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Investigating the Properties of Concrete Using Steel Slag as a Partial Replacement of Coarse Aggregate

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Abstract

Concrete is one of the best building materials, widely used for various purposes. Replacing coarse aggregate with steel slag not only supports economic growth but also helps conserve natural resources. The objectives of this research are to determine the optimum percentage of replacement of coarse aggregate with steel slag and to determine the water absorption, specific gravity, and compressive strength of the concrete. A blend ratio of 1:2:4 for concrete grade M20 was determined after analyzing the aggregates. The density of concrete is 2400 kg/m^3. The amount of each component such as coarse aggregate, fine aggregate, and cement needed for the molds of the entire 45 cubes was determined by which 9 cubes per age per mix in which average value was taken for each percentage of steel slag replacement (0%, 10%, 20%, 30%, 40%, and 50%) at a water-cement ratio of 0.6, also the average value of each age were recorded. The compressive strength, specific gravity, slump test, and water absorption of the concrete were all evaluated. The compressive strength gradually rises from 0 to 30% before declining to 50%. These findings indicate that the ideal percentage is 30% replacement, with values of 17.78, 21.91, and 26.14 N/mm^2 at 7, 14 and 28 days, respectively. Additionally, an M20 was achievable after 14 days of curing. This indicates that the concrete strengthened more quickly than anticipated because it surpasses the minimum needed for M20 grade concrete, which is 20 N/mm^2 at 28 days.

Keywords

Steel Slag, Coarse Aggregate, Sieve Analysis, Slump Test, Water Absorption,

Compressive Strength

1. Introduction

Concrete is made by combining different ingredients, such as cement, aggregates, water, etc. Among the main building materials used in civil engineering projects, concrete is special [1]. The grayish powder known as cement may bind other materials together and sets and hardens as it dries. It also reacts with carbon dioxide in the air in a defendant manner [2]. Portland cement is made by finely grinding and combining lime, silica, iron oxide, and alumina, burning the mixture to initiate, and then grinding the resulting clinker to a fine powder while adding gypsum to regulate the setting time. Portland cement is an active mixture of silicates, aluminates, and ferro aluminates of lime. The rotary kiln is then fed these thoroughly mixed raw materials. The kiln consists of a long, sloping cylinder with zones that heat up to 2700˚C [3]. The maximum aggregate size that can be used in concrete construction projects is 80 mm, which is the practical size. Sizes of aggregate in concrete are affected by Water requirement, Cement content, Shrinkage during and after drying, concrete cover, Spacing of reinforcement, Mixing, handling, and placing techniques and thickness of the section [4].

The coarse aggregates used in construction include sand, gravel, crushed stone, slag, and recycled concrete. As the most mined substance in the world, aggregates serve as the primary ingredient of composite products like asphalt and concrete [5]. Concrete often comprises roughly 70% - 80% of its volume; hence, it plays a significant role in its characteristics. Natural rocks, crushed stone, and natural gravels and sands are the sources of these granular materials [6]. Coarse aggregates are typically natural gravels or crushed stone that are greater than 5 mm, whereas fine aggregates are defined as natural sand with graded particles ranging from 5 mm down to the smallest particles, excluding those passing through a sieve opening of 0.063 mm (dust) [7]. Normal aggregates, heavyweight aggregates, and lightweight aggregates are the three types of aggregates. Normal aggregates serve the majority of applications, yielding concrete with a density of 2300 - 2400 kg/m^3. They are produced either by removing sand and gravel deposits created by glacial or alluvial action or by crushing quarry rock to the appropriate particle sizes. Sand and gravel aggregates should be cleaned to remove contaminants like silt and clay [8]. If river and marine aggregates are to be utilized in construction, their chloride concentration should typically be less than 1%. Lightweight aggregates absorb more water than regular aggregates, are very porous, and have good fire resistance. Because of the wide range of variations in their moisture content, they are often batched by volume. The bulk density of lightweight aggregates ranges from 350 to 1800 kg/m^3, whereas large aggregates have a bulk density of 3200 kg/m^3 and more [9]. A partially vitreous byproduct of ore smelting, slag is often a blend of silicon dioxide and metal oxides. Concrete is among the most advantageous applications for furnace slag [10]. Due to its stiffness, porosity, mechanical strength, resistance to wear, and ability to absorb water, steel slag is utilized as an aggregate in asphalt paving road mixes [11]. **Table 1** shows the steel slags physical properties. The inclusion of a material like this into concrete affects its mechanical and physical qualities, as well as its durability [12].

