Reducing concrete porosity using supplementary cementitious material (white slag)

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Abstract. This research aims at assessing the utility of the white slag as a secondary cementitious material in decreasing the porosity of concrete and enhancing the overall performance. As sustainable construction enjoys growing popularity, the industrial by-products like white slag prove to be a possible alternative to the partial replacement of the Ordinary Portland Cement. The concrete mixes were prepared with the replacement rates of white slag of 0, 5, 10, 15, and 20 percent using the same amount of water-cement ratio of 0.45. Cube, cylinder, and prism specimens were 7, 14 and 28 days cast and cured to study the effect of replacement with time. Mechanical properties such as compressive strength, split tensile strength, and flexural strength were also tested and water absorption was tested to determine the porosity. The findings showed that the mix with 10 percent white slag had the biggest improvement with the compressive strength of 29.0 MPa in 28 days, which was a 16 percent increment over the control mix (25.0 MPa). The water uptake of 4.5% in the control reduced to 3.9% in 10% replacement and this revealed a 13% decrease in porosity. These results validate that replacement with moderate levels of white slag improves strength and durability, and can be used in the development of sustainable cementitious material.

1 Introduction

Concrete is an essential component of construction worldwide and forms the basis of today's infrastructure. However, its naturally porous nature is one of the biggest challenges regarding its long-term durability because structures become vulnerable to the penetration of aggressive substances such as water, chlorides and sulfates which will eventually cause degradation and consequently lead to a diminished service life [1]. The search for novel, eco-friendly materials that can enhance concrete's performance while having the least negative effects on the environment is necessary due to the growing demand for sustainable

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construction methods. Traditional Portland cement manufacture is energy consuming, and a significant emitter of carbon dioxide globally, which has prompted pressing need for viable alternatives and partial substitutions [5-7].

Supplementary Cementitious Materials, especially industrial byproducts such as various forms of slag, are a promising way to find solutions that meet these challenges and may enhance the microstructure of concrete and the contribution of carbon dioxide to the environment [2-4]. It has been demonstrated that white slag, an industrial waste from the steel industry, works well as a pozzolanic material with refined pore structure in concrete. The porosity of concrete is an important parameter of the durability and service life of concrete. Higher porosity brings higher permeability and causes the harmful agents to enter the matrix of the concrete with ease. This leads to several ideas of deterioration such as alkali-silica reaction, freeze-thaw damage, sulfate-attack and corrosion of reinforcement. Cement and white slag are differentiated materials whose physical and chemical properties are different. The main strengthable component of concrete is cement which is a powerful binding material and hardens when mixed with water.

White slag is on the other hand an industrial by-product including useful compounds which lack the binding properties that cement had naturally. It acts as a Supplementary Cementitious Material (SCM), contributing to concrete performance through physical filling and secondary pozzolanic reactions. i.e. can contribute to the concrete properties only when combined with cement. Because of this distinction, white slag cannot completely replace cement; on its own, it cannot create the chemical reactions required for concrete to properly set and harden.

However, when used in smaller proportions typically between 5% and 20% white slag reacts with the by-products of cement hydration to form additional binding gels that improve strength and reduce porosity [13-15]. This is why partial replacement works effectively. This demonstrates that although white slag cannot fully replace cement, it can be a useful partial substitute to enhance strength, durability, and environmental sustainability of concrete. Unlike commonly studied SCMs such as fly ash or GGBS, white slag has been less explored for porosity-based durability performance, which forms the novelty of the present study [8-10]. The objectives of this study are to evaluate the effect of white slag on concrete porosity, to examine its influence on compressive, split tensile, and flexural strength, to assess durability through water absorption, and to identify the optimum replacement level.

2 Scope of the project

The project will involve some broad experimental research on white slag replacement in the levels of 0, 5, 10, 15 and 20% weight wise of the final concrete. The nature of the materials, mix design optimization, the preparation of the specimen, systematic testing concerning various ages of the curing and the analysis of the results in detail are some of the material employed in the research. The mechanical properties that are checked are compressive strength, split tensile strength and flexural strength and durability measures such as water absorption due to porosity.

