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# Performance of Sustainable Concrete Containing Bottom Ash as a Partial Replacement of Fine Aggregate along with Glass Fibers

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***Abstract: Concrete is one of the most widely used construction materials in the world; however, its extensive use results in the depletion of natural resources and increased environmental concerns. The growing demand for sustainable construction materials has encouraged the utilization of industrial by-products and innovative additives in concrete production. This study investigates the influence of bottom ash as a partial fine aggregate replacement along with glass fiber addition on the performance of sustainable concrete. Bottom ash obtained from the Koradi Super Thermal Power Station, Nagpur, was used to replace natural sand at varying proportions up to 30%, while short glass fibers were incorporated to enhance the mechanical properties of concrete. The experimental program evaluated the workability, strength and durability parameter of the modified concrete mixes. The results were compared with conventional concrete to assess the combined effect of bottom ash and glass fibers. The findings indicate that the incorporation of bottom ash and glass fibers can improve certain mechanical and durability properties while reducing dependence on natural fine aggregates and promoting the beneficial utilization of industrial by-product. The study demonstrates the potential of developing sustainable, economical, and environmentally friendly concrete suitable for modern construction applications through the combined use of bottom ash and glass fibers.***
***Keywords: Coal Bottom Ash, Glass Fibers, Sustainable Concrete, Mechanical Properties, Durability, fine aggregatet***

## I. INTRODUCTION

Concrete is the most extensively utilized construction material worldwide and serves as the backbone of modern infrastructure development. The rapid growth of urbanization and industrialization has led to a substantial increase in concrete consumption, resulting in excessive exploitation of natural resources, particularly river sand used as fine aggregate. Continuous extraction of river sand has caused several environmental issues, including riverbank erosion, depletion of natural resources, disturbance of aquatic ecosystems, and ecological imbalance. Consequently, the development of sustainable construction materials has become a major focus of contemporary research in the construction industry [1,3].

Coal Bottom Ash (CBA) is an industrial by-product generated during coal combustion in thermal power plants. Although bottom ash accounts for a significant portion of the total ash produced, it remains underutilized and is commonly disposed of in landfills or ash ponds, creating environmental and disposal challenges. The beneficial utilization of bottom ash as a partial replacement for fine aggregate in concrete offers a sustainable solution for waste management while reducing dependence on natural sand resources [1,3]. Previous studies have demonstrated that coal bottom ash possesses physical characteristics similar to those of natural sand and can be incorporated into concrete without significantly compromising its engineering performance [23,24].

The use of bottom ash in concrete contributes to environmental sustainability by reducing industrial waste accumulation and conserving natural aggregates. However, the porous texture and higher water absorption capacity of bottom ash may influence the fresh and hardened properties of concrete. Despite these limitations, several researchers have reported that optimum levels of bottom ash replacement can provide satisfactory mechanical properties and long-term durability performance [1,23].

Concrete is inherently brittle and exhibits low tensile strength, making it susceptible to crack formation under loading conditions. To overcome this limitation, short glass fibers can be incorporated into the concrete matrix. Glass fibers act as crack-arresting elements that improve tensile strength, flexural strength, toughness, and resistance to crack propagation. The inclusion of short glass fibers enhances the overall performance of concrete by improving internal bonding and reducing micro-crack development.

Although extensive research has been conducted on the individual application of coal bottom ash and glass fibers in concrete, studies investigating their combined effect remain limited. The synergistic interaction between bottom ash and glass fibers may lead to improved mechanical properties, enhanced durability, and greater sustainability of concrete. Therefore, the present study investigates the influence of bottom ash as a partial fine aggregate replacement along with glass fiber addition on sustainable concrete performance. The study aims to evaluate the mechanical and durability characteristics of concrete containing different proportions of bottom ash and glass fibers and to identify an optimum combination capable of producing durable, economical, and environmentally friendly concrete for modern construction applications [1,3,23,24].

## II. LITERATURE REVIEW

Rao & Kumar (2015) Rao and Kumar investigated the suitability of coal bottom ash as a partial replacement for natural sand in concrete. Their study found that up to 20% replacement resulted in satisfactory compressive strength and durability. The researchers emphasized the environmental benefits of reducing river sand consumption and promoting industrial waste utilization.