Steel is an alloy of iron and carbon, comprising trace elements of silicon, phosphorus, sulfur, and oxygen, with carbon content below 2% and manganese content below 1%. Slag's chemical makeup is typically described in terms of simple oxides, computed via elemental analysis based on X-ray fluorescence [13]. The mechanical characteristics of steel slag are listed in **Table 1**. For use as aggregate, processed steel slag possesses advantageous mechanical qualities, such as strong bearing strength, good soundness, and resistance to abrasion [14].

In concrete technology, concrete mixes are designed using the aggregate's specific gravity. Each component's specific gravity can be used to translate its weight into solid volume, which allows for the calculation of the theoretical yield of concrete per unit volume [15]. Natural stone reserves like granite and gravel are continuously being depleted due to the construction industry's increasing demand for concrete [16]. Additionally, the environmental ecology is impacted by some environmental issues linked to the ongoing use of these stone formations [17]. As a result, it becomes imperative to investigate substitute materials for traditional aggregates, which are crucial to the creation of concrete [18]. By making structural elements smaller, the construction industry in industrialized nations has recognized the use of waste material as a possible substitute for traditional aggregates [19]. An ecological imbalance in the environment needs to be addressed as a result of building businesses' extensive use of granite and gravel as natural aggregate. The utilization of solid waste materials, such steel slag, will promote economic growth and preserve natural resources, like coarse aggregate. One very intriguing idea is to replace natural aggregates in concrete with steel slag aggregates. Owing to their superior mechanical strength, stiffness, porosity, wear resistance, and water absorption capacity, steel slag particles are effectively utilized as aggregates in asphalt paving mixtures.

The objective of this study is to evaluate the impact of partially replacing coarse aggregate with steel slag on the properties of concrete and to determine the optimum percentage of replacement that produces workability of the concrete mix with different replacements of coarse aggregate. Also, the water absorption and specific gravity of the steel slag will be evaluated, as will the compressive strength of the concrete at different curing period.

2. Materials and Methods

2.1. Materials

The coarse aggregate, fine aggregate, steel slags, cement, and water are used in this research as key materials. The ordinary Portland cement used in this experiment was collected from a local dealer who certified that it was of recent supply, and was manufactured at Obajana by Dangote Cement Company Plc. The used fine aggregate was clean river sand and free from leaves, sticks, dirt, and other impurities. The fine aggregate was sieved through a 10 mm to 0.074 BS test sieve. The coarse aggregate used was free from any visible impurities, and its maximum size was 20 mm. The coarse aggregate was sieved through 37.5 mm, 20 mm, 14.0 mm, 10.0 mm, 6.30 mm, 5.00 mm, 3.35 mm, and 2.00 mm sieves, respectively. The specific gravity and water absorption of the aggregates were measured during the experiment. Steel slag, a co-product of the iron and steel manufacturing process, was utilized as a replacement for natural aggregates in concrete.

It can also be used as a material in asphalt road mixes because it is stiff, strong, porous, doesn't wear down easily, and can soak up water. The properties of steel aggregate involve 2.61 of specific gravity, 1.05% of water absorption, a flakiness index of 8.5%, an elongation index of 4.5%, an impact strength of 19.5%, and a crushing strength of 19%. The physical properties of steel slag make it suitable for use as aggregate. With a unit weight ranging from 1600 to 1920 kg/m^3 (100 - 120 lb/ft^3), steel slag also has a specific gravity between 3.2 and 3.6, and up to 3% water absorption capacity.

Table 1. Mechanical properties of steel slag [13].

Property	Value
Sodium Sulfate Soundness Loss (ASTM C88), %	<12
Los Angeles Abrasion (ASTM C131), %	20 - 25
Hardness (measured by Moh's scale)	6 - 7
California Bearing Ratio (CBR), top size 19 mm (3/4 inch)	up to 300
Angle of Internal Friction	40˚ - 50˚

2.2. Experiments Conducted

2.2.1. Sieve Analysis for Aggregates

As shown in **Figure 1** to determine the aggregates' particle size distribution, a sieve analysis was carried out. Initially, the soil sample was dried, and British Standard (BS) sieves spanning from 10 mm to 0.063 mm were stacked to reduce the diameter, starting from the top. Before being agitated for a set amount of time, the soil sample was weighed and placed onto the upper sieve. The sample that passed through the 6.3 mm sieve was collected and riffled, and a total of 150 g of this sample was agitated and passed through the remaining sieves. The volume of soil sample retained on each sieve was recorded. The percentage of grain passing through each sieve in the stack was subsequently calculated, and a semi-logarithmic scale was used to plot a graph against grain diameter. The zone of sediment was identified using the data that was obtained.

