ADVANCES AND INNOVATIONS IN UTILIZING STEEL SLAG AGGREGATE FOR SUSTAINABLE CONCRETE CONSTRUCTION: A COMPREHENSIVE REVIEW

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ABSTRACT

Slag disposal yards are commonly used for the storage of steel slag, a solid waste that is generated during the smelting of basic steel. Numerous land resources have been heavily occupied throughout time due to the huge production of steel slags and the ongoing usage of residual yards, raising serious environmental issues. Although steel slag particles have the potential to be used as concrete aggregates, they have low volume stability. Direct use of untreated steel slag aggregate (SSA) in concrete can result in problems including spalling and cracking. But the treated steel slag aggregate has a positive impact on concrete properties. However, SSAC outperforms concrete constructed with natural aggregates (NAC) in terms of mechanical characteristics and durability. The current study compares, evaluates, and summarizes the mechanical, chemical, and physical characteristics of steel slags. Additionally, it offers a summary of current advancements in treated steel slag aggregate concrete (SSAC). The report concludes by outlining potential directions for future research in this area to spur more inquiries and support decision-making.

Keywords: *: Steel slag, steel slag aggregate concrete, mechanical characteristics, durability*

1. INTRODUCTION

The most common building material used worldwide is concrete, which is consumed at roughly 12 billion tons a year (Hosseinnezhad et al., 2023). By mass, 10–20% cement, 70–80% natural aggregate (NA), and 5–10% water typically make up concrete (Abukersh & Fairfield, 2011). Excessive demand for concrete is depleting high-quality river sand and gravel, raising concerns about resource scarcity. Local resources are superior, but allocation is often inequitable. The intensifying demand exacerbates shortages in the concrete industry, as the use of river sand and gravel remains indispensable.

As a substitute resolution to the existing issue. Major irreversible environmental problems are caused by the storage of coal ashes (fly ash and bottom ash) at thermal power plants, the release of steel slag and other slag from iron and steel factories into the environment, and the expensive disposal of these materials. In the construction industry, significant initiatives pertaining to sustainable building materials have commenced. Due to these initiatives, numerous studies on steel slag, one of the most promising waste materials, have been conducted. (Brand & Roesler, 2015). Higher compressive strength can be achieved by replacing fine aggregate with steel slag while taking size distribution into account (Devi & Gnanavel, 2014). Steel slag is currently used as fine and coarse aggregates for concrete, as an asphalt pavement material on highways, as a raw material for clinker, as ballast for railways, and as a filler material in various excavations. Steel slag's release into the environment in the past may have posed a serious environmental threat. By using steel slag in these kinds of applications, we can slow down the depletion of our finite natural resources and, to some extent, address the environmental issues brought on by trash.

Steel slag may be useful in fostering a long-term partnership between the steel and concrete sectors. Steel slags have the potential to serve as hydraulic materials since C_2S, C_3S, C_4AF, and C_3A are typical Portland cement mineral phases. Steel slags can therefore be recycled by finely powdering them and using them as an additional cementitious material. It has been demonstrated that adding 10–20% steel slag powder instead of cement does not reduce the system's mechanical strength (Zhu et al., 2021) but lengthens the blended slurry's settling period (Zhao et al., 2022). As steel slag contains a high concentration of iron oxides, it can also be used as a corrective raw material for iron in the cement production process. Steel slags' poor grinding performance is a drawback (Iacobescu et al., 2011). The energy required for grinding steel slag particles into fine powder will rise, as will the mill fault ratio. The use of steel slag as an additional cementitious material and as a raw material for cement is severely limited by higher equipment maintenance and replacement costs.

The focus of the study is to gather all the knowledge of chemical, mechanical and physical properties of different types of steel slag from studying the previous works. This research offers a wealth of fresh data on the uses of steel slag in the cement and concrete industries from an alternative angle. Ultimately, the present research lacunae are delineated, and forthcoming research requirements are pinpointed.

