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TECHNICAL PAPER

Utilization of steel slag as partial replacement for coarse aggregate in concrete

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Abstract
The utilization of steel slag for industrial and construction purposes has gained significant attention in recent years due to its abundant availability and potential environmental benefits. This study explores the feasibility of utilizing steel slag as a coarse aggregate in concrete, aiming to determine the optimal replacement percentages for desired mechanical and structural properties. Experimental investigations were conducted, substituting steel slag for conventional coarse aggregate in varying proportions. The concrete mixtures were tested for compressive strength, flexural strength, workability, and other parameters. The results demonstrate the promising potential of incorporating steel slag as a partial replacement for coarse aggregate. The mixture with 30% steel slag replacement exhibited favorable strength properties and workability. Both compressive and flexural strengths showed significant improvement, highlighting the viability of steel slag as an alternative to conventional coarse aggregate. The findings provide valuable guidance for engineers, researchers, and decision-makers in the construction industry regarding the practical benefits and considerations of using steel slag in concrete mixtures. This utilization promotes resource efficiency, reduces environmental impact, and maintains or enhances the mechanical and workability properties of concrete.

Keywords Steel slag · Coarse aggregate · Concrete · Mechanical properties · Partial replacement

Introduction

Steel slag is a byproduct of the steel manufacturing process, formed when impurities are added to iron ore in blast furnaces or basic oxygen furnaces, resulting in a molten slag that is separated from the liquid metal. This industrial byproduct has gained increasing attention due to its potential applications in various industries. Its physical and chemical properties, such as high density, hardness, and angularity, make it suitable for diverse uses [1]. Steel slag's chemical composition includes calcium oxide (CaO), silicon dioxide (SiO_2), iron oxide (FeO), aluminum oxide (Al_2O_3), and smaller amounts of magnesium oxide (MgO), manganese oxide (MnO), and sulfur (S). The exact composition may vary depending on the steel production process and raw materials used [2].

These elements contribute to the unique properties of steel slag, making it a valuable resource with the potential to enhance various materials and products. Research has highlighted the benefits of incorporating steel slag in construction materials, showcasing enhanced mechanical properties and environmental advantages. Studies have shown that incorporating steel slag in concrete and asphalt mixes can lead to improved compressive strength, splitting tensile strength, and durability. Moreover, its stability and high shear strength make it suitable for use as fill material in land reclamation and embankment construction [3]. By utilizing steel slag in various applications, we can promote resource efficiency, reduce waste generation, and contribute to more

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sustainable and eco-friendly practices in different industries. This research aims to explore the potential benefits of steel slag as an alternative material, enhancing our understanding of its properties and applications and contributing to the advancement of sustainable practices. As shown in Fig. 1, there are two main types of furnaces used in the production of steel slag: the electric arc steelmaking furnace and the ladle furnace (refining center) [4].

The electric arc steelmaking furnace is a powerful, electrically operated furnace used to melt scrap steel and convert it into liquid steel. It employs an electric arc between the electrodes and the scrap steel to generate intense heat, melting the steel. The impurities in the scrap steel react with fluxes and other materials, forming a molten slag that floats at the top of the liquid steel. This slag is then extracted from the furnace and further processed to recover valuable materials [4].

On the other hand, the ladle furnace, known as the refining center, refines the liquid steel from the electric arc furnace. Chemical reactions take place here to adjust the composition and eliminate remaining impurities from the steel. The ladle furnace is equipped with heating elements and stirring mechanisms for thorough mixing and refining. Both furnaces are integral to steelmaking and produce steel slag with valuable properties, making it suitable for construction, road building, cement production, and more. Steel slag possesses unique properties and composition that make it highly versatile and attractive across various industries. In the construction sector, its applications have garnered significant attention due to its promising characteristics. Notably, one of its primary uses is in construction materials, particularly in concrete production. Incorporating steel slag as a substitute for traditional aggregates in concrete mixtures has yielded notable improvements in compressive and tensile strength properties, resulting

