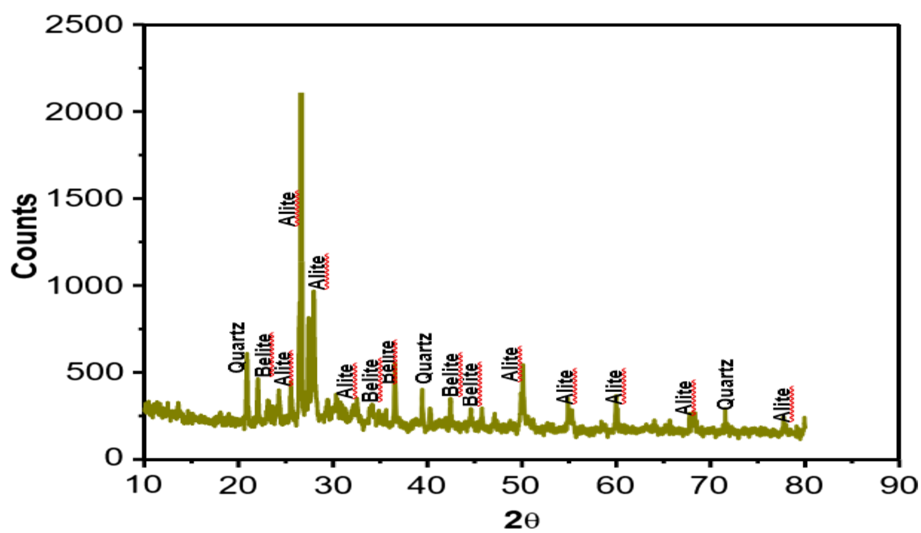

Fig. 18 X-ray diffractogram of concrete mix with PSC

of concrete and mortar mix when used as an aggregate replacing conventional aggregates. This research attempts to investigate the effect of replacing the natural aggregates with ladle slag aggregate in terms of strength, durability and microstructural modifications. The conclusions of the findings are as follows:

- The fresh properties of concrete have shown lesser improvement which can be attributed to the higher density, surface roughness and water absorption of ladle slag used as fine and coarse aggregate.
- Based on the results of compressive strength and flexural strength after 7 days, 14 days, and 28 days of curing, the optimum of 20% LSA is an effective proportion to replace natural coarse aggregates.
- The compressive strength increased with the increase in the curing period by 7, 14 and 28 days by 14%, 12% and 5% due to the replacement of NCA with 20% LSA. The flexure strength of the concrete also increased by 14%, 13% and 5.6% and followed a similar trend of reduction in the rate of increase with the increase in the curing period.

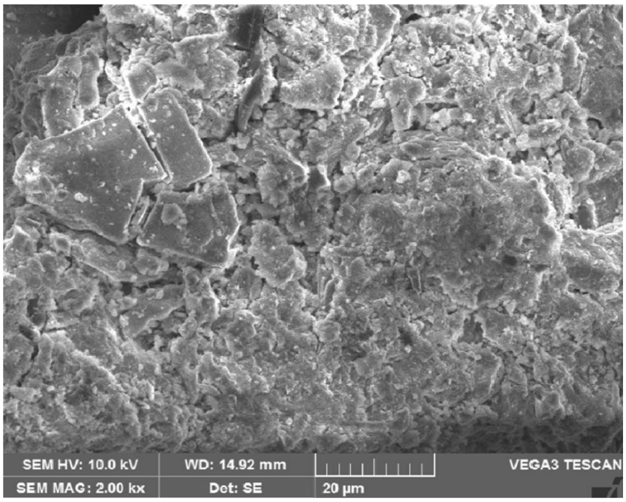

Fig. 19 Scanning Electron Micrograph of control concrete mix

- The acid attack test results showed a lesser rate of decrease in compressive strength loss (approx. 2.6%) in the case of concrete mix with 20% LSA, whereas the rate of strength loss increased with a further increase in NCA replacement with LSA. Sulphate attack also resulted in a similar trend of strength loss with a lesser rate in the LA20 concrete mix.
- The results of the acid attack test indicate that the ladle slag with 20% natural coarse aggregates for 28 days is within the limited value.
- The increase in the curing period did not significantly alter the resistance of the LA20 concrete mix to chloride ion permeability, and the concrete falls under the category of moderate resistance.
- The dominance of alite and belite in cement confirms the high amount of cementitious gel formation, increasing the strength and durability of the concrete mix.