Ibrahim et al. (2016) Ibrahim et al. evaluated the mechanical properties of concrete containing bottom ash. The study reported that moderate replacement levels improved particle packing and produced concrete with acceptable compressive and tensile strength. The authors recommended bottom ash as a sustainable alternative material in construction.

Chindaprasirt et al. (2017) The researchers examined the influence of coal ash materials on concrete performance. Their findings showed that bottom ash contributed to improved long-term strength development and reduced environmental impacts associated with waste disposal. Durability characteristics were also found to be satisfactory.

Verma & Gupta (2017) Verma and Gupta studied concrete incorporating bottom ash and observed that replacement levels up to 25% maintained structural-grade strength. The study highlighted the potential of bottom ash in reducing construction costs and conserving natural resources.

Jaturapitakkul et al. (2018) This study focused on the pozzolanic characteristics of coal ash materials in concrete. The researchers reported improved microstructural properties and reduced permeability when properly processed ash materials were incorporated into concrete mixtures.

Ramesh & Patel (2018) Ramesh and Patel investigated strength and durability properties of bottom ash concrete. Results indicated that optimum replacement levels improved resistance to water absorption while maintaining satisfactory compressive strength.

Singh & Sharma (2019) The authors evaluated the environmental sustainability of replacing natural aggregates with industrial by-products. Their research concluded that coal bottom ash could effectively reduce the environmental burden of concrete production without significant loss of mechanical performance.

Sharma & Reddy (2020) Sharma and Reddy evaluated the effect of coal bottom ash on the fresh and hardened properties of concrete. Their experiments showed that slump decreased with increasing CBA content due to its angular and porous particles, while density was also slightly reduced. In terms of strength, partial replacement up to 25% produced compressive strength similar to conventional mixes, while higher percentages weakened performance. The study further examined microstructural changes, noting that bottom ash acted as a filler material, improving particle packing when used in moderate quantities. The authors also suggested combining bottom ash with mineral admixtures to improve long-term durability. Their research adds to the understanding of how bottom ash affects both physical and mechanical properties of concrete. This makes the study significant for designing sustainable concrete mixes that balance environmental benefits with acceptable structural performance.

Lee et al. (2019) Lee and co-workers analyzed the effect of bottom ash on concrete density and strength. Their study found that concrete became lighter while retaining adequate structural capacity, making it suitable for specific construction applications.

Monika (2022) Monika conducted research on the use of industrial by-products as sustainable alternatives to natural sand in concrete. Her study examined materials such as coal bottom ash, quarry dust, and foundry sand, focusing on their mechanical and durability impacts. The results indicated that bottom ash, when used in controlled proportions, could produce concrete with strength and durability properties close to conventional mixes. Monika highlighted that environmental benefits, such as reduced sand mining and industrial waste management, were major drivers of this research. The study also noted that while bottom ash had potential, lack of awareness and absence of standardized guidelines limited its application. Monika recommended further research into optimization techniques and field applications to build confidence in its use. This study strengthens the case for bottom ash as a viable, eco-friendly material in concrete construction.

Ahmed et al. (2022) Ahmed et al. [11] studied the influence of coal bottom ash on non-destructive testing parameters, including ultrasonic pulse velocity (UPV) and electrical resistivity. Their experiments revealed that mixes with up to 20% CBA replacement exhibited UPV values and resistivity results comparable to conventional concrete, indicating good quality and durability. Higher replacement levels showed a decline in values, correlating with reduced density and strength. The authors emphasized the importance of NDT methods in assessing the internal quality of concrete without destructive testing. Their findings support the integration of CBA into sustainable concrete mixes while providing a reliable way to monitor structural performance. This research is significant because it bridges mechanical testing with durability assessment through advanced techniques. The study underlined that further long-term exposure tests were necessary to establish standardized guidelines for CBA use.

Review Study (2023) A comprehensive review study [12] analyzed the application of coal bottom ash as fine aggregate replacement in concrete. The paper summarized experimental results from multiple researchers, highlighting mechanical, durability, and environmental aspects. It concluded that partial replacement up to 30% is generally feasible, with optimal performance achieved at around 20%. The review emphasized the environmental advantages of reducing sand extraction and landfill disposal. It also identified key research gaps, including limited long-term durability studies, lack of field applications, and absence of international standards. The authors recommended combining bottom ash with fibers and supplementary cementitious materials for better performance. This review provides a holistic view of the state of research, offering valuable insights and setting the stage for future investigations like the present study.