2. CHARACTERISTICS OF STELL SLAG

2.1 Chemical Characteristics

The primary quality of concrete is strength. Aggregates are inert elements scattered throughout cement paste, whose strength is primarily influenced by its form, surface roughness, and cleanliness. It is hereby reported that completely smooth coarse particles reduced concrete strength by 10% as compared to when the aggregates were roughened.

Table 1 shows the comprehensive data that was gathered over a five-year period from the literature. Steel slag is primarily made up of several oxides; its concentration of CaO, SiO_2, Fe_xO_y (which stands for Fe, FeO, Fe_2O_3, and Fe_3O_4), Al_2O_3, and MgO is close to 90%, with the other oxides being P, Mn, S, Ti, Na, K, Sr, and other oxides. Although the chemical compositions of basic oxygen furnace

(BOF) and electric arc furnace (EAF) steel slags are largely similar, their distinct steelmaking processes allow for the analysis of the prevalence of greater amounts of particular components. Whereas the concentrations of SiO_2, Fe_xO_y, and Al_2O_3 are higher in EAF steel slag, the percentage of CaO is higher in BOF steel slag. Moreover, steel slag has been found to contain oxides of Cr, Pb, V, Mn, Zn, and other heavy metals (Pattanaik et al., 2022). Heavy metal oxide content rises when alloying materials are added during the smelting of EAF steel (Halli et al., 2020; Roy et al., 2018).

In steel slag, one can see about ten different types of mineral phases. The most prevalent mineral phases found in BOF steel slag are srebrodolskite (C_2F), brown millerite (C_4AF), larnite (C_2S), alite (C_3S), and wustite (FeO). The most prevalent mineral phases found in EAF steel slag are quartz (SiO_2), larnite (C_2S), wustite (FeO), magnetite (Fe_3O_4), and gehlenite (C_2AS). Steel slags have larger C_2S, C_3S, and C_4AF crystals than cement, and the concentration is substantially lower (Martins et al., 2021). In steel slag, hydrated inert mineral phases such as C_2S, gehlenite, and CaO-FeO-MnO-MgO solid solution only function as fillers and are unable to produce new products during the hydration process. Only C_4AF, C_3S, and CaO can react with water and exhibit low hydration activity; BOF and EAF steel slags lack pozzolana characteristics (Mahieux et al., 2009). There have also been reports of calcite ($CaCO_3$), portlandite ($Ca(OH)_2$), and brucite ($Mg(OH)_2$) in earlier literature. These mineral phases are primarily generated during the aging process of steel slag (Zhang et al., 2015).

Table 1: Chemical compositions of steel slags in the latest literature.