Specifically, the project activities are dedicated to the perception of the impact of the white slag on the mechanism of pore refinement and the presence of the relationship between the strength development and the porosity reduction. The environmental benefits in terms of cement reduction and associated carbon footprint reduction were also considered. The implications of findings to concrete construction are seen. Such findings are intended to provide viable instructions on white slag utilization and promote sustainability.

3 Materials and methods

3.1 Materials

In this project, we selected the natural river sand as the fine aggregate. Its sand was of density 1460 kg/m^3 and Fineness Modulus of 2.51. This indicates that it was of high grade and could be used to produce concrete of high quality. Its specific gravity measured 2.6 and this falls within the normal spring of natural sand. This proves that neither was the material too light or too heavy and would fit in the mix. The mixing and curing used clean drinking water that had a pH of 7. This was pure water which had neither organic matter nor impurities. It conformed to the requirements of IS 456:2000 and IS 3025:1964 [11] and it was ensured that no toxic elements could have any influence on the development of the concrete as well as on its strength. The cement used was Ordinary Portland Cement conforming to IS 12269:2013, and fine and coarse aggregates satisfied IS 383:2016 requirements. Table 1 indicates the physical properties of cement applied. The mix proportions adopted for all concrete mixes are given in Table 2.

Table 1. Physical properties of cement

S. No.	Physical Properties	Results
1	Specific Gravity	3.10
2	Consistency	31%
3	Final Setting Time	225 min
4	Initial Setting Time	32 min
5	Fineness	2.67%
6	Soundness	2.2 mm

Table 2. Mix proportion of concrete per m³

Mix ID	White Slag (%)	Cement (kg/m³)	White Slag (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	w/c Ratio
Control	0	394	0	682	1150	177	0.45
Mix A	5	374	20	682	1150	177	0.45
Mix B	10	355	39	682	1150	177	0.45
Mix C	15	335	59	682	1150	177	0.45
Mix D	20	315	79	682	1150	177	0.45

White slag served as the supplementary cement material. It was collected from a nearby steel manufacturing plant, where it is regularly produced as a by-product during metal refining. Before adding it to the concrete mix, the material was processed by drying, crushing, and grinding to reach a fineness level similar to that of cement. This made sure that the slag particles were fine enough to take part in the pozzolanic reaction and help improve the properties of the concrete. The chemical properties of white slag are detailed in Table 3. The characteristics of white slag were summarized in Table 4. The fineness of white slag was determined in accordance with IS 4031 (Part 1):1996.

Table 3. Chemical properties of white slag (%)

S. No.	Components	Composition (%)
1.	Silicon Dioxide (SiO_2)	30 - 40
2.	Aluminum Oxide (Al_2O_3)	10 - 15
3.	Iron Oxide (Fe_2O_3)	1.0 – 3.0
4.	Calcium Oxide (CaO)	35 - 45
5.	Sulphur Trioxide (SO_3)	0.5 – 2.0
6.	Magnesium Oxide (MgO)	5.0 - 10
7.	Chlorides (Cl^-)	< 0.05

Table 4. Characteristic of white slag

Materials	Particle Size (µm)	Fineness (m^2/kg)	Density (kg/m^3)	Reactivity / Chemical Property
White Slag (Powdered SCM)	5 – 45 µm (typical powder range)	400 – 450	2900	High pozzolanic reactivity (forms C-S-H gel with $Ca(OH)_2$

The concrete mix was designed for M25 grade as per IS 10262:2019 [12]. To determine the effect of different quantities of white slag on the mechanical and durability characteristics of M25 grade concrete, different mix proportions were prepared. There were 5 levels of white slag replacements; 0, 5, 10, 15, 20 Slag Replacement and Each percentage represents the quantity of the white slag that was used in place of the cement content in a total knecker. As an example, in this mix of 10 percent white slag, such that one-tenth of the cement weight was substituted with processed white slag and the remainder was Ordinary Portland Cement. The rest of the mixes were done using this method thus giving a clear comparison of the performance of all the replacement levels.