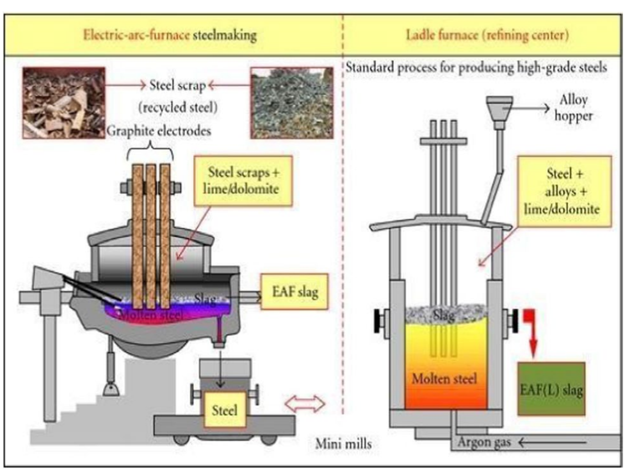

Fig. 1 Electric arc furnace and ladle furnace [4]

in more durable and resilient concrete structures. This enhanced mechanical performance of concrete makes it suitable for applications requiring high strength and durability. Furthermore, utilizing steel slag in concrete helps reduce the demand for natural resources, promoting resource efficiency and minimizing environmental impact.

The specific attributes of steel slag, such as its high hardness and angularity, also make it an excellent choice for road construction. As a replacement for natural aggregates, steel slag aggregates have demonstrated superior skid and rutting resistance in asphalt mixes, leading to safer and more durable road surfaces. Additionally, its stability and high shear strength enable its use as fill material in land reclamation and embankment construction. These applications of steel slag in the construction industry significantly contribute to sustainability and eco-friendliness in construction practices. Several studies have explored the utilization of steel slag in concrete and its impact on mechanical properties. Lai et al. [5] investigated the effect of incorporating electric arc furnace steel slag (EAFS) into hardened concrete. Their findings demonstrated that concrete with steel slag aggregates exhibited significantly higher compressive, tensile, and flexural strength, as well as a higher modulus of elasticity, compared to concrete with natural aggregates.

Another study by Sabapathy et al. focused on the use of steel slag as an aggregate in concrete [1]. They concluded that air-cooled steel slag, which has a low amorphous silica content and a high ferric oxide content, may not be suitable for blended cement production. However, they found that utilizing steel slag as an aggregate in concrete mixes offered advantages over conventional aggregate mixes. It is worth noting that electric arc furnace slag (EAFS) has a low amount of amorphous silica and a high content of ferric oxides, which limits its pozzolanic activity compared to blast furnace slag (BFS). Therefore, EAFS is not as suitable for use in blended cement production. These research findings collectively highlight the potential of steel slag as a beneficial alternative in concrete construction, presenting opportunities to enhance mechanical properties and explore sustainable practices [1, 5]

The primary objective of this study is to explore the practicality and advantages of incorporating steel slag as a coarse aggregate in concrete, catering to industrial and construction needs. The research specifically identifies the most effective replacement percentages of steel slag to attain the desired mechanical and structural characteristics in the concrete mixture. Through extensive experimental investigations and result analysis. This study aims to offer valuable insights into the use of steel slag in concrete production, with the overarching goal of promoting resource efficiency, minimizing environmental impact, and bolstering the overall sustainability of construction practices.

Materials and experimental procedures

This section is divided into two parts. The first part provides a comprehensive description of the materials utilized in this study, including sand, cement, coarse aggregate, and steel slag. The properties and characteristics of each material were thoroughly assessed through their physical, and mechanical properties which played a crucial role in evaluating their suitability for incorporation into the concrete mixtures. The second outlines the various tests conducted to evaluate the performance of the concrete mixtures produced using steel slag as a partial replacement for traditional aggregates. The tests include slump, compressive flexural, and splitting tensile strength tests. These tests provide crucial insights into the fresh and hardened state of concrete. Through these evaluations, the effectiveness of incorporating steel slag in the concrete mixtures could be determined and their suitability for different construction applications.

