Investigation of Mechanical Properties of Concrete by Partially Replacing Fine Aggregate with Cupola Slag

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Abstract: Cupola furnaces, which are typically used in foundry industries to melt metals, produce cupola slag, one of the industrial byproducts Waseem, S. A., et al. (2021). There aren't many studies in the literature that show cupola slag being used in the making of concrete, and it is underutilized Waseem, S. A., et al. (2021). An attempt has been made to look into how cupola slag, when utilized in part in the form of a fine aggregate substitute, affects the mechanical characteristics and concrete's resilience Thakur et al., (2021). Five different percentages of Cupola slag were utilized to replace fine aggregate: 0%, 10%, 20%, 30%, 40% Veena, N et al., (2021). Moreover, the Water cement ratio is varied from 0.400 to 0.450 to 0.500 at a consistent 380 kg/m3 cement content Lanjewar, B et al., (2021).At lower water cement ratios are the improvement in strength of compression was larger. For split tensile strength, similar trends were seen Bhat, S et al., (2022). As the percentage of replacement cupola (CR) increased from 0% to 40%, a A reduction in the amount of water that penetrates depth was seen for all curing ages; This decrease was very noticeable at the water cement ratio of 0.4 Meshram, S. S et al., (2024). In a similar vein, all of the aforementioned metrics showed a notable enhancement in resistance to abrasion in terms of a decrease in the depths of wear Adese et al., (2021). To validate the experiment's results, strength and durability qualities were correlated Nainwal, A. Both the "effect" and the "size of effect" of the water cement ratio and CR percentage on the characteristics of concrete were examined using statistically significant findings using two-way analysis of variance Venkatesan, B et al., (2021. To demonstrate how CR and w/c ratio affect concrete quality at every age of curing, a quadratic correlation was created. According to the study's findings, one substance that is sustainable is cupola slag. That may be applied to partially replace natural sand Sambhaji, Z. K., & Autade, P. B. (2016).

1 INTRODUCTION

In place of natural river sand, a variety of industrial byproducts have been used, such as waste Concrete is now a major an aspect of a country's economic development worldwide as a result of increased use brought on by growing industrialization. Recent data from the US Geological Survey Waseem, S. A., et al. (2021) shows that 4100 million metric tons of cement are manufactured annually throughout the world, corresponding to an approximate yearly consumption of 27000 million metric tonnes of concrete. Because it makes about 30–40% of the concrete's volume, fine aggregate has significant effect on natural resources. There are efforts underway to identify substitutes sources of river sand found naturally for the construction industry's future development because of the shortage of fine aggregates brought on by ongoing quarrying and rising transportation costs Waseem, S. A., et al. (2021). To protect natural resources and create a more sustainable construction sector, researchers from all over Researchers worldwide are looking into the possibility of using solid waste in the manufacturing of concrete Veena, N et al., (2021). Organic coarse or fine aggregates can be easily replaced with recyclable industrial waste products. Slag, a byproduct of the foundry industry, is one of these sources of fine aggregates Lanjewar, B et al., (2021). The disposal of slag has become an issue for the environment due to its large- scale production.

Concrete made with slag instead of natural sand contributes to a more sustainable environment by lowering the quantity of waste that ends up in landfills. Additionally, less energy will be required for