A mix was carried out to ensure good workability and even mixing of the dry materials (cement, white slag, fine aggregate and coarse aggregate) up to the point that they attained a homogeneous colour and texture. The water was also added slowly to avoid lumps and mixing was done until a homogeneous and workable concrete mix was realized. All the mixes were done with a lot of care so that there was no segregation and uniformity in all the specimens. Once the required workability had been arrived at, the fresh concrete was poured into standard cube, cylinder and prism molds.

The moulds were filled in layers and succinctly compacted by the tamping of hands and also by vibration to eliminate air pockets and creating a thick and consistent composing. The molds were then lined with wet gunny cloths once filled so that the moisture could not evaporate quickly; it also helps the mould hydrate properly in the beginning. The specimens were demolded gently after 24 hours and placed in a curing tank Representative images of specimen preparation, curing, and testing procedures are shown in Fig. 1 to document the experimental workflow and ensure reproducibility of the testing process. which was full of clean water maintained at ambient laboratory temperature (27 ±2°C). Depending on the test requirements, the samples had been stored 7, 14 and 28 days so that the development of strength and decrease in porosity were strictly evaluated with time.

Fig. 1. Specimen preparation and compression testing process.

3.2 Methods

In order to investigate the impact of white slag on mechanical and durability characteristics of M25 grade concrete, we due prepared a series of specimen in various shapes such that each specimen was developed with a specific test as the measurement of strength. To arrive at compressive strength, we took cube specimens of 150 x 150 x 150 mm. Also, we made cylindrical specimens that were 150 mm in diameter and 300 mm in height to test split tensile strength. Another criterion that we used to measure the strength of the same concrete flexural was the prism specimens of 100 x 100 x 500 mm. Three specimens were cast and tested for each mix and each test. All these types of specimens enabled us to determine the effects of adding white slag on the concrete performance in a broad number of aspects.

We went through an organized casting process so that we had accuracy and consistency for all the samples. After having prepared all the concrete mixes with the required percentage of white slag (0%, 5%, 10%, 15% & 20%), we carefully placed the freshly mixed concrete into the corresponding concrete molds. We paid special attention to ensure that we did not form air voids because air can have a significant effect of the strength and reliability. Compaction was performed by the manual tamping and mechanical vibration to achieve dense and homogeneous distribution of the mix in the molds. Once the molds were filled we allowed the specimens to rest fully for the first 24 hours to cure. During this period we displayed them in a controlled environment, suffocated by wet gunny bags to prevent such things as loss of moisture since this is essential in attaining adequate hydration. After initial curing, we carefully demoulded the specimens so as not to damage the edges and/or surfaces.

Each specimen was given a unique identification mark to be sure to link all the recorded test results to the correct white slag replacement level. Following demoulding processes we transferred the specimens to a curing tank filled with clean water kept at 27 $\pm$ 2°C. According to the specifics of the test schedule, they remained under water until 7, 14, and 28 days. This water-curing process is very critical in developing the concrete strength and durability as it supports the continuous hydration of the cement and also of the white slag. After going through the required curing period, we took the specimens out of the tank, dried the surface and put them to the test using calibrated machines. These machines used controlled loads to determine compressive, split tensile and flexural strengths.

We have also made tests with water absorption, in order to investigate the level of porosity. Compressive, split tensile, flexural, and water absorption tests were conducted as per IS 516:2018, IS 5816:1999, and ASTM C642 standards. The collected data offered us a clear picture in terms of how. The reported strength values represent the average of three specimens for each mix. The standard deviations for compressive, split tensile, and flexural strength were within ± 0.5 MPa, ± 0.08 MPa, and ± 0.10 MPa respectively, confirming the reproducibility of the results.

4 Results and discussion

4.1 Compressive strength

The 150 mm cubes were tested for compressive strength after 7, 14, and 28 days of curing. For every age group, three specimens of each mixture were tested; the average results are displayed. Table 5 contains compressive strength data for all mixes at all curing ages.

