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Effect of Varying Fine and Coarse Steel Slag Contents on Strength, Sorptivity and Freeze-Thaw Resistance of Micro Silica-Modified Concrete

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Effect of Varying Fine and Coarse Steel Slag Contents on Strength, Sorptivity and Freeze-Thaw Resistance of Micro Silica-Modified Concrete

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Abstract

The sustainable utilization of industrial by-products in concrete production has recently become a priority in modern construction engineering due to its global availability, environmental benefits, and potential engineering properties. The use of steel slag (SS) in fine and coarse sizes with mineral admixtures, including micro silica (MS), in concrete design must be thoroughly examined for durability and efficiency, considering several variables, including their types and contents. The combined impacts of MS and SS must also be well investigated. This article examined the mechanical and durability properties of concrete after adding SS and MS separately and in combination. In an experimentally based investigation, fine steel slag (FSS) and coarse steel slag (CSS) was substituted for natural fine and coarse aggregate, respectively in varying ratios (20% - 70%) in the same mixture with and without MS (10%) as partial cement replacement. The concrete mixtures' workability, density, compressive strength, flexural strength, splitting tensile strength, capillary water absorption rate (sorptivity), and freeze-thaw resistance were assessed. Results indicate that compressive strength increased progressively up to 40% SS replacement, achieving 42.1 MPa compared with 36.4 MPa for plain concrete. Beyond 50% replacement, strength declined despite continuous increases in density. According to the mechanical properties and durability investigated in the present study, the optimum performance was observed in the replacement of 30–40% SS along with 10% MS, which confirmed its modification. The findings provide engineers, researchers, and decision-makers in the construction industry with valuable guidance on the practical benefits and elements to consider when including SS and MS into concrete mixtures. This application maximizes resource efficiency and reduces environmental impact while enhancing the mechanical and durability properties of concrete.

Keywords: steel slag; sustainable concrete; mechanical properties; durability; recycled aggregates; micro silica

1. Introduction

Steel slag (SS) as a byproduct of the production of steel, due to its potential physical and chemical properties, such as its high density, hardness, and angularity, make it useful for a wide range of civil engineering applications [1]. SS consists of calcium oxide (CaO), silicon dioxide (SiO_2), iron oxide (FeO), aluminum oxide (Al_2O_3) and a little magnesium oxide (MgO), manganese oxide (MnO), and sulfur (S). The precise make-up can be different based on the process of steel production and the raw materials [2]. This is what renders it difficult among the researchers to determine the optimum content of SS in the concrete mixtures. The aspects mentioned above provide SS with its special properties, and it is a worthy resource that can be used to improve various products and materials. Studies have revealed that the addition of SS to construction materials has quite several merits, including improvement of mechanical characteristics, and environmental merits [3]. Studies also show that inclusion of SS in concrete and asphalt mixtures can enhance the mechanical and the durability properties of mixtures. Moreover, it is stable and has a high shear strength, making it possible to use it as fill material in building embankments and reclamation of land [4]. Through the application of SS in many activities, we can encourage resource conservation, minimize the generation of waste, and encourage more sustainable and environmentally friendly activities in most industries. The application of steel slag in concrete and the effects it has on the engineering properties of concrete have been studied on a variety of research. A recent research work [5]. examined the impact of steel slag addition to the concrete and as per their results, concrete with steel slag particles exhibited better flexural, tensile, and compressive strengths than natural aggregate concrete. Their results revealed that concrete containing SS aggregates had a much greater compressive, tensile, and flexural strength as compared to plain concrete. Another study [6] examined the use of steel slag as aggregates in concrete. They concluded that steel slag aggregates offered advantages above natural aggregate mixtures. Improved compressive strength with partial SS replacement was also reported elsewhere [7]. Enhanced rigidity and abrasion resistance were noted by another research [8]. The researchers concluded that, high replacement levels of SS can make the material less workable [6–8]. The combined usage of fine and coarse steel slag aggregates at high replacement ratios has not received much attention despite these investigations. Furthermore, there are still few thorough studies that include mechanical, durability, and non-destructive testing. There are a few SS-based concrete application-related problems that must be recognized and fixed. To effectively use SS under compression loadings, it is still necessary to understand the causes behind the mixed effects (positive, negative, or insignificant) of high SS dosage on concrete's mechanical and durability properties and reaching its full potential. It is also crucial to investigate how these materials (SS aggregates and micro silica) affect concrete to strengthen the binder matrix. The purpose of this study is to assess how different fine and coarse SS dosages up to 70% affect the characteristics of concrete. The impact of SS contents with and without micro silica (MS) (or silica fume) was also investigated to examine the function of bond strength in the matrix. Utilization of MS and SS aggregates in a concrete mixture may provide a synergistic solution for sustainable concrete production industry. This study supports sustainable construction practices including encouraging the recycling of industrial by-products, decreasing reliance on natural resources, assessing high SS replacement ratios, providing a thorough evaluation of durability, and supporting low-carbon construction practices. Although, several works have studied effect of MS and SS aggregate separately. However, limited research has systematically examined mechanical and durability performance of combined effect of fine and coarse steel slag aggregates, and MS at moderate water to binder ratios (e.g., w/b = 0.5). The moderate w/b ratios are typical for conventional structural concrete rather than high-strength or high-performance concrete mixtures.