Patel & Verma (2023**)** Patel and Verma evaluated the combined use of coal bottom ash and glass fibers in concrete. Their experiments revealed that bottom ash reduced workability but maintained compressive strength at moderate replacement levels. The inclusion of glass fibers improved tensile strength, flexural behavior, and crack resistance, compensating for the drawbacks of bottom ash. Durability tests also indicated improved shrinkage resistance and reduced water absorption in fiber-reinforced CBA concrete. The study concluded that combining industrial by-products with fibers could yield sustainable and high-performance concrete suitable for structural applications. Patel and Verma's findings are highly relevant to this research, as they provide experimental evidence of the synergistic effects of CBA and glass fibers, reinforcing the concept of eco-friendly and urable concrete.

Sani, Muftah & Muda (2010) The study focused on washed bottom ash (WBA) used as a partial sand replacement in concrete. Washing removed impurities, resulting in enhanced particle quality and improved bonding with cement paste. Mechanical testing showed that concrete containing WBA achieved comparable or superior strength to control mixes. Workability improved due to the smoother texture of washed ash. The research highlighted reduced water absorption and improved durability properties, demonstrating the long-term suitability of WBA in structural applications. The study concluded that washing bottom ash significantly increases its usability, making it a reliable and sustainable alternative to natural sand in concrete production.

## III. RESEARCH SIGNIFICANCE

present study was carried out to examine the performance of concrete incorporating coal bottom ash as a partial replacement for fine aggregate along with the addition of glass fibers. The primary objective was to evaluate the combined influence of these materials on the mechanical and durability characteristics of concrete.

For the experimental program, two categories of concrete mixes were prepared. The control mix consisted of conventional concrete, while the modified mixes contained varying percentages of bottom ash replacing natural sand and a predetermined dosage of glass fibers. The concrete was designed to achieve M40 grade strength using appropriate proportions of cement, fine aggregate, coarse aggregate, and water.

Standard specimens were cast for testing purposes. Cube specimens measuring 150 mm × 150 mm × 150 mm and cylindrical specimens of 150 mm diameter and 300 mm height were prepared. Glass fibers were incorporated to improve tensile strength, ductility, and crack resistance, whereas bottom ash was utilized to promote sustainable material usage and reduce dependence on natural sand resources.

After casting, all specimens were demolded and subjected to water curing under standard laboratory conditions for periods of 7, 14, and 28 days. Following the curing process, various tests were conducted to determine the engineering properties of the concrete.

The experimental procedure consisted of the following stages:

1) Preparation of concrete mixes with different percentages of bottom ash as a replacement for fine aggregate and the addition of glass fibers.
2) Casting of cube and cylinder specimens according to relevant standards.
3) Curing of the specimens for specified durations of 7, 14, and 28 days.
4) Evaluation of mechanical properties through compressive strength, split tensile strength, and flexural strength tests.
5) Assessment of durability characteristics including water absorption, density, and resistance to cracking.
6) Comparison and analysis of test results to identify the optimum combination of bottom ash and glass fiber content.

Conducting mechanical and durability tests to assess the performance of the modified concrete.

The investigation was intended to determine the effectiveness of combining bottom ash and glass fibers in concrete production. The findings provide valuable information regarding sustainable construction materials and demonstrate the potential of producing environmentally friendly concrete with enhanced strength, durability, and structural performance while reducing the consumption of natural aggregates.

### *A. Experimental Programme*

The coal bottom ash (CBA) used in the present study was collected from the Koradi Thermal Power Station (KTPS), Koradi, Nagpur, Maharashtra, India. Prior to its utilization, the collected CBA was oven-dried at a temperature of 110°C for 24 hours to reduce moisture content and ensure consistency in the experimental results. After drying, the material was passed through a 5.0 mm sieve to remove oversized particles and impurities. The processed CBA was then used as a partial replacement for natural fine aggregate (sand) in concrete. A detailed investigation of the physical characteristics of the CBA particles was carried out to evaluate their suitability for use in concrete mixtures.

Particle size analysis indicated that both coal bottom ash (CBA) and natural river sand satisfied the grading requirements for fine aggregates. The results demonstrated that the CBA particles predominantly fall within the coarse-to-medium sand range and exhibit a grading pattern comparable to that of natural river sand. Furthermore, the particle size distribution revealed that CBA possesses characteristics similar to those of conventional fine aggregate, making it suitable for use in concrete production. Due to its porous and irregular surface texture, the CBA particles were relatively lighter and slightly coarser than natural sand.