Type	**Year**	**References**	**Chemical Composition**									
			CaO	**SiO_2**	**Fe_xO_y***	**Al_2O_3**	**MgO**	**P_2O_5**	**Mn_xO_y***	**SO_3**	**TiO_2**	**Na_2O + K_2O**
BOF	2022	(Ho et al.,2022)	36.53–42.80	10.56–19.62	16.85–24.23	3.05–7.00	2.01–8.41	1.15–2.77	1.84–3.90	0.5–0.79	0.5–1.01	0.15
BOF	2021	(Kaja et al.,2021)	36.6–43.48	8.8–18.9	16.64–32.2	1.78–9.84	3.64–10.6	0.65–2.5	2.53–5.4	0.2–1.74	0.2–1.1	0.1–0.6
BOF	2020	(He et al.,2020)	37.6–49.66	9.86–17.4	8.5–27.3	1.4–9.3	2.51–9.2	0.05–2.32	0.4–4.8	0.22–1.1	0.3–0.68	0.04–0.61
BOF	2019	(Xu et al.,2019)	41–50.7	9.45–20.92	14.80–27.03	0.75–5.33	2.3–10.11	1.73–2.11	1.35–4.62	0.03–0.52	0.41–1.23	0.08–0.67
BOF	2018	(Lu et al.,2018)	38.5–45.17	11.08–18.46	15.57–29.55	1.01–5.37	4.67–9.95	1.15–1.69	0.42–4.39	0.01–0.75	0.45–2.44	0.09–0.58
EAF	2022	(Li et al.,2022)	24.53–55.21	12–22.42	4.4–46.74	3.01–12.6	3–8.5	0.03–0.5	0.33–5	0.143–0.4	0.22–6.16	0.12–3.04
EAF	2021	(Amani et al 2021)	24.53–35.62	10.89–20.29	16.5–36.06	4.07–9.16	1.99–12.4	0.56–1.1	0.84–6.28	0.03–0.36	0.16–0.78	0.05–0.66
EAF	2020	(Le et al.,2020)	19.4–51.23	8.59–21.99	16.78–38.7	1.29–12.2	2.97–7.53	0.311–1.52	0.3–7.9	0.205–0.94	0.441–1.02	0.31–1.51
EAF	2019	(Lim et al.,2019)	27–37.96	14.56–19.1	25.8–34	4.25–13.7	2.5–7.62	1.08–1.83	2.45–5.4	0–0.69	0.04–1	0.16–0.29
EAF	2018	(lam et al.,2018)	22.5–38.86	9.06–20.3	22.3–35.4	3.59–15.1	3–7.72	0.2–1.5	0.48–7.35	0.42–0.74	0.38–2.11	0.13–1.7
BOF EAF		Occurrence range	36.53–50.7 19.4–55.21	8.8–20.92 8.59–22.42	8.5–33 4.4–46.74	0.75–9.84 1.29–15.1	2.01–10.6 1.99–12.4	0.05–3 0.03–1.83	0.4–5.4 0.3–7.9	0.01–1.74 0–0.94	0.2–2.44 0.04–6.16	0–0.67 0.05–1.7
BOF EAF		Average values	41.68 30.88	14.99 16.77	23.66 29.26	3.70 7.75	5.95 5.09	1.74 0.65	3.12 3.79	0.40 0.92	0.78 0.36	0.26 0.49

Fe_xO_y* refers to Fe, FeO, and Fe_2O_3. Mn_xO_y* refers to MnO and Mn_3O_4.

2.2 Physical and Mechanical Characteristics

The physical and mechanical indices of granite, basalt, and SSA as reported in the most recent literature are displayed in Table 2. Because of the elevated concentration of metal oxides, particularly manganese and ferrite oxides (Zhang et al., 2019), SSA often has specific gravities of 3000 kg/m^3, which is 10–50% greater than natural aggregates (NA). The specific gravity of the EAF steel slag is marginally higher than that of the BOF steel slag due to the higher ferrite and manganese oxide concentrations in the former, as shown in Table 2.

Table 2: Physical and mechanical properties of steel slag aggregate in the latest literature.

Type		**Specific Gravity (kg/m^3)**	**Los Angeles Abrasion (%)**	**Crushed value (%)**	**Polished value (%)**	**Needle Flake Content (%)**	**Water absorption(%)**	**Reference**
BOF	Occurrence range	3000-3750	11.5-19.6	3.6-14.4	49-62	5.9-9.8	1.07-3.54	(Ho,J.,et al.,2022)
BOF	Average values	3370	15.84	7.96	54	7.81	2.12	(Costa et al.,2022)
EAF	Occurrence range	3000-3900	13.3-25.9	5.99-24.26	N/M*	0-9.42	0.922-2,93	(Lam et al.,2018)
EAF	Averege values	3530	17.93	14.54	N/M*	3.12	1.94	(Roy et al.,2018)
Basalt	Occurrence range	2500-3000	8-14	5-12	45-55	-	0.3-1.5	(Lang et al.,2019)
Granite	Occurrence range	2400-2800	18-22	19-24	45-56	-	0.2-1.2	(Zhang et al.,2019)

SSA has good mechanical qualities, such as great resistance to abrasion and impact and strong crushing and shear strength. It performs better than granite and limestone gravel in terms of crushing, Los Angeles abrasion value, and polishing values (Table 2). SSA exhibits low concentrations of needle-like particles and sub-angular to angular particles. These characteristics prevent the particles from shattering under extreme pressure. Furthermore, the surface texture of SSA's particles is significantly rougher than that of NA due to the honeycomb holes and tiny "dust" on its surface (Ziaee & Behnia, 2020; Yang et al., 2020).