Materials properties

Various tests were handled to characterize the materials used. Table 1 shows the variables of physical, and mechanical properties for material characterization of slag as coarse aggregate replacement, coarse and fine aggregate. This includes crushing, impact, and Los Angeles values, in addition to specific gravity, absorption percentage, and particle size distribution. It should be mentioned that the sive size distribution is presented with the upper and lower limits for coarse and fine aggregate, as shown in Fig. 2. The slag as coarse aggregate, in addition to the natural coarse and fine aggregate are within the limits according to their maximum aggregate size. The mechanical properties of natural and slag coarse aggregate are also within the limits as shown in Table 1. The specific gravity test on the sand, coarse aggregate, and steel slag revealed values of 2.78, 2.78, and 4.17, respectively. Steel slag's higher specific gravity suggests denser particles that can effectively fill voids in the concrete mixture, potentially improving its density and mechanical properties. This could lead to more durable and sustainable concrete structures. However, careful selection of the optimal steel slag replacement percentage is essential to balance desired properties without compromising other characteristics. Figure 2 shows the size particle distribution for slag, coarse, and fine aggregate within upper and lower limits according to ECP 203 [6].

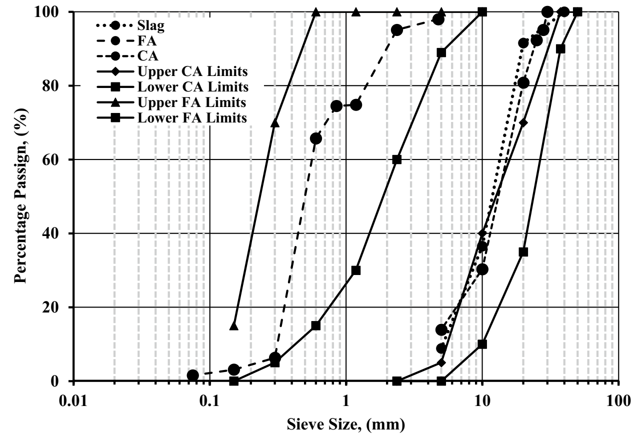

Fig. 2 The size particle distribution for slag, coarse, and fine aggregate

Experimental setup

The experimental setup involved preparing 6 concrete mixtures including the control with consistent proportions of ordinary Portland cement, fine aggregate (sand), and water. Varying percentages of steel slag were used as a partial replacement for coarse aggregate. Specimens included six cubes of $15 \times 15 \times 15$ cm^3 in dimensions for compressive strength at 7 and 28 days, three prisms dimensioned $50 \times 10 \times 10$ cm for evaluating the flexural strength, and three cylinders with a diameter 10 and height of 20 cm for determining the tensile strength. The flexural and splitting tensile strengths were performed at the age of 28 days. Thus, the curing process was performed for three cubes, cylinders, and prisms for 28 days. Only three cubes specimens were cured till 7 days of age.

Table 1 Concrete mix design

Mix ID	w/c	Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Steel slag (kg/m^3)	Fine aggregate (kg/m^3)
M0	0.44	202	411	1191	0	676
M10				1072	179	
M30				834	536	
M50				595	893	
M75				298	1340	
M100				0	1786	

Concrete mix design

Concrete mix design involves determining the proportions of cement, aggregates, water, and admixtures to achieve desired properties. This study focused on using steel slag as a partial replacement for coarse aggregate in concrete. Mixtures with varying percentages of steel slag (0%, 10%, 30%, 50%, 75%, and 100% of the coarse aggregate weight) were evaluated. The goal was to investigate the influence of steel slag on fresh and hardened concrete properties. The total aggregate volume was kept constant while adjusting the steel slag percentage.

This systematic approach explores the feasibility and effectiveness of steel slag as a sustainable alternative in concrete construction Table 1 presents the concrete mix design for the experimental program.