Overall, the findings suggest that coal bottom ash obtained from the Koradi Thermal Power Station (KTPS), Koradi, Nagpur, Maharashtra, India, possesses physical characteristics comparable to those of natural sand, highlighting its potential suitability as a partial replacement for fine aggregate in sustainable concrete production. The utilization of CBA contributes to the conservation of natural resources and promotes the beneficial use of industrial waste materials in the construction industry.

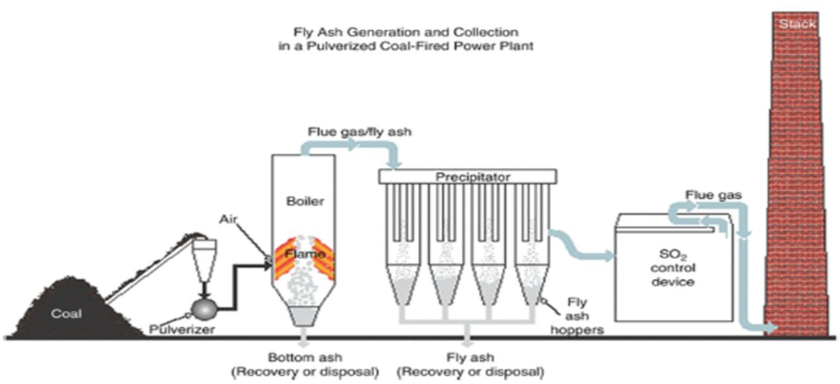


Fig. 1. Producing coal bottom ash in thermal power plants [31].

### *B. Fineness Modulus*

The fineness modulus (FM) of aggregate is a dimensionless numerical parameter that represents the average particle size and relative coarseness of an aggregate. A higher fineness modulus indicates coarser particles, whereas a lower value corresponds to finer material. In the present investigation, the fineness modulus of coal bottom ash (CBA) and river sand was determined through sieve analysis. The fineness modulus was calculated by summing the cumulative percentage of material retained on a standard series of sieves and dividing the total by 100, following standard testing procedures.

The fineness modulus of fine aggregate is a critical parameter when alternative materials such as coal bottom ash are used in concrete, as it directly influences workability, packing density, paste requirement, and mechanical performance of concrete mixtures. In this study, the fineness modulus of river sand was found to be 2.94, while that of coal bottom ash was 2.93. These nearly identical values indicate that the particle size distribution of CBA is highly comparable to that of natural river sand.

According to ASTM C33, the acceptable fineness modulus range for fine aggregates lies between 2.3 and **3.1**. Fine aggregates with fineness modulus values beyond this range are generally considered unsuitable unless supported by satisfactory concrete performance. Both the river sand and coal bottom ash used in this investigation fall well within the prescribed limits and can therefore be classified as coarse sand, confirming the suitability of CBA for partial replacement of natural fine aggregate in concrete.

Table 1 presents a comparison between the fineness modulus values obtained in the present study and those reported in previous investigations. Earlier studies have documented a wide variation in fineness modulus values for coal bottom ash, largely attributed to differences in coal source, combustion conditions, collection methods, and post-processing techniques. Abdulmatin et al. [16] reported a fineness modulus of 2.09 for coal bottom ash obtained from the Mae Moh Power Plant in Thailand. Pal et al. [14] observed a fineness modulus value of 2.32 for coal bottom ash sourced from the National Thermal Power Station in India, while Kadam and Patil [7] reported a comparatively lower value of 1.50 for coal bottom ash from the Ropar Thermal Power Station. Studies by Hasim et al. [13] and Ramzi Hannan et al. [9] reported fineness modulus values of 1.70 and 2.79, respectively, for coal bottom ash obtained from Malaysian power plants.

The fineness modulus value obtained in the present study **(**2.93**)** is slightly higher than most values reported in earlier research, indicating a relatively coarser particle structure. Such variations are commonly observed even among coal bottom ash samples produced from similar coal-fired thermal power plants, as highlighted in the literature [1,13,14,16,19]**.** According to Gooi et al**.** [17]**,** the fineness modulus of coal bottom ash can be modified through mechanical processing such as grinding or sieving to suit specific construction applications. Furthermore, ASTM C33 permits the use of fine aggregates that do not strictly meet grading limits, provided that concrete prepared using such materials demonstrates acceptable performance characteristics.