The average water absorption values of steel slag particles are 2.12% and 1.94%, respectively, which are greater than those of NA. Water can be stored in the steel slag's non-interconnected pores. It was being revealed that although the process of absorption was comparatively slow, the water absorption of BOF steel slag was higher than that of limestone aggregate. Limestone took only 8 hours to reach the saturated state, but BOF steel slag took 24 hours. (Sun et al., 2021)

3. EFFECTS OF TREATED SSA IN CONCRETE PRODUCTION

Concrete's basic characteristics, like its strength, durability, and suitability, are closely related to the caliber and characteristics of the mixing ingredients used in its manufacture. In this regard, one of the most important elements of concrete is aggregate (Qasrawi et al., 2009). Concrete is created by binding aggregates which are made by using natural resources to smash large stones with cement paste (Maslehuddin et al. 2003).

For many years, the uncontrolled use of natural resources in the manufacturing of concrete has resulted in significant environmental issues. Unrestrained removal of sand and gravel from stream beds has resulted in environmental harm. Recycling materials in various forms for use as concrete aggregates has grown in popularity in recent years. Examples include using slag from various metallurgical sectors and fine-crushed and sieved pebble stone from construction detritus in place of natural aggregate (Pellegrino & Gaddo, 2009). Iron oxide content is high, while amorphous silica content is low in steel slag. It cannot be used in blended cement because, in comparison to granulated blast furnace slag, it exhibits little or no pozzolanic activity. Thus, the primary application of steel slag is as an aggregate substitute. For constructions like bases, retaining walls, bulwark blocks, acoustic barriers, and radiation insulators, the high density of steel slag is advantageous (Manso et al., 2006).

The mechanical characteristics and durability of concrete using steel slag aggregate were compared to concrete made with crushed limestone aggregate in a study (Maslehuddin et al., 2003). The bulk density, compressive strength, and permeability of the steel slag aggregate concrete reported in this work are shown in Figures 1 and 2.

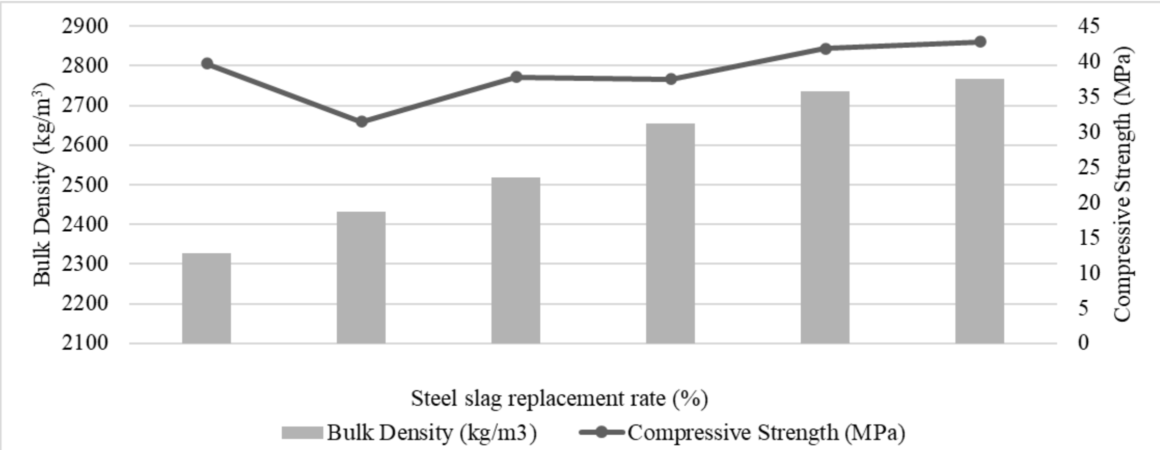

Figure 1: Compressive strength of concrete with steel slag aggregate (Maslehuddin et al., 2003).