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the extraction or refinement of aggregates, thus reducing the quantity of greenhouse gases discharged into foundry sand, copper slag, and slag from electric arc furnaces Meshram, S. S et al., (2024) the atmosphere. Because of their underutilization, these leftovers are usually disposed of at waste disposal sites. Cupola slag is a manufacturing byproduct that might be used to partially replace aggregate in concrete. In foundry industries, among the cupola furnaces are common tool for melting materials like cast iron and bronze. A cupola furnace produces roughly 50 kg of slag for every ton of molten metal Adese et al., (2021). Only a small amount of study has been published in the research on the viability of substituting for some or all of the cupola slag the cement or aggregates in concrete Nainwal, A. The possible combination of cupola slag and blast furnace as an alternative to coarse aggregates entirely in the production of concrete was investigated by Baricova and associates Venkatesan, B et al., (2021). Examined the potential for replacing coarse particles entirely in the manufacturing of concrete using cupola slag and blast furnace slag. These concretes are said to be suitable for the middle sections of framed structures as well as the base or leveling layers and foundation of buildings. Granulated cupola slag was used by Arum and Mark Saravanakumar, A et al., (2019) to create low permeability concrete. A 31% increase in compressive strength was seen when 15% cupola slag was substituted for cement. According to them, concrete’s porosity dropped, indicating that it is suitable for hard environmental conditions were minimal Permeability is necessary.

When Alabi and Afolayan Sambhaji, Z. K., & Autade, P. B. (2016) looked into how Slag from a granulated cupola furnace affected the concrete’s mechanical characteristics, they discovered that it marginally improved compressive strength. Alabi and Mahachi Velumani, M (2023) discovered that at all higher temperatures, the compressive strength of concrete mixed with slag from a cupola furnace was superior to that of regular concrete. Cupola slag was added in different amounts up to 12% to create high-performance concrete, according to Thomas and associates. The mechanical properties were said to have improved by 10%. Primulova et al. conducted A thorough investigation on the characteristics and uses of slag from cupola boilers Kaish et al., (2021). They concluded that the building industry may considerably profit from the usage of cupola slag, pointing out that it is completely underutilized in several countries. Thomas et al. conducted a thorough experimental program that included microstructural 2haracterization and assessment of the powder’s mechanical and fresh properties Rajasekar, A et al., (2019) investigated whether cupola slag powder might be used in mortars. 20% cupola slag was found to be the optimal percentage of cement substitution, and the resulting mortars were shown to have improved mechanical and durability attributes. Sosa et al. conducted experimental study with cupola slag powder up to 30% in place of cement to examine the feasibility of using it as a binder instead of cement. Chakravarty and associates carried out a comprehensive investigation into the possible uses of cupola slag Afolayan et al., (2022). Except for of a little amount utilized in the construction sector to replace cement and fine and coarse stones, they concluded that cupola slag has no purpose whatsoever.

2 MATERIALS AND METHODS

The materials utilized for a project that looks at the mechanical qualities of concrete with the use of cupola slag instead of some of the fine aggregate include both conventional and specialty components. In concrete, cement, usually Ordinary Portland Cement, or OPC is the main binding agent that promotes hydration and strengthens the mixture. Cupola slag partially replaces fine aggregate natural river sand or crushed stone sand, a byproduct that is collected during iron casting. The replacement is proposed to study the impact of cupola slag on the mechanical and sustainability properties of concrete. In this study, the coarse aggregate (crushed stone/gravel) is used as recommended and not replaced. The quantity and quality of water, which is used in cement hydration and workability control, are strictly controlled. In some cases, the addition of superplasticizer can be added into the mixture to overcome the consistency change of concrete due to cupola slag. To improve strength and durability over time, fly ash or other pozzolanic minerals may also be added as optional ingredients. Additives like accelerators or retarders could also be used to optimize curing conditions and regulate the setting time Mounika et al., (2024). A number of concrete combinations designed to evaluate the effects of slag cupola on workability, mechanical functionality along with environmental sustainability are based on the combination of these components. The concrete mixtures were designed in accordance with IS 10262. Three control concrete mixes in all with 0.40, 0.45, and 0.50 water cement ratios were produced. Table 1. Shows the Chemical Composition of Cupola Slag and Comparison with IS

8112 Standard Limits. Table 2. Shows the Cement's physical characteristics. Table 3. Shows the Aggregate's physical characteristics.

Varying proportions of cupola furnace slag (10%, 20%, 30%, and 40%). Table 6 provides information about each concrete combination.

Table 1: Chemical composition of cupola slag and comparison with is 8112 standard limits.