The relatively higher fineness modulus of coal bottom ash used in this study offers practical advantages, as coarser fine aggregates with fineness modulus values close to 3.0 have been reported to enhance workability and compressive strength, particularly in concrete mixtures with higher cement content [10,26]**.** In contrast, aggregates with lower fineness modulus values tend to increase paste demand, resulting in improved finishability but potentially higher shrinkage. It should be noted that fineness modulus alone does not fully describe aggregate grading, as different particle size distributions may yield similar fineness modulus values. Therefore, both particle gradation and fineness modulus should be jointly considered during concrete mix design.

Table 1. Fineness Modulus of Coal Bottom Ash (CBA) and River Sand

| Reference No. | Authors / Source | Fineness Modulus of CBA | Fineness Modulus of River Sand |
|---|---|---|---|
| [13] | Hasim et al. (2021) | 1.70 | – |
| [14] | Pal et al. (2020) | 2.32 | 2.60 |
| [9] | Ramzi Hannan et al. (2020) | 2.79 | 3.00 |
| [7] | Kadam and Patil (2013) | 1.50 | – |
| [16] | Abdulmatin et al. (2018) | 2.09 | 3.07 |
| [1] | Ku Meh et al., (2016) | 2.93 | 2.94 |

Based on the close similarity in fineness modulus values of coal bottom ash and river sand, along with compliance with ASTM C33 requirements, the utilization of coal bottom ash as a partial replacement for natural fine aggregate in concrete is technically feasible and well justified.

### *C. Specific Gravity*

Specific gravity represents the ratio of the mass of an aggregate to the mass of an equal volume of water at identical temperature conditions. It is a key physical parameter used to assess aggregate density, internal composition, and overall material quality. Aggregates with lower specific gravity values are typically lighter and more porous, while higher values indicate denser and mechanically stronger particles.

In this investigation, the specific gravity of coal bottom ash (CBA) and river sand was evaluated using the pycnometer technique in accordance with BS EN 1097-6:2013. The measured specific gravity of CBA was 2.32, whereas river sand exhibited a higher value of 2.63.

The lower specific gravity observed for CBA compared to river sand can be primarily attributed to its porous and vesicular microstructure developed during coal combustion. The presence of internal micro- and macro-voids results in reduced density, making CBA particles lighter and relatively more fragile than natural sand. Similar characteristics of coal bottom ash, including lower density and porous texture, have been widely reported in previous research [10, 22, 23].

Earlier studies have demonstrated that the specific gravity of coal bottom ash is highly variable and strongly influenced by factors such as the origin of coal, combustion temperature, cooling mechanism, and subsequent processing or treatment. Reported values in the literature typically fall within the range of **2.01 to** 2.54 [11–13, 19–21]. Investigations conducted on CBA sourced from Malaysian thermal power plants have also shown noticeable variation in specific gravity values, even when derived from comparable facilities, highlighting the influence of operational and handling conditions [9, 19–21].

The specific gravity value of **2.32** obtained in the present study lies comfortably within the range reported by earlier investigations. Variations in combustion technique and coal properties have been identified as significant factors affecting CBA density [10, 16]. Additionally, it has been reported that mechanical processing such as grinding can increase the specific gravity of CBA by reducing particle porosity and enhancing packing efficiency [16].

Natural river sand generally exhibits specific gravity values between **2.5 and 3.0**, which aligns well with the value of **2.63** measured in this study [2, 29]. When compared with river sand, the specific gravity of CBA was approximately **11.38% lower**, confirming its classification as a relatively lightweight material. Despite this reduction, the obtained value remains within acceptable limits reported in the literature, supporting the feasibility of using CBA as a **partial substitute for natural fine aggregate in concrete**, particularly in sustainable and lightweight construction applications [1, 17, 23].

### *D. Water Absorption and Chemical Characteristics of Coal Bottom Ash and River Sand*

Water absorption and chemical composition are key parameters governing the performance of aggregate materials in concrete. High water absorption adversely affects workability by causing rapid slump loss, while chemical composition influences pozzolanic activity, durability, and long-term strength development.