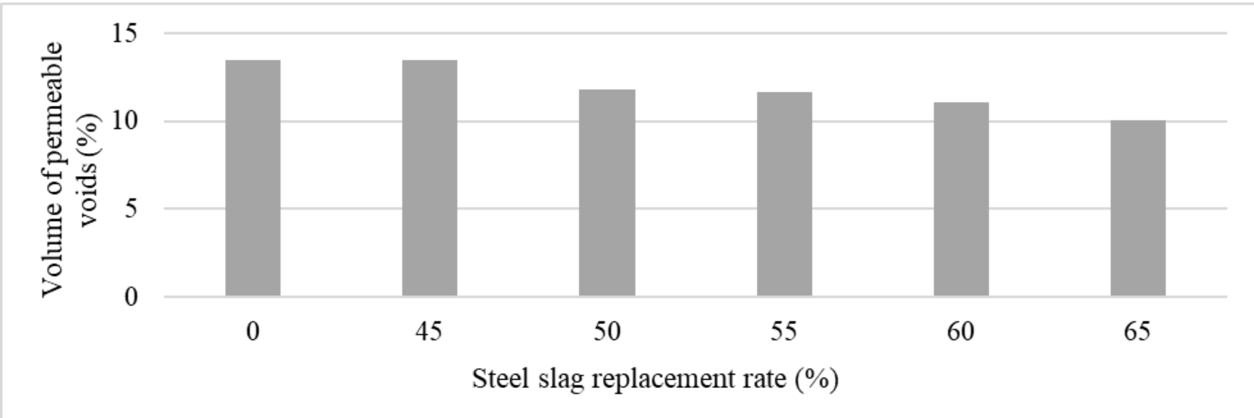

Figure 2: The volume of permeable voids of concrete with steel slag aggregate (Maslehuddin et al., 2003).

In the study, concrete mixes with steel slag showed higher specific bulk gravity than those with crushed limestone. As aggregate ratios increased, so did the compressive strength, with steel slag mixes exhibiting greater strength than crushed limestone at the same ratios. Higher steel slag rates led to reduced permeable pores, enhancing workability and achieving higher strengths in the concrete (Maslehuddin et al., 2003).

A study investigated the feasibility of replacing natural aggregates with steel slag in conventional concrete (Pellegrino & Gaddo, 2009). The researchers evaluated modulus of elasticity, compressive and tensile strength, and durability under various conditions (accelerated curing, freezing-thawing, and wetting-drying). Concrete mixtures were prepared with steel slag and natural aggregates, maintaining specific proportions. Compressive strength was measured at 7, 28, and 74 days, while modulus of elasticity was assessed using cubic and cylindrical samples. Accelerated curing involved four conditions, including warm water exposure, outdoor weathering, freeze-thaw cycles, and wetting-drying cycles, applied to both steel slag and ordinary concrete samples.