The obtained results indicate that all mixes increase in strength as they age, as is expected because they are still absorbing moisture. At 7 days, the control mixture had a strength of 16.0 MPa; at 14 days, it had a strength of 21.0 MPa; and at 28 days, it had a strength of 25.0 MPa. The mixture with 10% white slag fine aggregate replacement performed better, with strengths of 18.0 MPa at 7 days, 24.5 MPa at 14 days, and 29.0 MPa at 28 days. This is a 16% improvement over the control mixture at 28 days. Moreover, modified mixture A with 5% replacement also showed a further improvement, with a strength of 27.5 MPa at 28 days, which is a 10% improvement over the control mixture. The 15% replacement of C gave a strength of 28.0 MPa, which is a 12% improvement. In contrast, a reduction in strength started with a replacement percentage of 20%. The binary mixture (D) with a 20% replacement showed a strength of 26.5 MPa, which is merely a 6% improvement.

Fig.2 compressive strength as function of white slag percentage Fig. 2 - Compressive strength as a function of white slag percentage. The compressive strength is plotted on the vertical axis, and the white slag percentage is plotted on the horizontal axis. The graph shows three curves corresponding to results at 7, 14, and 28 days. At all ages, the optimum substitution rate was found when 10% replacement takes place. From the trend of increasing strength, it might be noticed that within a moderate white slag replacement of 10%, pozzolanic strength improvements are enhanced. White slag reacts with calcium hydroxide generated from the hydration reaction of cement to produce additional calcium silicate hydrate gel, which suggests pore refinement behavior based on strength and absorption trends.

Beyond 10% replacement, however, there is a limit in the amount of cement available to provide the required amount of calcium hydroxide for the pozzolonic reaction, and the slower reaction rate of the slag becomes dominant compared with the faster reaction rate of cement. This leads to strength loss with higher replacement levels. The order of magnitude of improvement that was realized by the 7-day specimens was quite similar but smaller than that obtained for the later age. As explained earlier, it is because the pozzolanic reaction in the slag takes time to develop its contribution. Therefore, these will become significant at later ages. This was confirmed from the increase in strength of all of the slag mixes from 7 to 28 days, which was greater than the strengthening of the control mix during this time.

Table 5. Compressive strength of concrete (MPa)

Mix	White slag (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
Control	0	16.0	21.0	25.0
Mix A	5	17.5	23.0	27.5
Mix B	10	18.0	24.5	29.0
Mix C	15	17.0	23.5	28.0
Mix D	20	16.0	22.0	26.5

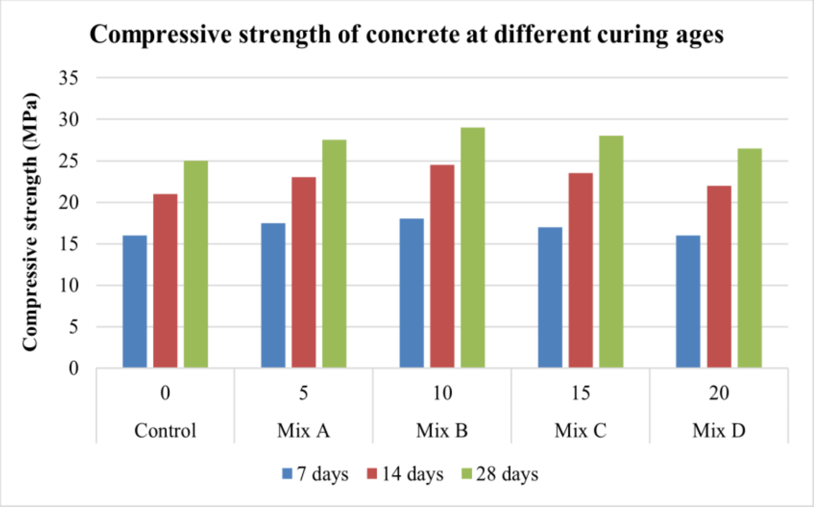

Fig. 2. Average compressive strength of concrete at 7, 14, and 28 days.