In the present investigation, coal bottom ash (CBA) exhibited significantly higher water absorption than natural river sand. The measured water absorption value of CBA was **26.38%**, whereas river sand showed a much lower value of **1.66%**. This large difference is mainly attributed to the highly porous, vesicular, and irregular internal structure of CBA particles formed during coal combustion. The presence of interconnected voids and microcracks increases the capacity of CBA to retain water within its pore system. In contrast, river sand particles possess a denser and smoother surface texture, resulting in minimal water uptake.

Previous research has reported a wide variation in water absorption values for CBA, generally ranging from **6.80% to 31.48%**, depending on coal source, combustion conditions, and post-processing methods. River sand, on the other hand, typically exhibits water absorption values below **2.46%**, which comply with the requirements of **BS 812-2:1995**, where the maximum permissible water absorption limit for aggregates is **3%**. Although the water absorption of CBA exceeds this limit, several studies have demonstrated that its adverse effect on workability can be effectively controlled through optimized mix design and the use of chemical admixtures such as superplasticizers. Lower replacement levels of CBA (around **10%**) generally produce acceptable slump values, while higher replacement ratios (**20–40%**) tend to cause a noticeable reduction in workability.

The elevated water absorption behavior of CBA is closely linked to its chemical composition. X-ray fluorescence (XRF) analysis revealed that the major oxides present in CBA were **$SiO_2$ (26.40%)**, **$Al_2O_3$ (10.83%)**, **$Fe_2O_3$ (18.30%)**, and **CaO (11.18%)**. The combined content of **$SiO_2$ + $Al_2O_3$ + $Fe_2O_3$** was **55.53%**, while **$SO_3$** and **loss on ignition (LOI)** were found to be **0.43%** and **3.18%**, respectively. According to **ASTM C618-12a**, materials having a combined oxide content between **50% and 70%**, with $SO_3$ ≤ 5% and LOI ≤ 6%, can be classified as **Class C pozzolanic materials**. Based on these criteria, the CBA used in this study falls within the Class C category.

The relatively high calcium content in CBA indicates its potential contribution to early strength development, while the presence of unburned carbon, reflected by the LOI value, contributes to increased porosity and water absorption. Variations in chemical composition reported in the literature arise due to differences in coal type, combustion temperature, cooling conditions, and handling practices, which explains why some studies classify CBA as Class F rather than Class C.

In contrast, river sand was found to be predominantly rich in **$SiO_2$ (54.30%)**, with comparatively low contents of **$Al_2O_3$ (6.14%)**, **$Fe_2O_3$ (0.21%)**, **CaO (0.83%)**, **$K_2O$ (0.28%)**, and **$TiO_2$ (0.32%)**. Oxides such as magnesium, sodium, and sulphur were not detected in river sand. The high silica content and low porosity of river sand contribute to its low water absorption and stable performance in concrete.

Table 2: Chemical Composition of Coal Bottom Ash and River Sand

| Oxides Content (%) | Coal Bottom Ash | River Sand |
|---|---|---|
| Silicon dioxide ($SiO_2$) | 26.40 | 54.30 |
| Aluminium oxide ($Al_2O_3$) | 10.83 | 6.14 |

| | | |
|---|---|---|
| Iron oxide ($Fe_2O_3$) | 18.30 | 0.21 |
| Calcium oxide (CaO) | 11.18 | 0.83 |
| Potassium oxide ($K_2O$) | 0.48 | 0.28 |
| Titanium oxide ($TiO_2$) | 0.81 | 0.32 |
| Magnesium oxide (MgO) | 2.84 | – |
| Sodium oxide ($Na_2O$) | 0.23 | – |
| Sulphur trioxide ($SO_3$) | 0.43 | – |
| Loss on ignition (LOI) | 3.18 | – |
| $SiO_2 + Al_2O_3 + Fe_2O_3$ | 55.53 | – |

Overall, the combined evaluation of water absorption and chemical composition confirms that, although coal bottom ash exhibits higher porosity and water absorption than river sand, its chemical characteristics and compliance with ASTM requirements make it suitable for partial replacement of natural fine aggregate in concrete, particularly when appropriate mix design modifications are adopted.