2. Methodology

Throughout the present study, newly produced lump-free ordinary Portland cement with a specific gravity of 3.15 that is now sold in the local market in Kurdistan, Iraq was utilized. Initial and final settings took 145 and 225 minutes to configure, respectively. 10% (by weight) of micro silica (sometimes called silica fume) with a specific gravity of 2.26 was substituted for some of the cement in the selected mixtures. Table 1 lists the primary chemical compositions of cement, micro silica (MS), and steel slag.

Table 1. Primary compositions of cement, micro silica, and steel slag.

Composition (%)	Cement	Micro silica	Steel slag
CaO	64.3	0.7	36.2
Al_2O_3	5.7	1.1	5.2
Fe_2O_3	4.1	0.1	31.9
SiO_2	23.3	90-93	19.7

The SS were collected for this study from a local steel factory in Erbil, Kurdistan region [9]. The SS had a specific gravity of 3.10, a blackish color, a granular appearance, and a 2.77% water absorption rate. The typical 4.75mm fine steel slag (FSS) and 12.5mm coarse steel slag (CSS) aggregates were obtained by sieving the SS that was provided from the plant. The chemical properties of the SS are also displayed in Table 1. As a fine aggregate, locally accessible natural sand was utilized. The used sand particles met the standard requirements for grading fine aggregate by passing through a 4.75 mm sieve. Specific gravity, water absorption, and fineness modulus were 2.66, 2.67, and 1.25 percent, respectively. Additionally, local sources of clean crushed natural coarse material with a maximum size of 12.5 mm were used. Any material that passed the 4.75 mm sieve was eliminated after the aggregates were sieved. The water absorption value was 0.9%.

2.1. Mix Proportions

Eleven mixtures of concrete were prepared with and without MS using different replacement ratios of FSS and CSS. Compared to the reference mix, these mixtures were compared. The w/b ratio was maintained at 0.5, in all the mixtures. Prisms, cylinders, and cubes of concrete were prepared and experimented in a laboratory state. The proportions of FSS and CSS were used substituting the weight of natural fine and coarse aggregates at 0, 20, 30, 40, 50, 60 and 70 percent. The amount of FSS and CSS was calculated based on their replacement percentage and specific gravity. To determine the effect of MS on the properties of the steel slag (SS) concrete, four concrete mixtures of 0% (control), 30, 50 and 70 percent, were selected to add 10% MS. Each mix was cast, and a slump test carried out immediately to determine the workability of the concrete. It was aimed to achieve a slump of 80mm to 150mm with the help of 1.4 percent of superplasticizer by binder weight. The additional water resulting from the higher water absorption of SS aggregates has been added to the total water content of SS concretes in the mixer. Additional details on the mix design are given in Table 2.

Table 2. Mix proportions (kg/m³).

Mix No.	OPC	Micro-silica		Sand	Gravel	Fine-SS		Coarse-SS		Water
		%	Kg/m³			%	Kg/m³	%	Kg/m³	
1	400	0	0	800	1200	0	0	0	0	200
2	**360**	**10**	**29**	**800**	**1200**	**0**	**0**	**0**	**0**	**200**
3	400	0	0	640	960	20	187	20	280	200
4	400	0	0	560	840	30	280	30	420	200
5	**360**	**10**	**29**	**560**	**840**	**30**	**280**	**30**	**420**	**200**
6	400	0	0	480	720	40	373	40	560	200
7	400	0	0	400	600	50	467	50	700	200
8	**360**	**10**	**29**	**400**	**600**	**50**	**467**	**50**	**700**	**200**
9	400	0	0	320	480	60	560	60	840	200
10	400	0	0	240	360	70	653	70	980	200
11	**360**	**10**	**29**	**240**	**360**	**70**	**653**	**70**	**980**	**200**