4.2 Split Tensile Strength

Split tensile strength tests were carried out on the 28-day cured cylinders. Tensile strength is a measure of stress or resistance to cracking and overall structural performance. The results for the split tensile strength tests are given in Table 6. These show a similar improvement trend as that obtained in compressive strength. The control mix had given a tensile strength of 2.34 MPa. Mix B gave the maximum tensile strength of 2.68 MPa, which was about a 14.5% improvement with 10% replacement. Mix A, with 5% replacement, yielded a tensile strength of 2.52 MPa, showing an improvement of 7.7%.

For Mix C, with a replacement of 15%, the tensile strength was 2.58 MPa, giving an improvement of 10.3%. Beyond this, at higher replacement levels, the tensile strength decreases, similar to the loss pattern in compressive strength. Mix D, containing 20% replacement, obtained only 2.44 MPa, with an increase of merely 4.3%. This increase in tensile strength at the optimum replacement level is related to the improvement in bonding within the interfacial transition zone between the cement paste and aggregate. The end products of pozzolanic reaction at the transition zone make it less porous and give strength. Microcracks are reduced by this effect, thus helping in the mechanism of the load transfer and thereby increasing the tensile capacity.

Table 6. Split tensile strength (MPa)

Mix	White slag (%)	Failure Load (kN)	Split Tensile Strength (MPa)
Control	0	165	2.34
Mix A	5	178	2.52
Mix B	10	189	2.68
Mix C	15	182	2.58
Mix D	20	172	2.44

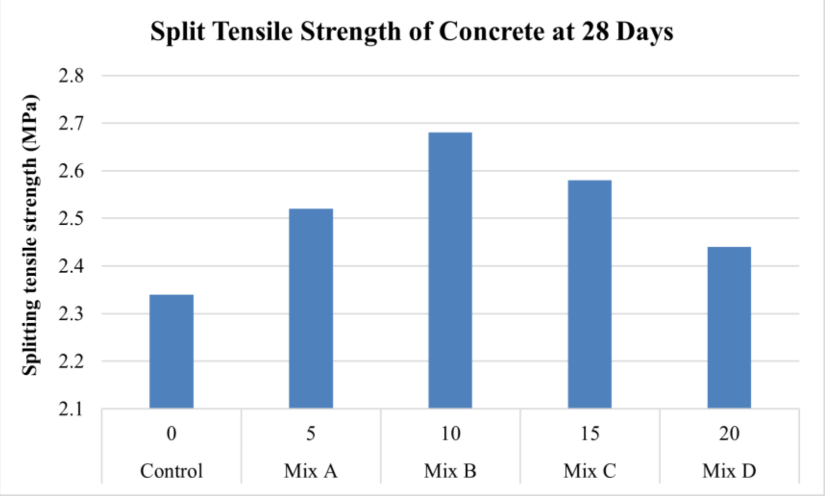

Fig. 3. Split tensile strength of concrete at 28 days.

4.3 Flexural Strength Test

Two-point loading method was applied to the prisms for flexural strength tests after 28 days. Flexural strength is of importance for structural elements that are under bending loads. The results are shown in Table 7. Values of flexural strength follow the trends of compressive and tensile strength. For the control mix, it attained a flexural strength of 4.37 MPa. Mix B, which had 10% replacement, attained the maximum flexural strength of 4.99 MPa. This was an increase of 14.2%.

This conforms to 10% as the best replacement level based on all mechanical properties. Mix A and Mix C showed an improvement of 7.1% and 9.8%, respectively. However, Mix D had negative trends with only 3.9% improvement, respectively. It can be seen that the tensile-compressive-flexural strengths are related. This further shows that improvements in microstructure from white slag beneficially affect all mechanical properties combined.