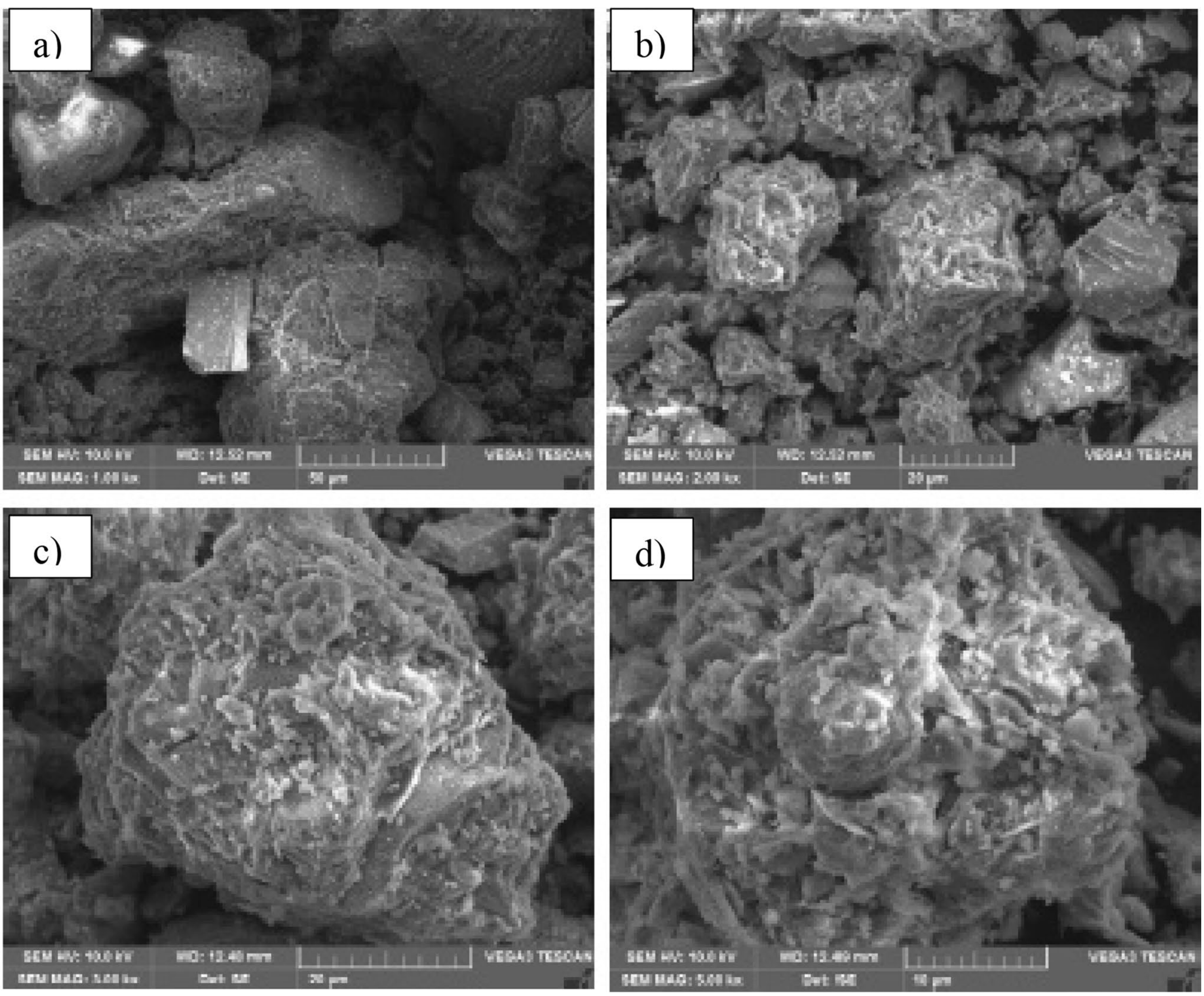

Fig. 20 Scanning electron micrographs of LA20 concrete mix after 28 days of curing