2.2. Preparation and Testing Methods

As soon as the concrete was removed from the drum mixer, measurements of the slump for each batch were made. Standard cubicle molds of 100 × 100 × 100 mm were used to test cast concrete samples for compressive strength in all designed mixtures. On the twenty-eighth day of curing, three samples were analyzed and evaluated. Prior to compressive strength test, the same samples' ultrasonic pulse velocity (UPV) values were noted. Cylindrical specimens of 100 × 200 mm were used for the splitting tensile strength test. On the twenty-eighth day of curing, the test was conducted. On the twenty-eighth day of water curing, the flexural strength test was also conducted. For every concrete mixture that was designed, the prism specimens were 400 mm long and 100 mm by 100 mm on the sides. After 24h, the concrete samples were demolded and cured in water at 20 ± 2°C until testing at 28-day. The method employed in the earlier study [10] was used to ascertain the rate of capillary water absorption (sorptivity) of concrete samples. Since sorptivity is the slope of the first linear relationship between cumulative water absorption and the square root of time, the first sixty minutes of water absorption by capillary action have been computed in the present study. For the sorptivity test, specimens of 100 × 100 × 100 mm were utilized (Figure 1). Until a consistent dry weight was reached, saturated surface dry (SSD) specimens were maintained at 80º C in a hot air oven. When only 2-3 mm of one surface of the specimen is exposed to water on a support device, the rise in mass that results from water absorption is measured as a function of time to estimate the concrete specimens' absorption for the sorptivity test. The remaining surfaces were covered with sheets of nylon. Increase in weight was recorded at 1, 3, 5, 10, 15, 30, 45, 60, 120, and 1440-minute intervals. The water level remained steady during the test. Three samples were averaged to determine the sorptivity values. The average sorptivity of three samples for each mixture was computed by taking the square root of the time (minute) and comparing it to the weight (g) of water absorbed per unit area (mm^2). The 100 mm cubic specimens were subjected to the Freeze-Thaw (F-T) test [11]. The specimens were water cured for 28 days before the experiment was carried out. Instead of using a laboratory chamber, the F-T durability test of the concrete specimens was conducted using a standard freezer set at -18 °C, as seen in Figure 1. The specimens were then manually frozen for four hours and thawed by submersion in water at room temperature for four hours, for a total of eight hours. This process was repeated ninety times (90 cycles) over thirty days.

Figure 1. Freeze-Thaw and Capillary water absorption tests.

3. Results and Discussion

In this section, instead of analyzing and discussing the experimental results of each test separately, the effect of steel slag (SS), micro silica (MS), and the combination of both on all mechanical properties and durability performance is investigated simultaneously. In addition, the correlation between the properties is also evaluated in this section.

3.1. Effect of Steel Slag

Figures 2 and 3 displays the compressive strength findings for each concrete mixture with their strength change percentage compared to control (0% SS). 36.4 MPa was attained by the control mix and strength reached 42.1 MPa with SS substitution up to 40% (without MS). The strength reduced drastically with increasing replacement (50 percent and above) to approximately 31.8 MPa at 70 percent replacement, which is likely due to increasing porosity and absorption. The increase in compressive strength of concrete containing up to 40% SS replacement can be attributed to better interlocking and improved bonding due to the specific geometry of SS aggregates in terms of angularity and surface roughness [12].

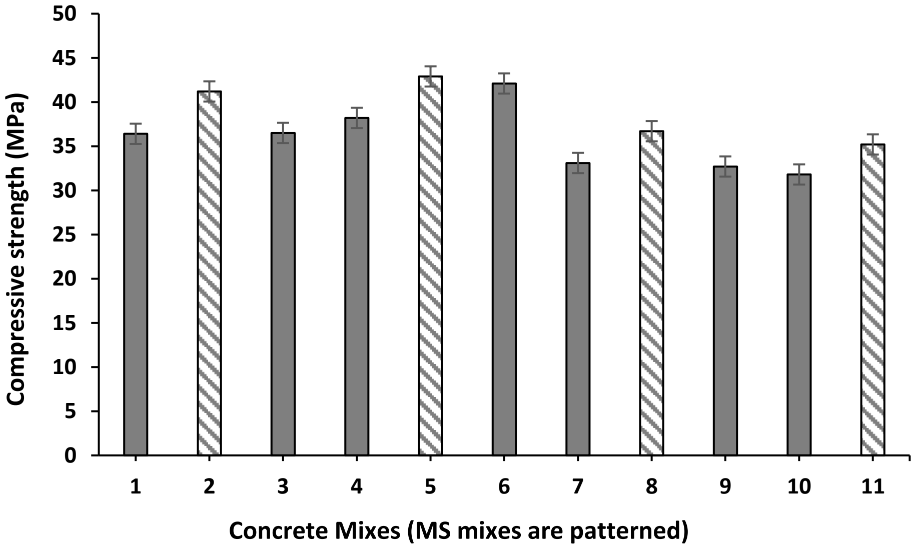

Figure 2. Compressive strength of concrete mixtures containing varying content of SS and MS.