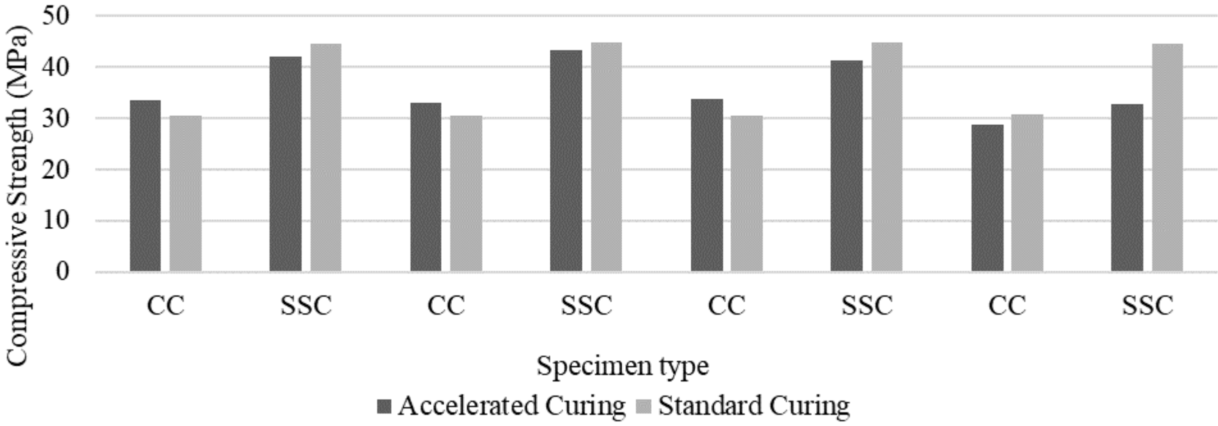

Figure 3: Compressive strength of conventional concrete (CC) and steel slag concrete (SSC) (Pellegrino & Gaddo, 2009).

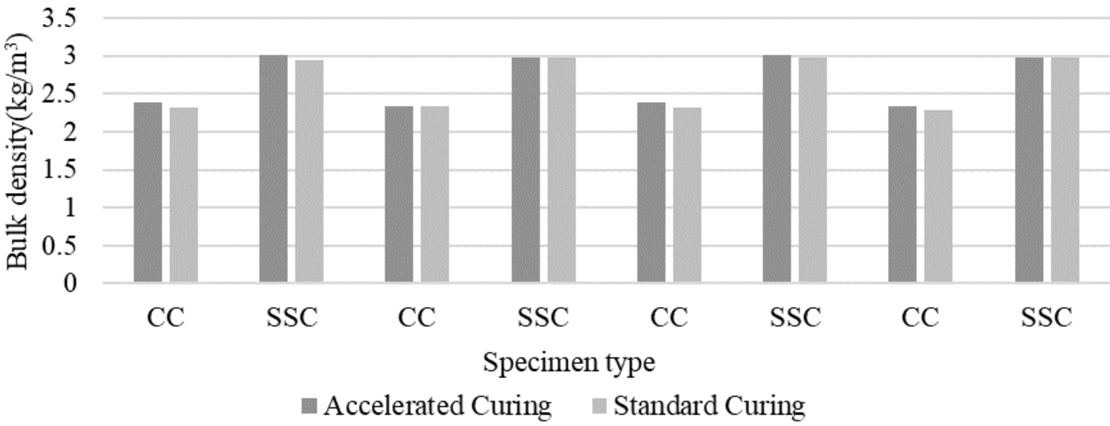

Figure 4: Bulk density of conventional concrete (CC) and steel slag concrete (SSC) (Pellegrino & Gaddo, 2009).

In typical conditions, it was found that concrete containing steel slag had comparable or higher compressive strength than standard concrete. Steel slag mixtures exhibited higher specific bulk densities than those with natural aggregate. Tensile splitting strengths were also higher in concrete with steel slag aggregate. Despite a decrease in compressive strength after freezing-thawing cycles, adding a small amount of air-entraining mitigated the strength loss to tolerable levels (Pellegrino & Gaddo, 2009).

The mechanical properties of concrete mixtures using steel slag, with replacement ratios ranging from 0% to 100% for fine aggregate, were investigated in another study. The study included workability, fresh specific bulk densities, compressive strength, and flexural strength, using mixtures with compressive strengths of 25 MPa, 35 MPa, and 45 MPa. Cubic samples were tested for compressive strengths after various durations, while prismatic samples were used for flexural strengths. Workability was adversely affected at replacement ratios of 50% and higher. Steel slag enhanced compressive and tensile strengths, especially in low-strength concretes, with the highest compressive strengths observed at replacement rates between 15% and 30%. The fresh specific bulk density of concrete mixtures with steel slag was higher due to the higher specific gravity of steel slag compared to natural sand (Qasrawi et al.,2009).