Weight of Sample Retained (g) = (Sieves Weight + Sample) – Weight of Empty Sieves

$$\text{Weight retained } \% = \frac{\text{Retained weight of sample}}{\text{Total sample weight}} \times \frac{100}{1} \tag{1}$$

Weight passing % = 100 – retained weight cumulative percentage

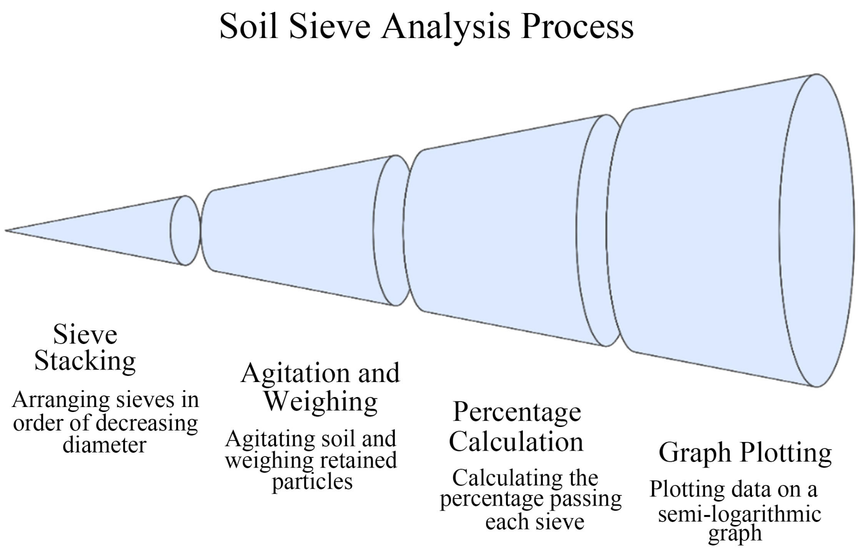

Figure 1. Soil sieve analysis process.

2.2.2. Mix Proportions

The apparatus utilized for concrete mix design includes a weighing balance sensitive to 0.1 g, a BS test set of sieves ranging from 28 mm to 5 mm for coarse aggregate, a scoop and brush, a mixing container measuring 900 mm × 900 mm × 50 mm, and a shovel. The material was balanced by weight with a mix ratio of 1:2:4 for grade M20. The procedure commenced with the calculation of the mold's volume for the cube. The density of concrete is 2400 kg/m^3. The mass of each component (cement, fine aggregate, and coarse aggregate) necessary for a total of 45 cube molds was computed for each percentage of steel slag replacement (0, 10, 20, 30, 40, and 50 percent), using a water-cement ratio of 0.6. A tray of 900 mm × 900 mm × 50 mm, constructed from a non-absorbent substance resistant to concrete, was utilized. The sample was mixed manually using a shovel to form a conical shape on the sampling tray. Following BS 1881: Part 106, the cone was turned over and remixed to form a new cone, a process that was repeated three times to ensure uniformity.

The concrete was subsequently poured into 150 mm × 150 mm × 150 mm cube molds, with each form filled with about equal volume in three layers. Upon completing each layer, the concrete was manually compacted using a 16 mm dia and 600 mm height tamping rod for 35 strokes. During compaction, each layer was tamped using a rod with strokes evenly distributed across the entire cross-section of the mold. Care was taken to avoid the rod penetrating the layer below or hitting the bottom of the mold during the first layer compaction. After casting, the concrete cubes were left in their molds for 24 hours before being demolded and transferred to a curing tank. The curing durations were set at 7, 14, and 28 days. After each curing period, the cubes were air-dried, and their densities were recorded prior to conducting the compressive strength test.

2.2.3. Water Absorption and Specific Gravity

After carefully washing about 2 kg of the aggregate sample to get remove of any small particles, it was drained and put right into a wire basket. The basket was submerged in distilled water, ensuring at least 50 mm of water above its top. To eliminate entrapped air, the basket was raised about 25 mm above the base of the tank and allowed to drop 25 times at a rate of approximately one drop per second. After this process, the basket containing the aggregate remained fully submerged in water for 24 ± 0.5 hours. Finally, the basket and the sample were weighed while still submerged in water, maintained at a temperature between 22˚C and 32˚C.