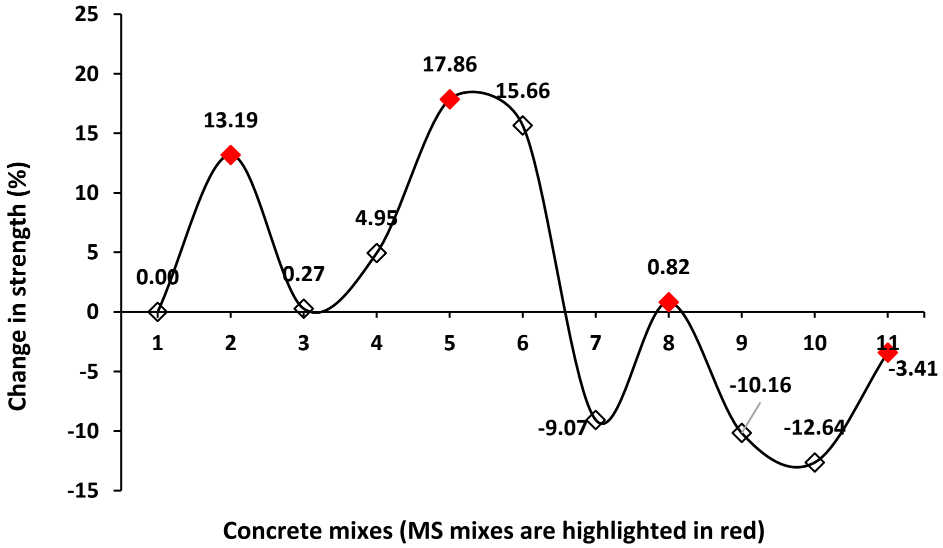

Figure 3. Change in strength with SS contents and MS.

Despite the increase in density (Figure 4), the strength of concrete containing high SS content (50% and higher) was reduced due to the possible volumetric instability and increased brittleness caused by the high SS content. The trend of splitting tensile strength (Figure 5) was like that of compressive strength. Although, stress transfer capacity and crack resistance were enhanced by low and moderate SS replacement levels. However, tensile performance was slightly lowered because of excessive SS replacement (50% SS and higher). Like compressive strength and tensile strength, flexural strength (Figure 5) increased too up to 40% with SS content. Stiffness and possible improved aggregate interlocking were factors in this behavior; strength was seen to decrease after this level of replacement [13].

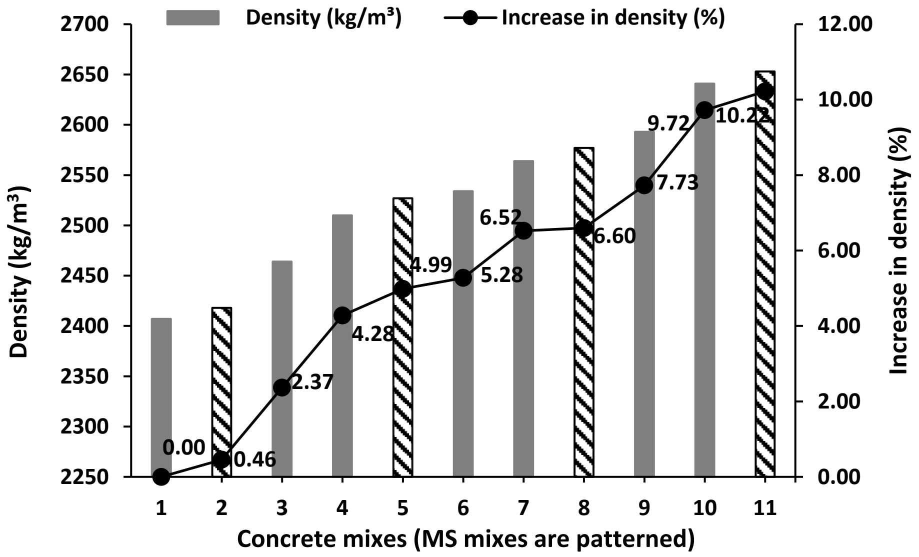

Figure 4. Dry density of concrete mixtures with their net changes containing varying amount of SS and MS.