As shown in the table, the percentage of coarse aggregate was progressively replaced with steel slag for each mixture, while keeping the total aggregate volume constant. The amount of fine aggregate remained the same for all mixtures. The varying percentages of steel slag replacement investigate its impact on the concrete's mechanical properties. By altering the percentage of steel slag, its potential benefits in terms of enhancing concrete strength and other performance attributes were assessed as aimed. The mix identification represents the letter '*M*' stands for mix and '0, 10, 30, 50, 75, and 100' represents the replacing percentile of natural coarse aggregate with slag as a coarse aggregate. For instance, "M30" denoted a mix with 30% natural coarse aggregate replaced by slag.

The concrete mix design was formulated to ensure consistency in the cement content and water–cement ratio across all mixtures, thereby facilitating a meaningful comparison of the results. The w/c ratio was also kept constant with a value of 0.44 to explore the effect of the coarse aggregate replacement with slag. The variations in steel slag content enabled the assessing its effects on concrete properties, contributing valuable insights into its potential as a sustainable and resource-efficient alternative in construction applications.

Slump and density

The slump was measured before pouring the concrete mixture into the molds to evaluate the workability of these mixes including the influence of the natural coarse aggregate replacement on the workability. Also, after hardening the cube specimens were weighed and the volume of the cuber specimens was known through the dimension ($15 \times 15 \times 15$ cm^3). The density for each mixture was calculated by averaging the weights of three cubes cured at 28 days and divided by their volumes as per ECP 203 [6].

Compressive strength test

After an initial curing period of 7 days, three cubes from each concrete mixture were selected for compressive strength testing. The cubes were placed in a compression testing machine, and gradually increasing loads were applied until failure occurred. The maximum load at failure was recorded, and the compressive strength was calculated. During testing, a typical cube specimen in compression into the universal testing machine of capacity 2000 kN for mechanical properties evaluation. The cube specimens were tested at a pacing rate of 240 kg/cm^2 per minute as the EGP 203 [6] and B.S.1881–116 [7] recommended until the specimens failed.

Splitting tensile strength test

After the 28-day curing period, the cylinders underwent tensile strength testing. The cylinders were subjected to a gradually increasing tensile load until failure occurred. The maximum load at failure was recorded, and the tensile strength was calculated by dividing this load by the cross-sectional area of the cylinder. The tensile strength test provides valuable information about the concrete's ability to resist pulling or stretching forces, which is particularly relevant in situations where tension is applied. Cylinder specimens were tested at a pacing rate of 12 kg/cm^2 per minute by implementing compression loading on the cylinder specimens' longitudinal direction as per BS-1881 part 117 [8].

Flexural strength test

Following the 28-day curing period, flexural strength testing was conducted on the prisms. The prisms were placed horizontally on supports, and a load was applied at the center until failure occurred. The maximum load at failure was recorded, and the flexural strength was calculated by dividing this load by the cross-sectional area of the prism. The flexural strength test helps assess the concrete's ability to resist bending or flexural stresses, which is important in applications where the concrete is subject to such forces. Prism specimens were tested at a pacing rate of 24 kg/cm^2 per minute by implementing compression loading on the prism specimens' longitudinal direction in two-point loading [9].

Results and discussion

This section presents the results of the fresh and hardened properties of the concrete mixture produced. This includes the specimens for evaluation slump, density, compressive, tensile, and flexural strength tests conducted on concrete specimens with varying percentages of steel slag replacement.

Slump

The slump test determines the ability of the concrete mixture to be workable and fluid for compaction into the formwork or the mold with the least external effort. The slump as shown in Fig. 3 decreases as the natural coarse aggregate replacement increases. This is due to the high angularity of the slag used which reduces the flowability of the concrete mixture.

Only M10 and M30 showed nearly the same slump which means that above them would rely on other parameters than workability to select between the two percentiles.