Twelve concrete mixtures with water/cement rates of 0.40, 0.55, and 0.70, respectively, a cement dosage of 350 kg/m^3, and a fine aggregate/coarse aggregate ratio of 0.65 were examined in a study. (Gülderen et al., 2011). The compressive strengths of the concrete were measured at 3, 7, 28, and 90 days. Samples measuring 150 x 150 x 150mm cubic units were ready for the compressive strength test. A compressive strength test was performed on three samples of varying ages. Table 3 displays the samples' 28-day mean compressive strengths based on the study's findings.

The compressive strength of concrete dropped as the water/cement ratio increased, as Table 3 illustrates (Gülderen et al., 2011). When comparing concrete combinations made with simply crushed limestone aggregate to control mixtures made with slag coarse aggregate mixtures, higher strengths were typically obtained. Steel slag has greater compressive strengths than limestone, which is one of the factors contributing to the high strengths of slag combinations. Furthermore, the slag coarse aggregate had a fineness modulus of 5.43, and the limestone coarse aggregate had a fineness modulus of 5.53.

Table 3: Compressive strength results (Gülderen, 2011)

Water/Cement	**Compressive Strength (MPa)**		
	Coarse Aggr. Limestone+ Fine Aggr. Limestone	**Coarse Aggr. Steel Slag+ Fine Aggr. Limestone**	**Coarse Aggr. Steel Slag + Fine Aggr. Steel Slag**
0.40	53.9	54.8	48.2
0.55	35.8	37.5	34.7
0.70	25.6	26.8	25.3

Using slag instead of limestone increased the total surface area of aggregates, requiring more water and decreasing the effective water/cement ratio. This contributes to the enhanced strength of slag concrete. Additionally, slag's angular and rough surface structure strengthens the transition zone and improves adhesion between mortar and aggregate, further enhancing strength. However, the decline in compressive strength with steel slag fine aggregate may be attributed to reduced workability due to the angular structure of the slag. This aligns with findings from previous studies. (Pellegrino & Gaddo, 2009; Maslehuddin et al., 2003). Table 4 presents the impact of steel slag on the compressive, flexural, and tensile strengths of concrete.

Table 4: Steel slag usage in concrete and its effect on properties (after 28-days curing).

Authors	**Slag Used in Concrete**	**Compressive Strength (MPa)**		**Flexural Strength (MPa)**		**Split Tensile Strength (MPa)**	
		Control Sample	**Steel Slag**	**Control Sample**	**Steel Slag**	**Control Sample**	**Steel Slag**
(Roslan et al., 2016)	0–20% Cement Replacement	34.7	22.3–37.1			3.57	2.32–3.28
(Dongxue et al.,1997)	0–30% Cement Replacement	69.1	49.9–66.6	8.0	6.5–9.7	–	–
(Hu, 2017)	0–30% Cement Replacement	58–82.5	52–82.5	–	–	4.75–6.2	3.7–5.8
(Pan et al., 2019)	0–50% Cement Replacement	48	28.1	–	–	3.1	1.8
(Guo et al., 2019)	0–100% Fine Agg.	30.76–70-33	34.55–4.23	–	–	–	–
(Olonade et al., 2015)	0–100% Fine Agg.	21.48	21.06	2.74	2.34	–	–
(Dineshkumar & Suchithra, 2017)	0–50% Fine Agg.	65	72.5	5.5	5.66	4.2	4.41