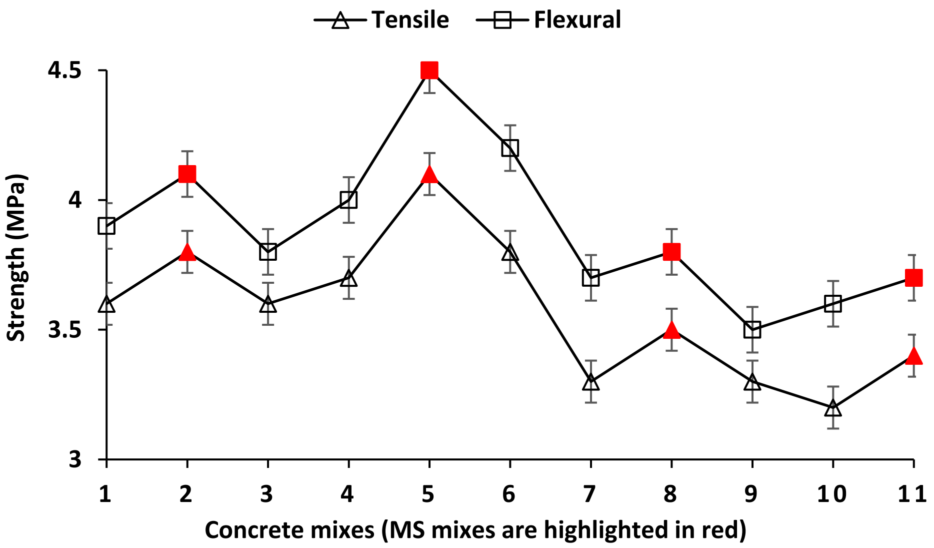

Figure 5. Tensile and flexural strengths of concrete mixtures containing varying content of SS and MS.

The durability properties investigated in the present study followed a similar pattern to the mechanical properties explained earlier. After freeze-thaw (F-T) exposure, the loss of strength declined to 40% of the SS level then rose at 50% SS and over (Figure 6). Both UPV (Figure 7) and absorption characteristics by capillary action (sorptivity) (Figure 8) showed a similar pattern [14].

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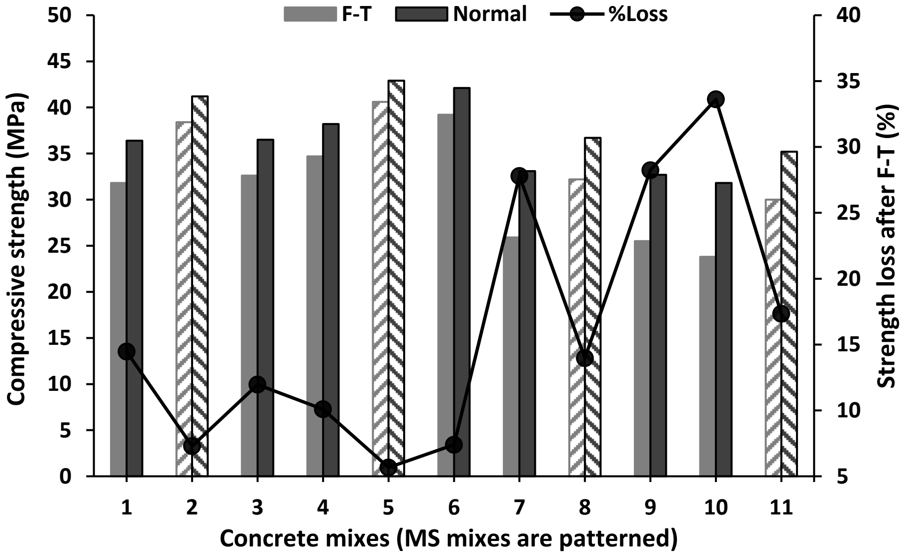

Figure 6. Normal and under F-T exposure compressive strength of concrete mixtures with their strength loss.

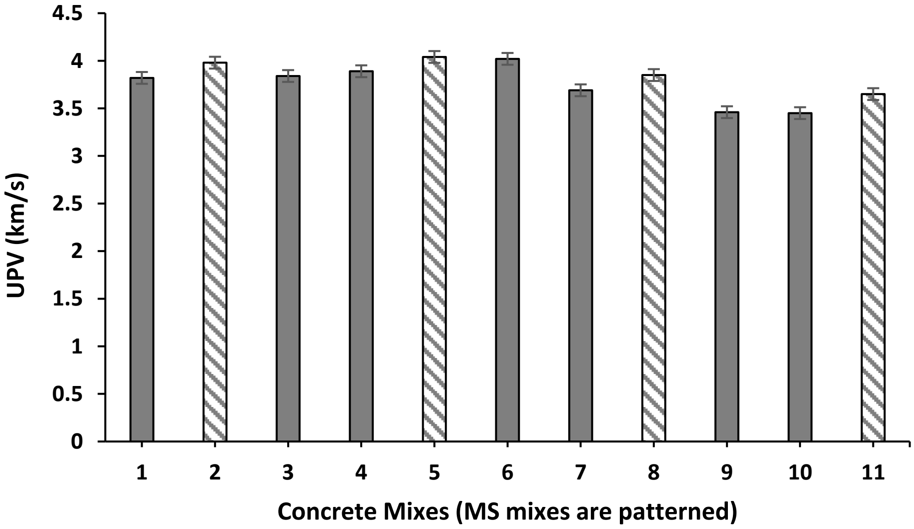

Figure 7. UPV values of concrete mixtures containing varying amount of SS and MS.