Chemical composition	Test out (%)	(%) Restrictions outlined in IS 8112 [20] (%)
(SiO2)Silica	22	–
Ferric,or oxide (Fe2O3)	3.3	–
(Al2O3)Alumina	5.4	–
Calcium,or oxide (CaO)	61.2	–
(MgO)Magnesia	3.4	≤6.5
Anhydride of sulfur (SO3)	1.44	≤3.4
Insoluble The residue	1.4	≤4.3
Ignition Loss	2	≤5.5
Ignition Alkali content loss due to insoluble residues in terms of Na2O K2O	0.43	≤0.6
Ratio of Al2O3/Fe2O3	1.52 0.81	≥0.66 ≥0.66 & ≤ 1.03

Table 2: Cement's physical characteristics.

Property	Units	Test result	Limiting values
Soundness	Mm	1.6	≤10.6
Relative density	–	3.19	3.15
Minutes of setting time			
First time		93	≥30
Last time		400	≤600
Strength of compression	MPa		
3 days			
7 days		24.1	≥23
28 days		34.2	≥33
		44.2	≥43

Table 3: Aggregate's physical characteristics.

Physical attributes	Coarse-grained material	Fine-grained material
Relative density Water absorption (%) Color Zone	2.67 1.3 Grey –	2.66 2.5 – I I

The proportions of the corresponding mix containing cupola slag as fine aggregates were intended to be partially replaced using the DWR approach, or direct weight replacement, has been applied in the literature for circumstances where materials with varying specific gravities are swapped out for one another. During this process, the amount of weight that each ingredient contains remains constant, with the exception of the material that needs to be changed, in this case fine aggregate. Since its specific gravity (2.65) is larger compared to cupola slag (2.45), fine aggregate quantities are reduced in the current study to get identical volumetric output. This is due to the fact that cupola slag and fine aggregate with similar weights may take up various quantities depending on the specific gravity. Very little volumes of superplasticizer were used to generate the mixtures, which had a consistent slump of 75 ± 10 mm. A traditional concrete mixer with a 300-liter rotating drum was utilized to thoroughly mix all of the ingredients. Every sample was castat the standard temperature. Three layers of the samples were cast to guarantee adequate compaction and the elimination of air gaps. For 7, 28, and 56 days, the concrete samples were demolded and allowed to moisten after a 24-hour casting time Gupta and Bakshi (2023).

3 STATISTICAL ANALYSIS

3.1 Mechanical Characteristics

Testing the concrete's mechanical characteristics is crucial to ensure that it performs well and is safe for use in construction. Several common tests are used to evaluate how concrete behaves under different conditions .The test for compressive strength is the most commonly utilized, in which cubes of concrete or cylinders are pressed until they break. This measures the concrete's ability to withstand crushing forces. The tensile strength test checks how well concrete can resist stretching or pulling apart, often using a split cylinder method where a concrete cylinder is cracked by pressure. The flexural strength test is used to measure how concrete bends or resists breaking when subjected to bending forces, usually by placing a beam on supports and applying pressure in the middle Venkatesan, B et al., (2021) and Saravanakumar, A et al., (2019).

The elasticity modulus test measures Concrete's stiffness, or how much it will bend under pressure. Rebound hammer tests are a quick way to check the surface strength of concrete without damaging it, using a tool that bounces back after hitting the surface, giving an estimate of its strength. Not only strength, but concrete's durability is also put to the test. The water absorbtion test measures the amount of water absorbtion of the concrete, while the chlorid penetration test checks if harmful chemicals can penetrate the concrete and create damage to the concrete in aggressive environments. Engineers use these tests to ascertain how strong and flexible and how resilient to the ravages of time concrete will be, to ensure that it is safe and appropriate to be used in a construction project Waseem, S. A and Lanjewar, B (2021).