The weight of the aggregate was measured while suspended in water (W1) g, then the basket and aggregate were removed from the water, allowed to drain, and then transferred to a dry absorbent cloth. The empty basket was returned to the tank of water, jolted 25 times, and the weight in water (W2) g was recorded. The aggregate was placed on the dry absorbent cloth and surface-dried until no additional moisture could be extracted. Subsequently, the aggregate was relocated to a second dry cloth, arranged in a single layer, covered, and allowed to dry for a minimum of 10 minutes until it was entirely surface-dry. The surface-dried aggregate was then weighed (W3) g. The aggregate was set in a shallow tray and subjected to an oven temperature of 110˚C for a duration of 24 hours. The item was thereafter extracted from the oven, allowed to cool in an airtight container, and weighed (W4) g. Equation (2) and Equation (3) established the specific gravity and water absorption, respectively.

$$\text{Specific gravity} = \frac{W_4}{W_3 - (W_1 - W_2)} \tag{2}$$

$$\text{Water absorption} = \frac{W_3 - W_4}{W_4} \times 100 \tag{3}$$

2.2.4. Slump Test

According to BS 1881, a slump test was carried out using a metal cone of dimensions 300 mm high, having a bottom diameter of 200 mm and a top diameter of 100 mm. The slump cone was inspected to make sure that the internal surface was clean, dry, and free from set cement. The cone was then placed on a smooth, flat, non-absorbent surface of a steel plate and the mold was held firmly in place while it was being filled. The mold was filled in 3 different layers with concrete and tamped using 25 strokes of a 16 mm rod and 600 mm long. The mold was then removed by raising it vertically after filling. The molded concrete was finally allowed to subside and then the height of the specimen was measured. The result of the slump test is shown in **Figure 2**.

2.2.5. Compressive Strength (Crushing) Test

After being weighed and allowed to air dry, the cubes were axially positioned in the crushing machine so that two of their sides touched the testing machine's platen. Compressive strength test was conducted to determine the mechanical properties of concrete specimens by using compression testing machine. The manual crushing machine was used due to the size of the cube. After curing period of 7, 14 and 28 days the crushing strength was determined and it was conducted under **BS 1881: part ii: 1983** [20] standard. **Figure 3** shows the result of test which computed by Equation (4). Crushing strength is the maximum load a concrete can sustain in compression.

To ensure accurate and standardized compressive strength testing of concrete specimens, specific constraints related to both the crushing load and the effective area must be observed:

1) Crushing Load Limits

a) Maximum Load Capacity: The load that is applied must not be more than what the testing machine can handle, which is usually 2000 kN. b) Failure Mode: The specimen must fail by proper crushing, not by bad ways like lateral cracking or buckling. c) Loading Rate: The rate of load application must comply with established standards, such as ASTM C39, which specifies a loading rate of 0.25 ± 0.05 MPa/s.

2) Effective Area Constraints

a) Specimen Geometry: The effective area is determined by the geometry of the specimen, which is commonly either cubic or cylindrical. Standard cubes have a size of 150 mm × 150 mm, which gives them an area of 22,500 mm^2. For standard cylinders, the diameter is 150 mm and the height is 300 mm, which gives an area of about 17,671 mm^2. b) Surface Contact: The loading surfaces of the specimens must be flat and smooth so that they can fully and evenly touch the testing machine platens. c) Loading Alignment: The load must be applied in the middle to avoid eccentric loading, which can change the accuracy of the test and cause failure modes that aren't representative.

$$\text{Mathematically,}\quad \text{Compressive strength} = \frac{\text{Crushing Load}\left(\text{N}\right)}{\text{Effective Area}\left(\text{mm}\right)} \tag{4}$$

3) Results and Discussions

Table 2. Distribution of the particle size for coarse aggregates (Gravel).

Size of Sieves (mm)	Empty Sieves Weight (g)	Weight of sieves sample (g)	Weight of sample retained (g)	Weight retained (%)	Cumulative retained (%)	Passing (%)
20.00	1476	1649	173	34.74	34.74	65.26
14.00	1398	1590	192	38.55	73.29	26.71
10.00	1346	1440	94	18.88	92.17	7.83
6.30	1346	1375	29	5.82	97.99	2.01
3.35	1349	1359	10	2.01	100	0
1.18	388	388	-	-	-	-
0.60	470	470	-	-	-	-
0.425	437	437	-	-	-	-
0.30	263	263	-	-	-	-
0.15	422	422	-	-	-	-
0.075	369	369	-	-	-	-
Pan	813	813	-	-	-	-
TOTAL			498			

As shown in Table 2 above, the weight of the sample before sieving = 500 g, but after sieved, we had a total of 498, which means little stuck in the sieve. This shows the various particle sizes present in the coarse aggregates. This result shows that, according to the overall grading limit (BS 82: 1992), in this test, using all the coarse aggregates satisfied; aggregates are suitable for making concrete mixes and replacing them with steel slag material.