Authors	Slag Used in Concrete	Compressive Strength (MPa)		Flexural Strength (MPa)		Split Tensile Strength (MPa)	
		Control Sample	Steel Slag	Control Sample	Steel Slag	Control Sample	Steel Slag
(Mishra & Bharosh, 2018)	0–50% Fine Agg.	33.27	32.5–36.70	–	–	4.48	3.24–4.98
(Anifowose et al., 2017)	0–50% Coarse Agg.	23.55	23.70–26.95	–	–	–	–
(Priya et al., 2017)	40–50% Coarse Agg.	30.8	43.85–31.99	5.65	8.16–5.8	3.63	3.62–4.62
(Sekaran et al., 2015)	0–50% Coarse Agg.	36.4–39.62	34.1–42.29	5.8–7.2	6.2–7.53	3.69–4.37	3.87–4.43
(Khafaga et al., 2014)	0–100% Coarse Agg.	69.1–60.8	55.2–68.5	10.9–13.1	9.6–12.2	4.1–4.4	4.1–5.3
(Subramani & Ravi, 2015)	50–70% Coarse Agg.	33.55	35.33–4.45	7.5	7.36–7.75	3.75	3.89–4.03
(Chunlin et al., 2011)	100% Fine and Coarse Agg.	45.4	59.6	9.5	9.3	–	–
(Pang et al., 2015)	100% Fine and Coarse Agg.	48.2	60.5	–	–	–	–
(Yu et al., 2016)	100% Fine and Coarse Agg.	22.8–50.3	23.0–40.5	6	4.56	–	–
(Gupta & Saxena, 2017)	0–40% Fine and Coarse Agg.	32.54–39.25	37.22–44.21	2.73–3.35	3.42–3.97	2.53–3.37	2.87–3.79

4. CONCLUSIONS

Steel slag's cementitious mineral is a member of the crystalline phase, which lacks pozzolanic activity yet has low hydraulic activity. Steel slag particles are similar to basalt gravel and stronger than granite and limestone gravel. They also have a rough surface roughness, high density, and good mechanical capabilities. Their specific gravity is 10–50% higher than that of NA. As a result, steel slag particles may be employed as fine or coarse aggregate for making concrete. Incorporating steel slag into concrete mixtures, whether as coarse or fine particles, results in an elevation of the specific bulk density of the concrete. Research has shown that, among various concrete blends, the highest compressive strength is achieved when slag is employed as coarse aggregate, while the lowest compressive strength is observed when used as fine aggregate. Replacement ratios of up to 100% can be applied while maintaining suitable mechanical properties. The utilization of steel slag as coarse material in mixes is found to be more favorable compared to its use as fine aggregate. Incorporating industrial by-products like steel slag in cement-concrete production reduces emissions and energy use while maintaining key concrete properties. While complete replacement of Portland cement is not possible, a significant reduction is achievable by blending with ground steel slag binder. As 80% of concrete consists of aggregates, using cost-effective artificial aggregates like steel slag promotes sustainable concrete and development. Balancing mechanical, durability, and sustainability considerations is crucial in optimizing the use of steel slag for maximum compressive strength and impermeability in concrete.

Using Steel Slag Aggregate (SSA) in concrete offers significant benefits for sustainability, the environment, and the economy. SSAC proves cost-effective with a 20% higher cost than Natural Aggregate (NA), resulting in concrete production at a lower overall cost. Despite being less water-tight, SSAC effectively resists corrosion, carbonation, and freeze-thaw cycles, preserving concrete strength. Utilizing SSAC extends the lifespan of structures, reducing the need for repairs and maintenance and resulting in cost savings. Additionally, it helps prevent the overexploitation of premium sand and gravel, mitigating the risk of slag disposal yard occupation and environmental damage. SSAC has demonstrated sufficient environmental safety, reinforcing the potential for an ideal industrial-ecological link between the steel and concrete industries for sustainable development.

5. SCOPE OF FUTURE RESEARCH

Steel slag has the potential to be used as concrete aggregates, according to evaluations of previous operations. But there are still a lot of unanswered questions in this area that require more research, which would strengthen the case for using steel slag. The following suggestions for additional study are sent in light of the literature review:

1) Steel slag performance reports differ across sources, hindering the application of mix proportions and concrete characteristics from one source to another. To advance SSA research and utilization, future studies should establish a primary dataset and conduct a global data survey on SSAC. Subsequently, training an artificial neural network with this dataset can help predict SSAC attributes.

2) Key mechanical aspects of SSAC include cube compressive strength, flexural strength, and flexural strength. To further support SSAC's applicability in various fields, future research should explore its fracture mechanics, deformation capacity, and bonding characteristics with steel bars.

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