3.2 Durability Properties

How resistant it is to damage and strength when exposed to various environmental conditions over time is the durability of concrete. DIY-2 Concrete: The Good, The Bad, the Ugly Concrete can be susceptible to hitting water, chemicals, and extreme weather, plus things that can weaken it. One important thing is water resistance concrete has to keep the water out, water coming in can crack the concrete, rust the steel within. Freeze-thaw resistance is also critical in cold climates where water that becomes trapped inside concrete can freeze and expand, cracking it.) Concrete also has to be resistant to chloride ions, which can be found in seawater or de-icing salts and will attack the steel reinforcing rods inside. In places where soil or water has high sulfates, concrete must be resistant to that attack that can cause it to expand and crack. A second problem is carbonation, which occurs when carbon dioxide from the air interacts with the concrete, reducing its ability to protect the internal steel Sambhaji, Z. K (2016) and Velumani, M et al., (2023).

Table 4: Chemical composition of slag examples.

Compounds	Weight of Jalandhar Slag (%)	Slag in Ludhiana	Slag in Batala
MgO	8.97	4.81	7.32
Al_2O_3	16.01	8.78	12.61
SiO_2	47.06	23.56	48.20
SO_3	0.39	–	0.13
K_2O	1	–	1.33
CaO	12.10	17.59	15.02
Feo	16.51	5.32	16
CO_2		43.61	

Alkali-aggregate reaction can also happen when certain aggregates react with the cement, causing cracks. Abrasion resistance is important for concrete exposed to wear, like floors or roads, to prevent surface damage. Concrete must also resist chemical attacks from substances like acids or oils, which can break it down. Shrinkage and expansion are natural changes that happen as concrete dries or absorbs moisture; if they're too severe, they can cause cracks. Lastly, corrosion resistance is essential to protect the steel reinforcement inside concrete, especially in areas with water or aggressive chemicals. Testing these durability properties helps ensure concrete lasts longer, especially in harsh conditions, and reduces the need for repairs, making buildings and structures safer and more reliable. Table 4. Shows the Chemical composition of slag examples. Table 5. Shows the Physical Properties of slag samples.

Table 5: Physical properties of slag samples.

Physical Property	Values obtained Jalandhar	Ludhiana	Batala Slag
Specific gravity Water absorption Color	2.22 1.51% Light Grey	1.75 1.62% Light Grey	2.46 1.46% Dark black

4 RESULT

4.1 Strength of Compression

The results of each cube specimen's strength of compression evaluation after 7, 28, and 56 Days are displayed. All concrete mixes received the include cupola slag, which increased the strength of compression by up to 30% when fine particles were replaced. Then, as additional cupola slag was added to the concrete mixtures, a decrease in strength was seen. For example, substituting 10% cupola slag for fine aggregates following seven days of curing, yields increases in strength of compression of 15.76%, 14.12%, and 1.93%, respectively. These increases correspond to 0.40, 0.45 and 0.50 water-binder ratios.A 20% replacement of slag from cupola furnaces for fine aggregates may result in Compressive strength growth of the corresponding w/c ratios were 20.40, 0.5, and 13.9%, 21.97%, and 24.22%. Furthermore, increases using w/c ratios of 0.40, 0.45, and 0.50, respectively, with compression strengths of 30.08%, 27.81%, and 29.11%-occur When using cupola slag instead of fine aggregates by 30%. Strength was then shown to diminish with the addition of more cupola slag.

Table 6: Proportions of the mixture for different water-to-cement ratios and cupola replacement percentages.