Density

Density is a crucial parameter especially when speaking about load reduction on formwork while casting or reducing loads to reduce sections of the structural elements for more economical construction. The trend of density is nearly shaping the trend of compressive strength. As shown in Fig. 4, as the natural coarse aggregate replacement increases the density increases. This is attributed to the higher specific gravity of slag than that of natural coarse aggregate by more than 50%. Thus, the replacement by volume requires more weight to occupy the similar volume of the natural coarse aggregate. Similarly, it is expected to see the same trend in the results of compressive strength.

Compressive strength

As shown in Fig. 5, compressive strength increased from 7 to 28 days. The gaining of compressive strength would reach about 83.5% through aging between 7 and 28 days.

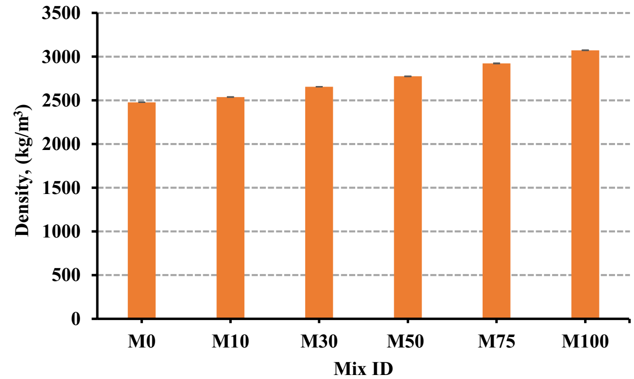

Fig. 4 Density for the mixtures with natural coarse replacement by slag

The highest compressive strength among the 6 mixtures was achieved in M100 with 100% steel slag replacement. This can be attributed to the pozzolanic activity of steel slag, which contributes to the formation of additional hydration products, resulting in increased strength development. The formation of calcium silicate hydrates (C–S–H) gel due to the reaction between steel slag particles and calcium hydroxide in the presence of water contributes to the higher compressive strength. However, the increase in compressive strength was not consistent with higher replacement percentages, suggesting an optimum replacement level.

Splitting tensile strength

As shown in Fig. 6, the highest splitting tensile strength was observed in M30 at 30% replacement. This enhancement can be attributed to the formation of a denser and more refined microstructure due to the incorporation of steel slag. Beyond 30% replacement, splitting tensile strength slightly decreased. This is attributed to the weakened bond between the cement matrix and slag in

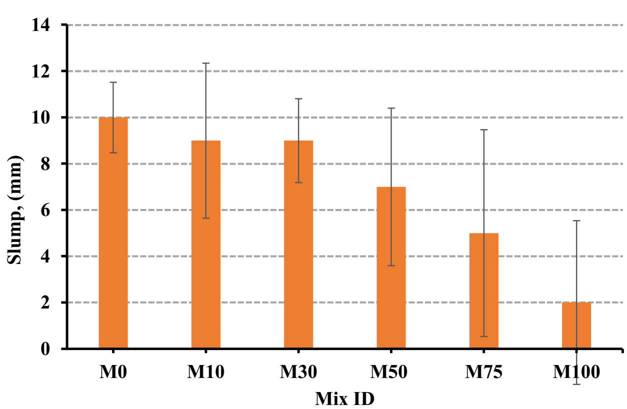

Fig. 3 Slump for the mixtures with natural coarse replacement by slag

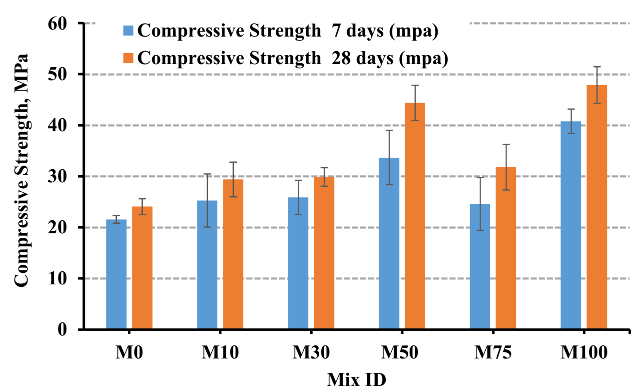

Fig. 5 Compressive strength for the mixtures with natural coarse replacement by slag