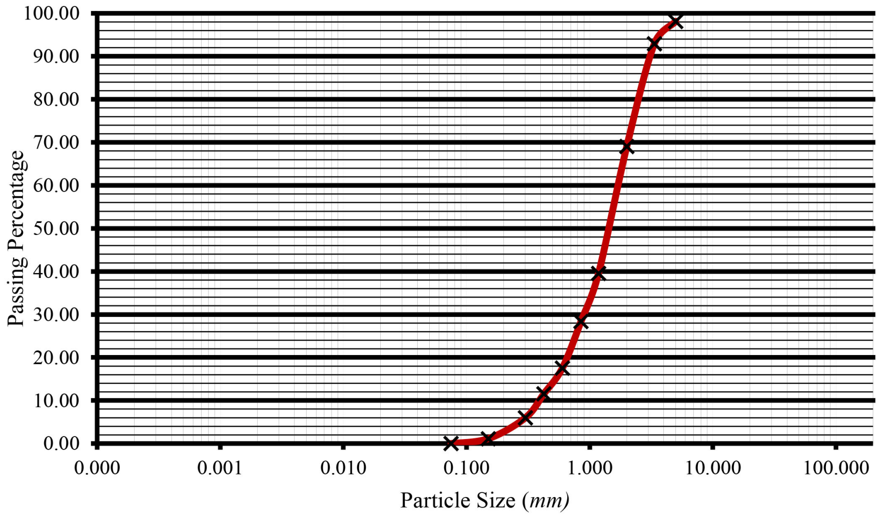

Figure 2. Particle size distribution curve illustrating the gradation characteristics of the steel slag sample.

Figure 2 illustrates the gradation characteristics of the steel slag sample, revealing a well-graded profile with a balanced representation of particle sizes across the entire range from the maximum to the minimum size. It shows various sieve sizes with the percentage weight of samples retained and passing through them.

Table 3. Water absorption and specific gravity.

S/N	Samples	Water Absorption
1	Fine Aggregate	5%
2	Coarse Aggregate	0.5%
3	Steel Slag Aggregate	6.4%
S/N	Samples	Specific Gravity
1	Steel Slag	2.64
2	Fine Aggregates	2.70
3	Coarse Aggregates	2.69

The absorption characteristics of aggregates influence the bond between the cement paste and aggregate, the concrete resistance to freezing and thawing, and its overall chemical stability. As shown in Table 3, steel slag, fine aggregate, and coarse aggregate had water absorption of 6.4%, 5%, and 0.5% respectively. Steel Slag Aggregate (6.4%) has high water absorption and demand more water (pre-wetting) to avoid robbing the mix water. This shows that steel slag absorbs more water than fine and coarse aggregate. The effective water–cement ratio, which directly influences concrete workability and strength, must be carefully controlled. It subtracted the amount of water that the fine aggregates absorbed from the total amount of water needed for the mix. Due to high water absorption (≥5%) of Steel Slag Aggregate, more water was added (but carefully to prevent an excessively high w/c ratio) during mix design. Steel slag, with a high water absorption value (6.4%), can significantly affect the long-term durability of concrete if not properly managed. The specific gravity of the sample presented in Table 3 indicates that the steel slag has a higher specific gravity than both coarse and fine aggregate. All materials are within the permitted range of 2.6 to 2.7 specific gravity.