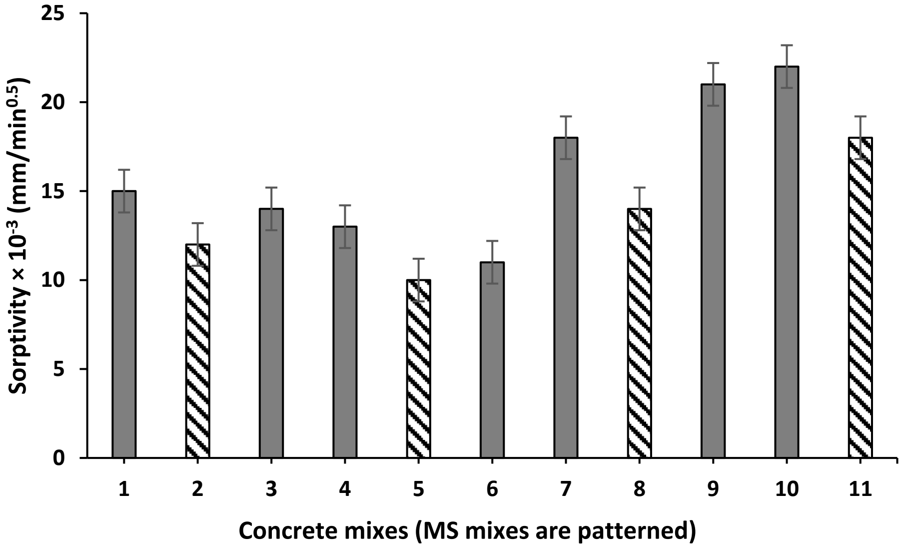

Figure 8. Sorptivity values of concrete mixtures containing varying amount of SS and MS.

The increased specific gravity of SS aggregates is also proved by the increased density of 2407 kg/m³ (plain concrete) to 2534 kg/m³ (40% SS). Compressive strength however dropped to approximately 36 MPa as compared to 42.1 MPa. However, density continued to increase, to 2641 kg/m³ at 70% but strength had dropped to approximately 32 MPa (Figures 2 and 4). Therefore, it can be confirmed again that matrix quality is more important than concrete density alone in determining strength. According to the results obtained the low and moderate addition of SS aggregates raised the UPV values, suggesting better internal structure and density in the concrete. On the other hand, increased porosity and internal micro-cracks may be reflected in lower UPV values at high SS replacements [15].

To explain and justify this phenomenon, and as seen in the Figure 7, similar trends were realized in the UPV values, which peaked at 3.72 km/s and were categorized as "good quality" concrete for the 40% SS mixture. This shows reduced microcracking and increased compactness in the matrices although there was a reduction in UPV with 50 percent and more replacements of SS. These findings indicate that discontinuities in the internal structure may be created by increasing SS aggregates, which is most likely due to SS volumetric instability, insufficient SS compaction, and increased internal microcracks and possible brittleness. Additionally, the findings of the compressive strength test after 90 freeze-thaw (F-T) cycles showed the same pattern as explained earlier. The control concrete's strength loss was 14.47%. For a 20% SS concrete mixture, the strength loss was reduced to 11.96%, and for a 40% SS concrete mixture, it was further reduced to 7.49% (Figure 6). This again shows that increasing the percentage of SS replacement to 40% reduces the effect of concrete exposure to F-T, such that the strength loss after 40% SS replacement increases dramatically, reaching approximately 34% at 70% SS content (without MS) [16]. From the above discussion, it can be summarized that when SS fine and coarse aggregates were replaced with natural fine and coarse aggregates, different effects on the engineering performance of concrete mixtures were observed. Mechanical performance and durability were balanced and an optimal level of SS replacement (in the absence of MS) of 30-40% was realized. The strength gradually increased from 36.5 MPa at 20% replacement, to 38.2 MPa at 30% replacement and to 42.1 MPa at 40% replacement due to better particle density at the intermediate replacement ratios. However, at 50%, 60% and 70% SS, the strength decreased to 33.1, 32.7 and 31.8 MPa, respectively, indicating an ideal replacement level of 30–40%. On the other hand, it is interesting to see that the compressive strength at levels of 50%, 60% and 70% SS is almost similar at 32 and 33 MPa.