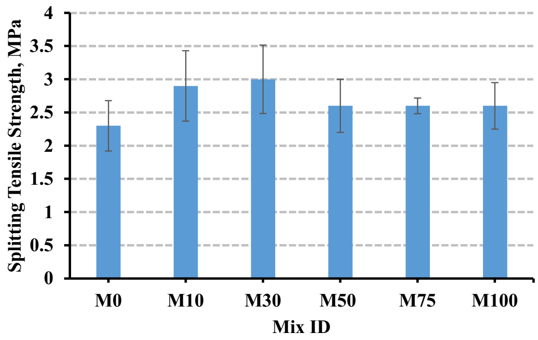

Fig. 6 Splitting tensile strength for the mixtures with natural coarse replacement by slag

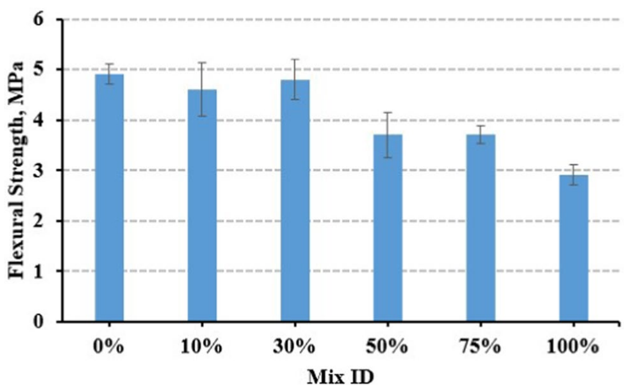

Fig. 7 Flexural Strength for the mixtures with natural coarse replacement by slag

the interfacial transition zone which leads to crack propagation easily around the aggregate. The cement matrix surrounding the aggregate is expected to create a thinner layer in the case of slag rather than that of natural coarse aggregate due to the higher absorption percentile which might have absorbed some of the cement matrix within the voids of slag aggregate leaving.

Flexural strength

As shown in Fig. 7, Flexural strength decreased with higher steel slag replacement percentages. The addition of steel slag as a partial replacement has a diminishing effect on flexural strength. This decrease can be attributed to the relatively brittle nature of steel slag particles, which might have resulted in micro-cracks and reduced the overall flexural performance of the concrete. Additionally, the angular and irregular shape of steel slag particles may have hindered the distribution and alignment within the concrete matrix, further contributing to the reduction in flexural strength.

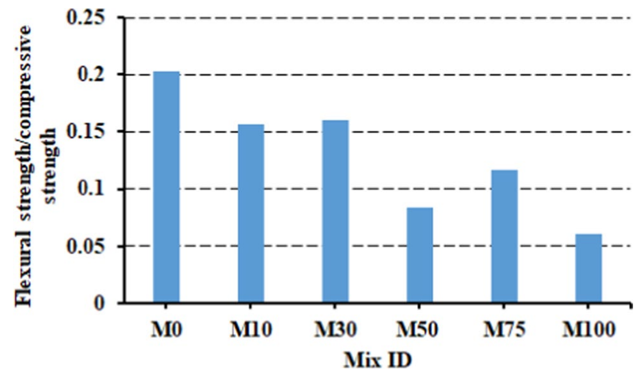

Fig. 8 Flexural strength/compressive strength for the mixtures with natural coarse replacement by slag