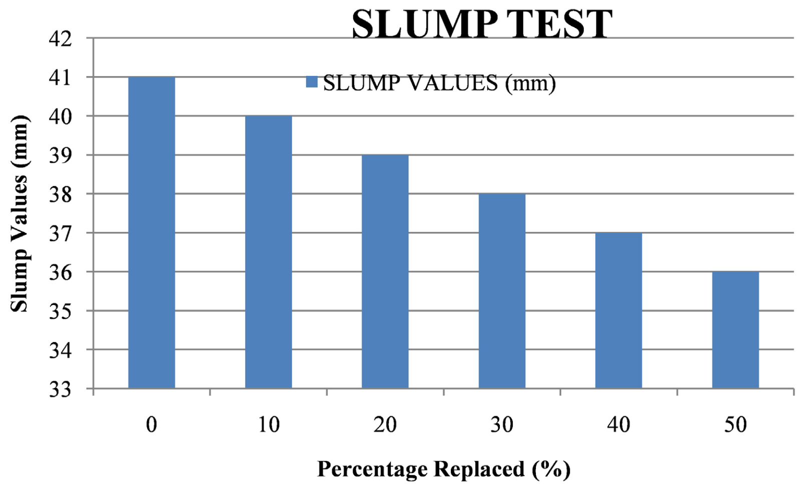

Figure 3. Slump test with steel slag for the replacement of coarse aggregate.

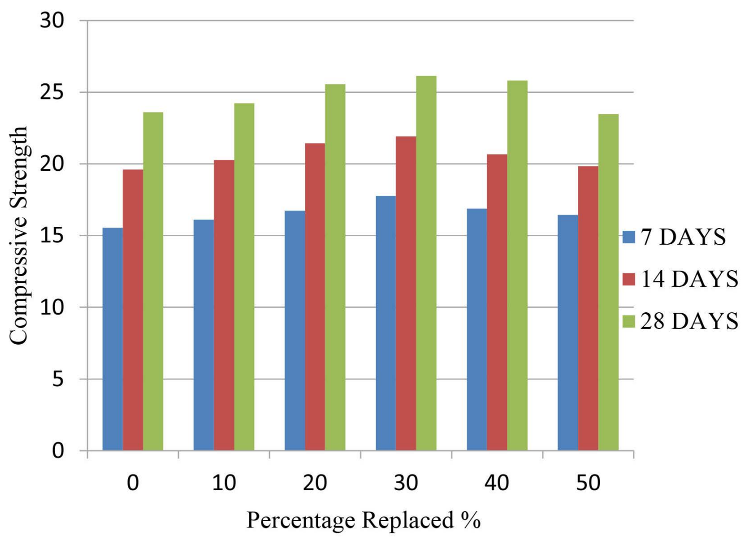

Figure 4. Compressive Strength of the specimen after replacement (0% - 50%).

Figure 3 presents the results of the slump test, which indicates that the percentage added to the mix influences the nature of the slump. The range is from 0 to

50% coarse aggregate with steel slag replacement. The height of the slump is inversely proportional to the percentage of coarse aggregate replaced.

As shown in Figure 4 shows compressive strength increases progressively from 0% - 30% and decreases to 50%. These show that the optimum percentage at 30% replacement with values of 17.78, 21.91 and 26.14 N/mm^2 at 7, 14 and 28 days, respectively. The compressive strength increases with higher cement content and is significantly influenced by curing conditions and the amount of mixing water. Therefore, the partial replacement of coarse aggregate with steel slag in concrete mixtures is recommended for structural applications, with a 30% replacement level identified as the optimal proportion for enhancing compressive strength.

4) Conclusion and Recommendation

Based on the results obtained on the use of steel slag as a partial substitute for coarse aggregate in concrete, the following conclusions were made:

a) The percentage added to the mix influences the nature of the slump, ranging from 0%, 10%, 20%, 30%, 40% to 50% replacement of coarse aggregate with steel slag, with respective slumps of 41%, 40%, 39%, 38%, 37%, and 36%. The height of the slump is inversely proportional to the percentage of coarse aggregate replaced. The optimum mixture was at 30% replacement with a slump height of 38 mm.

b) Steel slag, fine aggregate, and coarse aggregate had water absorption of 6.4%, 5%, and 0.5% respectively, which shows that steel slag absorbs more water than fine and coarse aggregate, also fine aggregate (2.70) has a higher specific gravity than both coarse (2.69) and steel slag aggregate (2.64).

c) The compressive strength increases progressively from 0 to 30% and decreases to 50%. These show that the optimum percentage at 30% replacement with values of 17.78, 21.91, and 26.14 N/mm^2 at 7 and 14, and 28 days, respectively, and M20 was able to be obtained at 14 days of curing.

The following recommendations are suggested for future work:

a) Based on this research, a 30% replacement of steel slag as coarse aggregate is recommended because it achieves an optimum balance between workability and compressive strength.

b) To investigate other mechanical properties, such as flexural and tensile strength, when coarse aggregate was replaced with steel slag.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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