3.2. Effect of Micro Silica

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As can be seen in Figures 2 and 3, the addition of 10% micro-silica (MS) improved the compressive strength in all corresponding mixtures (patterned mixes of M2, M5, M8 and M11). For example, MS led to an improvement of approximately 13% in the strength of plain concrete (without SS aggregates) which increased from 36.4 MPa to about 41.2 MPa. Similarly, the addition of MS increased the strength of the 30% SS mixture from 38.2 MPa to about 42.9 MPa. As a result, the increase in strength occurred through better pozzolanic reaction and micro-filler effects, which led to the modification of the interfacial transition zone (ITZ) and the densification of the pore structure. The increase in internal homogeneity and the reduction in porosity were confirmed by the improvement of the UPV values as previously described [17]. In addition to significantly increasing compressive strength, the addition of 10% MS to concrete mixtures also improved other properties investigated in this study. Tensile and flexural strengths and UPV values all showed a similar trend, and sorptivity and freeze-thaw resistance were improved, such that 10% MS enhanced the quality of the concrete [18]. The enhancement is explained by the presence of pozzolanic reaction between amorphous SiO_2 and calcium hydroxide that generates more calcium-silicate-hydrate (C-S-H) gel. As mentioned earlier, this reaction densifies the ITZ and modifies the pore structure. It should be mentioned that the strength enhancement at a rather moderate w/b ratio of 0.5 is high though not as high as the strength of MS tends to exhibit stronger interaction at lower w/b ratios (i.e., 0.4 and below). However, the observed improvement indicates that MS greatly improves matrix integrity and internal compaction even at standard water content. The higher concrete compaction is supported by a concomitant improvement in the engineering properties, including UPV, as higher UPV is usually associated with improved homogeneity and reduced porosity [19].

3.3. Synergistic Effect of MS and SS

The observed strength decrease with increasing SS content was significantly reduced by adding 10% MS to all SS mixtures containing high SS contents. For example, when MS was added, the strength increased significantly from 33.1 MPa to 36.7 MPa and from 31.8 MPa to 35.2 MPa at high SS contents with 50% and 70% SS replacement (Figures 2 and 3). Similarly, MS improved the UPV values and sorptivity capacity, reduced the effect of F-T exposure, and partially restored the tensile and flexural strengths at 50% and 70% replacement levels (Figures 5–8). Several reasons could explain this synergistic activity. For example, MS effectively modifies the ITZ and enhances the aggregate-paste bond by filling the micropores and generating additional C-S-H. On the other hand, SS aggregates have rough surfaces but may also contain micropores or weak boundary layers. The second factor is the very fine particles of MS which increase compaction and decrease capillaries, compensating for matrix defects caused by excessive SS aggregates. The last explanation could be that the SS aggregates’ free CaO can reacts better with addition of reactive silica, in result reducing the possible volumetric instability. Despite the aforementioned improvements, as shown in the figures, the ideal mixture of 40% SS without MS was not outperformed by mixtures with 50% or more SS aggregates plus MS. Accordingly, silica fume improves the quality of the matrix but is not able to fully compensate for the excessive SS replacement that compromises the integrity of the structure. Therefore, it can be concluded that at medium levels of SS, the synergistic interaction between MS and SS aggregates was much more effective than at high levels of replacement [20–23].

3.4. Correlation

The data demonstrate a high correlation between UPV and compressive strength (Figure 9), with $R^2 = 0.9$, confirming a high possibility for compressive strength to be predicted from UPV values in the present study. UPV might be a dependable non-destructive testing (NDT) technique for the concrete quality index since stronger mixtures usually show higher pulse velocity [24].

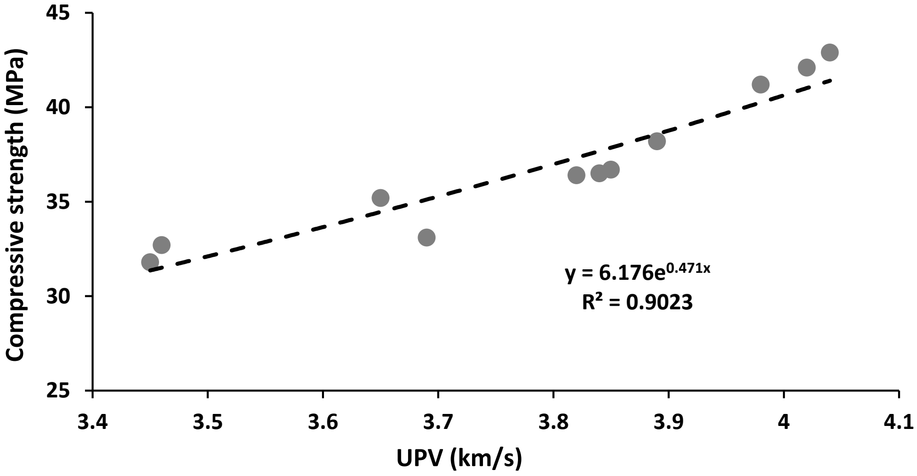

Figure 9. Very strong correlation between compressive strength and UPV values.