Table 7. Flexural strength (MPa)

Mix	White slag (%)	Failure Load (kN)	Flexural Strength (MPa)
Control	0	18.2	4.37
Mix A	5	19.5	4.68
Mix B	10	20.8	4.99
Mix C	15	20.0	4.80
Mix D	20	18.9	4.54

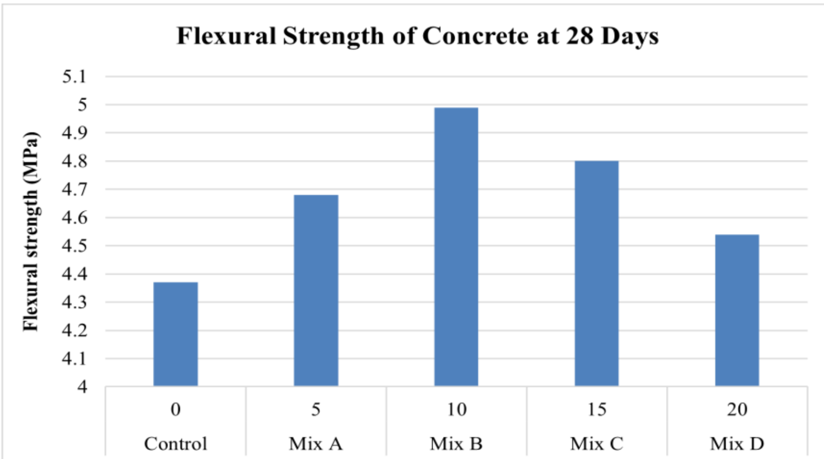

Fig. 4. Flexural strength of concrete at 28 days.

4.4 Water absorption test

Absorption tests were carried out after 28 days curing duration to determine porosity characteristics. Lower absorption of water indicates lower porosity and more durability. For the all mixtures, the results of the water absorption test are presented in Table 8.

The results clearly show that water absorption decreases as white slag content / increases. The water uptake of the control mixture was 4.5%. When A was mixed with 5% replacement, absorption decreased to 4.1%, for an 8.9% reduction. The absorption of B with 10% substitution showed 3.9%, showing 13.3% reduction compared to control. As white slag content continued increasing and absorption decreased. The mixture C with 15% replacement had an absorption of 3.7% which represents a reduction of 17.8%. A 20% replacement with D gave 3.6% absorption, 20% less. Figure 5 presents a graph of the absorption of water in various mixes. Water The scatter graph is used to display water absorption percentage through the vertical axis and white slag percentage at the horizontal axis, in a downward trends from 4.5% to 3.5%. The steady reduction in water absorption as slag content increases is in favor of better pore refinement idea. Fine particles of white slag fill the voids between larger particles of slag, which reduces the overall porosity. Pozzolanic Reaction products also provide the closing of capillary pores, thus making the concrete more impervious and dense. A finely pulverized pore structure absorbs lesser water due to decreased permeability. Interestingly, although the compressive strength was highest at 10% replacement and then declined, water absorption continued to decrease even at higher replacement rates. This suggests that the mechanisms for reducing porosity physical filling and pozzolanic reaction are still working good even with cement content. However, since no microstructural tests such as SEM or MIP were performed, pore refinement interpretations are based on indirect durability indicators. Reduced absorption of water improves resistance to harmful substances such as chlorides and sulfates (adds to greater durability). From a durability point of view, the higher the slag content, up to 20%, seems to be of benefit. However, for strength as well as durability the optimum is shown to be that 10% replacement results in improvements in both factors.

Table 8. Percentage of water absorption

Mix	White Slag (%)	Dry Weight (kg)	Saturated Weight (kg)	Absorption (%)
Control	0	8.250	8.621	4.5
Mix A	5	8.280	8.620	4.1
Mix B	10	8.310	8.634	3.9
Mix C	15	8.290	8.597	3.7
Mix D	20	8.265	8.563	3.6