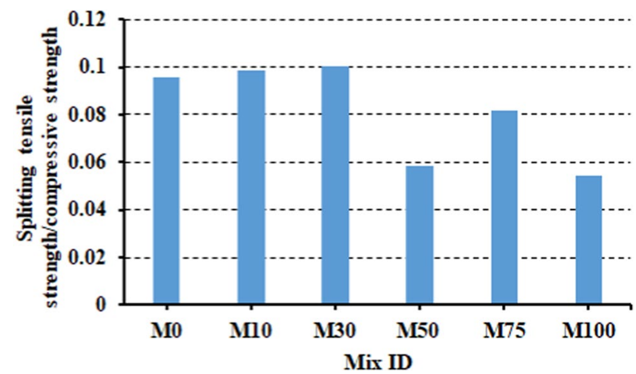

Fig. 9 Splitting tensile strength/compressive strength for the mixtures with natural coarse replacement by slag

Relationship between different mechanical properties

From the above mechanical properties, one can deduce a relationship between compressive and flexural strength, as shown in Fig. 8. The flexural strength of normal concrete usually attains between 10 to 23% of its compressive strength [10]. Here in this study, the relationship between the compressive and flexural strength was between 6 and 20% with an average of about 13% across the various mixtures including the replacement of natural aggregate with slag. Such an average is acceptable and close to reported values in the literature

Similarly, Fig.9 shows the ratio between the splitting tensile strength and the compressive strength for the different mixtures. It is well known that the empirical tensile strength for normal concrete can be deduced from the compressive strength and ranges between 10 and 15% [10]. However, due to the replacement of natural coarse aggregate and the sense of too much void onto the slag used the

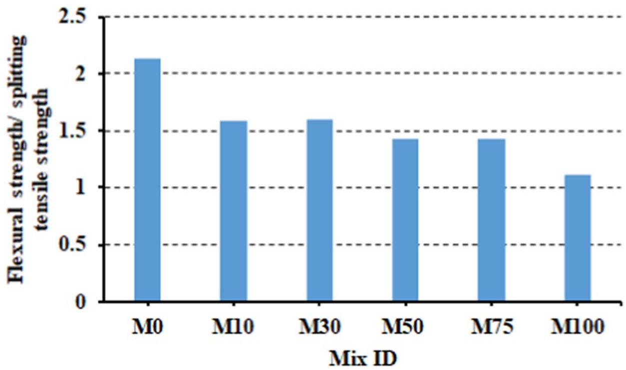

Fig. 10 Flexural strength/compressive strength for the mixtures with natural coarse replacement by slag

ratio showed values between 5.4 and 10% with an average of about 8.1% across the various mixtures.

A final relationship was deduced between the flexural and splitting tensile strength for the various mixtures as shown in Fig. 10. The ratio between flexural strength and splitting tensile strength showed values between 1.12 and 2.13 with an average value of 1.55. It should be mentioned that flexural strength represents the indirect tensile strength of concrete generated by another form of loading than compression; as in splitting tensile, which is the bending moment that generates tensile stresses on the bottom and compression on the top fiber of the section [10]. Thus, Poisson's ratio is not developed here as in the splitting tensile strength.

Conclusion

This study investigated the use of steel slag as a partial replacement for traditional aggregates in concrete. The results revealed that the optimal replacement percentage for steel slag is 30% to achieve the desired strength properties. At this level, steel slag demonstrated the potential to enhance compressive strength and splitting tensile strength of concrete, contributing to more durable and resilient structures. Also, the relationship assigned between the compressive, flexural, and tensile splitting strengths is very important to predict the flexural and splitting tensile strength using the compressive strength values. Thus, generating equations in case of using slag as a natural coarse aggregate replacement. These findings contribute to sustainable construction practices by utilizing industrial byproducts like steel slag, promoting resource efficiency, and reducing environmental impact. The research provides valuable insights for decision-making in concrete mix design and construction, paving the way for greener and more eco-friendly practices in the construction industry.

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Author contributions All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Mohamed Elwi Mitwally, Amr Elnemr, Ahmed Shash, and Ahmed Babiker. All authors read and approved the final manuscript.

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Data availability Data will be available upon request.

Declarations

Conflict of interest The authors have no financial or proprietary interests in any material discussed in this article.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, no informed consent is required.

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