Cupola Replacement ratio (%)	w/c ratio	Water (kg/m3)	Cement (kg/m3)	Fine aggregate (kg/m3)	Coarse aggregate (10mm-20mm) (kg/m3)	Coarse aggregate (4.75mm-10mm) (kg/m3)	Cupola slag (kg/m3)
0	0.5	190	380	650	700	420	-
10	0.5	190	380	579	700	420	66
20	0.5	190	380	508	700	420	131
30	0.5	190	380	440	700	420	196
40	0.5	190	380	370	700	420	260
0	0.45	171	380	671	710	426	-
10	0.45	171	380	599	710	426	68
20	0.45	171	380	525	710	426	132
30	0.45	171	380	453	710	426	201
40	0.45	171	380	380	710	426	268.4
0	0.4	152	380	695	730	438	-
10	0.4	152	380	620	730	438	69.6
20	0.4	152	380	545	730	438	138
30	0.4	152	380	470	730	438	208.4
40	0.4	152	380	394	730	438	279

4.2 Split Tensile Strength

The correlation between cupola replacement (CR) percentages and split tensile strength for different curing ages and w/c ratios. Table 4 shows that Slag from cupola furnaces is up to 30% replaced with fine aggregates replacement only as the concrete's increased split tensile strength. For every concrete mix utilized in this investigation, this is generally the case. There's a noticeable reduction in the split tensile strength. When using cupola slag instead of 10% of fine aggregates at a curing age of seven days, for instance, the tensile strength increases by with w/c ratios of 0.40, 0.45, and 0.50, respectively, of 11.11%, 8.75%, and 3.94%. Likewise, for 20% and 30% cupola slag replacement levels with fine aggregate, respectively, tensile strength rose by 31.48%, 22.91%, 19.73%, and 32.09%, 30.41%, and 22.8% for the previously stated w/c ratios. That pattern is almost exactly the same as the compressive strength numbers. It is also clear that the rate of growth in compressive strength is Situated a little above the rate of rise in Tensile strength of split for lower ratios.

The reactive properties of cupola slag are responsible for this increase in tensile strength. which strengthen the connections among the particles in the ITZ. Split tensile strength is comparable to compressive strength seen to decline as cupola slag additions go over 30%. Figure 1 Shows the Effect of Cupola Replacement Percentage on Thickness Loss at Different Water-Cement Ratios and Curing Periods

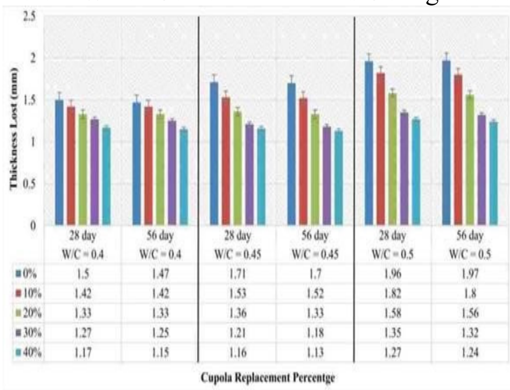

Figure 1: Effect of Cupola Replacement Percentage on Thickness Loss at Different Water-Cement Ratios and Curing Periods.

4.3 Water Permeability

This study examines the effects of adding cupola slag to concrete in place of some of the fine sand on the material's strength and durability. Using cupola slag, a byproduct of the manufacturing of iron, in concrete can help cut waste and increase sustainability. In the project concrete cubes are prepared by replacing the ordinary sand with various percentage of cupola slag (5%, 10% & 15%). The compressive strength of the cubes is tested at different periods (7, 14, and 28 days) to assess the durability of the concrete. In addition, to determine the water resistance of the concrete, a water permeability test is conducted that is important for durability. Other testing methods, like stress testing of the concrete and examining the tensile strength and elasticity of the concrete, provide insight into the performance of the concrete as a whole. The study aims to determine whether cupola slag can be used as a partial sand replacement in concrete to improve concrete durability and mechanical properties and to decrease its environmental impact.