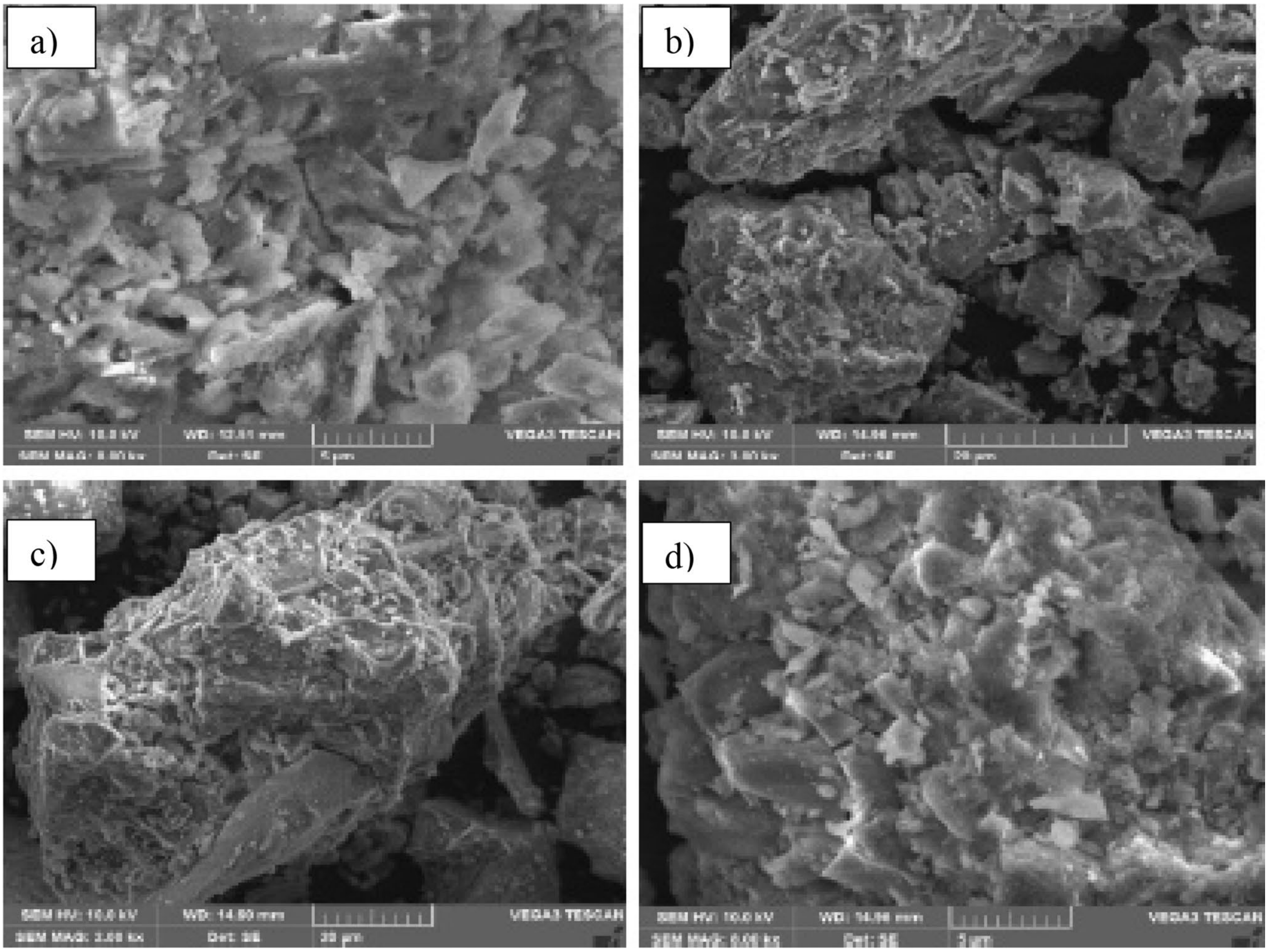

Fig. 21 Scanning Electron Micrographs of LA20 concrete mix after 56 days of curing

- The increase in the porous structure of LA20 concrete mix with an increase in the curing period is indicative of the insubstantial development of C-S–H and their link with C-S–H gel. The calcium hydroxide generated during cement hydration might be the consequence of interaction with the active amorphous silica present in slag and cement to create C-S–H gel, which contributed to the mechanical and durability property of slag-based concrete.

The findings of the study confirm the efficacy of steel slag waste (i.e. ladle slag) to be used as a sustainable material to replace natural aggregate used in the concrete mix such that there is a significant increase in the strength, durability and decrease in the environmental burden.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval I assure you that I am committed to conducting this research in full compliance with ethical standards and regulations.

Informed consent Informed consent was obtained from all individual participants included in the study.

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