Although, the correlation between compressive strength and density is usually high for conventional concrete. However, the very weak correlation between density and compressive strength (R^2 = 0.3) (Figure 10) proving that the mechanical behavior relied on both the density and structure characteristics. It means that a lower application value for using the density as a predictor of compressive strength in the present work. When MS is added to moderate SS replacement levels of 30% - 40%, the ideal balance between material stability and mechanical performance is attained. The strength dropped below the ideal substitution threshold even though the density increased steadily with the SS concentration. This confirms that not only mechanical properties can be influenced by mass density, but it can be affected by bonding quality, and the microstructure integrity as well.

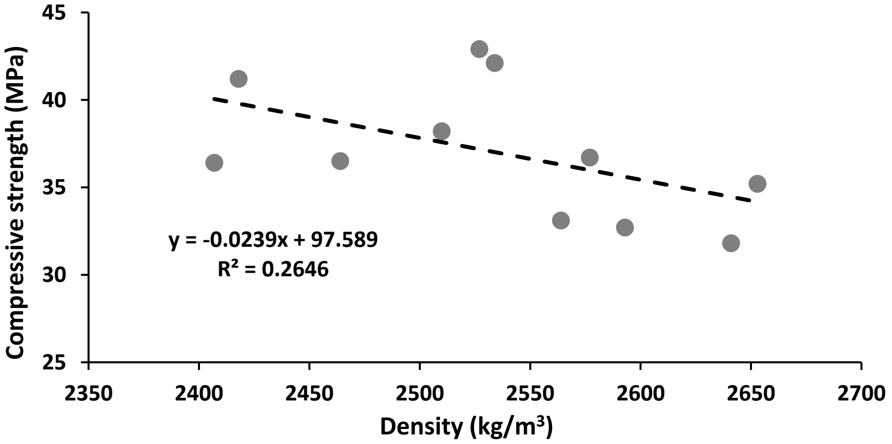

Figure 10. Very weak correlation between compressive strength and density of concrete mixtures.

The data also show a very good relationship between sorptivity values and compressive strength (R^2 = 0.92), suggesting that there is a greater chance of predicting sorptivity from compressive strength within the range under study. Concrete mixtures with higher compressive strengths generally have lower sorptivity values (Figure 11).

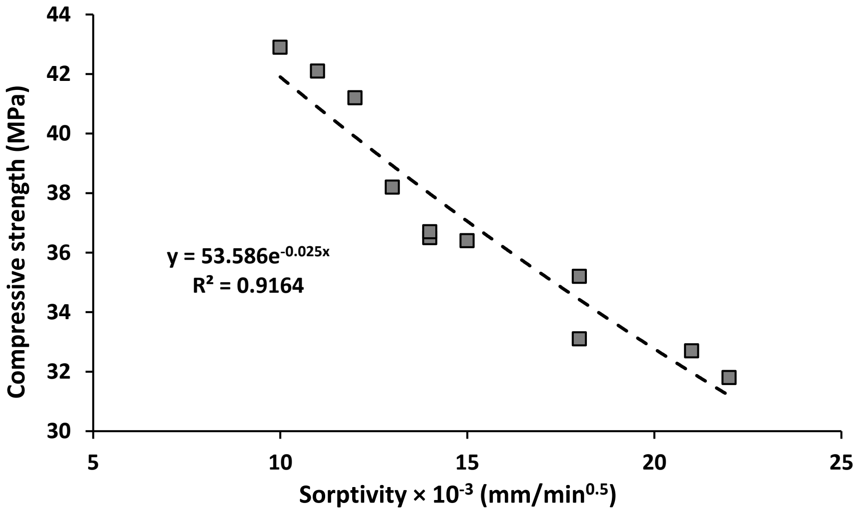

Figure 11. Very strong correlation between compressive strength and sorptivity values.

4. Conclusions

The following conclusions can be made based on the current experimental investigation:

- Steel slag (SS) concrete promotes construction sustainability.
- Compressive strength, tensile strength, and flexural strength of concrete increased with utilizing up to 40% SS, and freeze-thaw (F-T) and sorptivity improved.
- Strength of 50% or higher SS concrete decreased, despite increasing in density.
- By adding 10% micro silica (MS), the mechanical and durability properties of all concrete mixtures examined in this study increased.
- The combination of 10% MS with 30-40% SS provided optimal engineering performance.
- Compressive strength, sorptivity and UPV have a highly significant correlation, which confirms the use of UPV non-destructive testing for concrete quality assessment.

The evaluation of long-term durability of concrete containing high SS content is recommended as future research.

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Data Availability: Data is available upon reasonable request.

Conflicts of Interest: The author declares no conflict of interest.

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