4.4 Abrasion Resistance Test

Therefore, a study was carried out using cupola slag, an iron-producing residue, to investigate the properties of concrete. Different proportions (5% 10% and 15%) of cupola slag are used with the concrete. and tested for its mechanical properties the cube test assesses slag influence on strength over time by determining compression strength at the 7th, 14th, and 28th day. The abrasion resistance Examine was designed to simulate difficult or busy atmospheres to evaluate how good the concrete deals with surface area damage. It aims to serve as a better alternative to conventional materials by assessing whether cupola slag has an impact on the advantages of concrete such as strength, durability, and sustainability. (Bakshi 2019)

4.5 Discussion

The regression analysis reveals insights into the compressive strength and split tensile strength of concrete at different curing periods, influenced by the water-cement ratio and varying levels of cupola replacement. For compressive strength, the R^2 value observed at 7 days is 0.864, indicating a strong correlation between the variables and the strength outcome. After 28 days, the compressive strength shows a slightly lower R^2 value of 0.743, reflecting moderate predictability. At 56 days, the compressive strength shows improvement, with an R^2 of 0.811, suggesting an enhanced level of correlation over time.

The split tensile strength values are detailed across several model evaluations. One model lists an intercept value of 57.376 with a cupola replacement coefficient of 48.156. Another model presents coefficients of -99.383 and -78.521 for the intercept and cupola replacement, respectively. In subsequent models, the intercepts and cupola coefficients vary: 48.820 and 52.775 in one, and -108.787 and -45.110 in another. A more comprehensive regression includes an intercept of 72.076, with cupola replacement values of 55.941 and -121.691, and a water-cement ratio coefficient of -85. The associated standard errors are also reported—5.585 and 4.385 for the first model, followed by 5.095 and 11.321. Another model lists errors of 27.125 and 11.124, then 5.776 and 12.826, and later 30.745 and 12.600.

The t-values and p-values correspond to the respective models. For example, t-values of -3.661 and -7.058 are paired with p-values of 0.00000024 and 0.00135872. Another model includes t-values of -3.534 and 10.646, with p-values of 0.00374134 and 0.00002100. Additional models show values like -3.376 and -6.738 (t-values), and p-values of 0.00000387 and 0.00172665. For 7-day split tensile strength, the R^2 remains 0.743. This trend continues across 28-day and 56-day split tensile strength measurements, both maintaining R^2 values of 0.743.

Water permeability results are also consistent across durations. At 28 days, water permeability has an R^2 value of 0.743, and the same is observed at 56 days. In terms of abrasion resistance, the analysis at 28 days includes coefficients like 8.453 for the intercept and -7.881 for cupola replacement. A more complex model includes values of 4.526, 4.478, -9.072, and -4.550 for the intercept and other parameters. Another includes 4.448, 3.835, -7.951, and -3.860. The standard errors range from 0.473 to 35.600 across models.

T-values and p-values for abrasion resistance are similarly documented. For example, values include -3.488 and -4.278 with associated p-values of 0.024 and 0.016, while another model notes values such as -2.466 and -2.909, with p-values of 0.04303907 and 0.00000144. These results again suggest strong statistical significance.

Finally, for abrasion resistance at 56 days, the water-cement ratio becomes more influential. The model includes an intercept of 2.580 and coefficients of 0.564, -1.410, and 2.540 for cupola replacement and water-cement ratio. The standard errors for this model are 0.054, 0.026, 0.017, and 0.058. The p-values recorded for these variables are 0.00043216, 0.05476431, 0.00000235, and 0.00091579 respectively, reinforcing the statistical significance of the model. The R^2 value for this 56-day abrasion resistance model also remains at 0.743, suggesting consistent reliability across the study's models.

5 CONCLUSIONS

This study examined the effects of substituting cupola slag for some of the sand in concrete on the material's strength. The findings demonstrated that adding up to 30% slag in place of sand strengthened the concrete.It also improved how well the concrete resists pulling forces, but not as much as it did for pressure. The concrete was a little harder to mix because the slag particles are rough, but this can be fixed by adding more water or special chemicals. Using cupola slag is also good for the environment because it helps recycle waste and lowers the cost of concrete. It may also make the concrete last longer. The best results were seen when 20-30% of the sand was replaced, but using too much slag could make the concrete weaker. In the end, using cupola slag in concrete can make it stronger and more affordable while being better for the environment, but more studies are needed to see how it holds up over time.

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