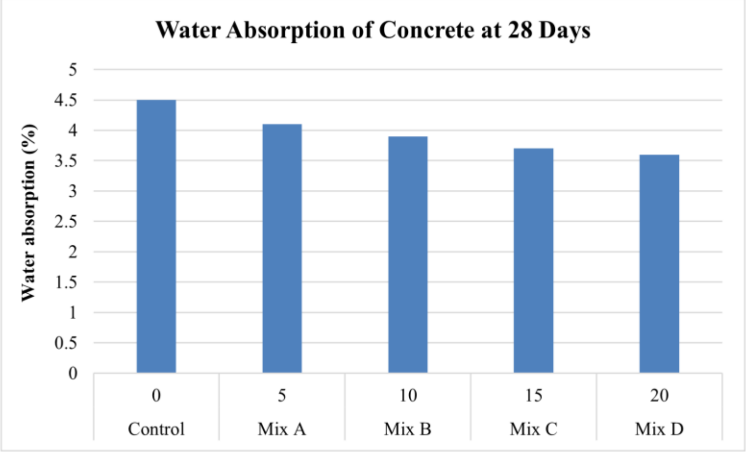

Fig. 5. Water absorption of concrete at 28 days.

The water absorption test was carried out to determine the effects of replacing cement with white slag long-term durability performance of concrete affects the porosity, overall durability of concrete. Water absorption is directly proportional to the internal pore structure of concrete. Less absorption means fewer pores, that means greater durability and reduced risk of deterioration with the passage of time. The control mix, which was white slag, had a water absorption value of 4.5%. This is the natural level of porosity of regular concrete. When 5% white slag was added (Mix A), the absorption went down to 4.1%. This was found to be an 8.9% reduction from the control mix. This indicates that even small amounts of white slag contribute to pore refinement and reduced water absorption, which are said to be in tightening the internal pore structure. The largest improvement took place at the 10% replacement level (Mix B). Here, the water absorption declined to 3.9%, that is, 13.3% reduction with respect to control mix. This indicates that 10% white slag has the best pore-filling and densification effect so that the concrete is more compact and less permeable. As the white slag content was increased to 15% and 20% (Mixes C and D), the amount of absorption decreased further to 3.7% and 3.6%, respectively. These figures correspond to decreases of 17.8% and 20.0% respectively, compared to the control. While the betterment continues, rate of gain decreases beyond 10% replacement level This is because the greater content of white slag still helps refining the pores, but the optimum balance between particle packing and reactivity is obtained at about the 10% replacement.

Over all the results were quite clear that the addition of white slag reduces water absorption and greatly enhances durability of concrete. The decrease of water intake indicates a denser microstructure, improved pore filling and improved long term performance. This supports the potential of white slag as a useful supplementary cement material.

5 Conclusion

This paper presents an assessment of concrete performance when Ordinary Portland Cement is partially replaced with white slag at 0%, 5%, 10%, 15%, and 20%. The objective was to characterize how white slag affects the mechanical resistance and durability properties that come with porosity in concrete. Discussion on compressive strength test results, split tensile strength, flexural strength, and water absorption, therefore, follows, and the following conclusions were obtained:

1. The workability of concrete changed little with increased white slag content, despite its finer particle size which increased the water demand slightly. Nevertheless, all mixes remained workable for casting.

2. Addition of white slag significantly improved the mechanical properties of the concrete mixtures: The concrete mixtures with 5-15% white slag showed higher compressive, split tensile, and flexural strengths than the control mixture, which indicated that white slag takes part in strength development.

3. In general, the mix with 10% white slag gave the best performance. The compressive strength gain from such a mix was the highest-about 16% improvement from the control-with relatively better split tensile and flexural strengths. This also means that 10% replacement strikes the best balance between the chemical reaction and particle packing.

4. The durability characteristics of the concrete improved with the increase in the percentage of white slag. All the mixes containing slag had a lower water absorption than the control mix, reflecting a refined pore structure with a denser inner matrix. While reduced water absorption directly indicates lower porosity, long-term durability implications are inferred and require further microstructural validation.

5. The minimum water absorption was recorded for the mix with a replacement of 20%, proving that white slag is efficient in reducing porosity. However, the optimum comprehensive performance of strength and durability occurred at 10% replacement level because beyond this value, strength gains did not show a significant increase.

The obtained results confirm that white slag is a very promising supplementary cement material. It significantly enhances the strength and durability of concrete at an appropriate replacement level, mainly around 10%, while contributing to sustainable construction with the reduction in the use of cement and industrial waste.

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