### *E. Fresh properties of Concrete:*

#### *1) Workability*

Several researchers have investigated the influence of coal bottom ash (CBA) as a partial replacement of fine aggregate on the workability of concrete. Generally, the workability decreases as the percentage of bottom ash increases in the concrete mix. This reduction is mainly due to the porous structure, irregular particle shape, and high water absorption capacity of bottom ash compared to natural sand, which increases the water demand of the mix. As a result, the slump value of fresh concrete tends to decrease with higher replacement levels of bottom ash, indicating reduced workability and flowability of the concrete mixture [10, 22, 23].

However, several studies reported that acceptable workability can still be achieved at moderate replacement levels of bottom ash with proper mix design adjustments. When the replacement level is kept within a limited range, the reduction in workability is not very significant and can be controlled by optimizing the water–cement ratio or using chemical admixtures such **as superplasticizers**. Therefore, although bottom ash generally reduces the workability of concrete due to its physical characteristics, suitable mix proportioning and the use of admixtures can help maintain the required consistency and ease of placement **[10, 22, 23]**.

| Mix Designation | Bottom Ash Replacement (%) | Slump Value (mm) |
|---|---|---|
| Control Mix (CM) | 0 | 113 |
| BA10 | 10 | 102 |
| BA20 | 20 | 82 |
| BA30 | 30 | 61 |

The test results indicate that the slump value decreased progressively with an increase in the percentage of coal bottom ash. The control mix exhibited the highest slump value of 113 mm, indicating good workability. When 10% bottom ash was used as a replacement for fine aggregate, the slump value decreased slightly to 102 mm. Further replacement levels of 20% and 30% resulted in slump values of 82 mm and 61 mm, respectively.

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The reduction in workability can be attributed to the porous texture, angular particle shape, and high water absorption capacity of coal bottom ash. These characteristics increase the water demand of the concrete mix, thereby reducing its flowability. As the percentage of bottom ash increased, more water was absorbed by the ash particles, leading to lower slump values.

Despite the reduction in workability, all concrete mixes remained workable and suitable for casting. The results suggest that coal bottom ash can be effectively used as a partial replacement for fine aggregate in concrete; however, higher replacement levels may require the use of water-reducing admixtures or superplasticizers to maintain the desired workability. The observed trend is consistent with findings reported in previous studies on coal bottom ash concrete.

Fig. 2: Slump Cone Apparatus Used for Workability Test

*2) Bleeding*

Bleeding is a phenomenon in fresh concrete in which water rises to the surface after the concrete has been placed and compacted. The use of coal bottom ash (CBA) as a partial replacement for fine aggregate can influence the bleeding characteristics of concrete. Due to the porous structure and high water absorption capacity of bottom ash particles, the amount of free water available in the concrete mix is reduced. As a result, concrete containing bottom ash generally exhibits lower bleeding compared to conventional concrete. This reduction occurs because bottom ash absorbs part of the mixing water and improves the internal water retention within the concrete matrix [10, 22, 23].

Several studies have reported that the incorporation of bottom ash helps in reducing bleeding and segregation in fresh concrete, particularly at moderate replacement levels. The fine and porous particles of bottom ash improve particle packing and reduce the upward movement of water in the mix. However, at very high replacement levels, improper grading or excess water demand may still affect the stability of the mix. Therefore, proper mix proportioning and control of the water–cement ratio are important to achieve stable concrete with minimal bleeding when bottom ash is used as a fine aggregate replacement [10, 22, 23].

*3) Density*

Density is an important property of concrete that indicates the compactness and mass of concrete per unit volume. The incorporation of coal bottom ash (CBA) as a partial replacement for fine aggregate affects the density of concrete due to its lower specific gravity compared to natural sand. Bottom ash particles are generally lighter, porous, and irregular in shape, which leads to a reduction in the overall density of concrete. Studies have reported that as the percentage of bottom ash increases, the density of concrete slightly decreases because bottom ash has a lower unit weight than conventional fine aggregates [10, 22, 23].

Several researchers have observed that the reduction in density is more noticeable at higher replacement levels of bottom ash. However, at moderate replacement levels, the decrease in density is relatively small and does not significantly affect the structural performance of concrete. In some cases, the use of bottom ash can contribute to the production of lighter concrete with improved sustainability, as it utilizes industrial by-products and reduces the consumption of natural sand. Therefore, the use of bottom ash as a fine aggregate replacement can slightly reduce the density of concrete while still maintaining acceptable engineering properties [10, 22, 23].

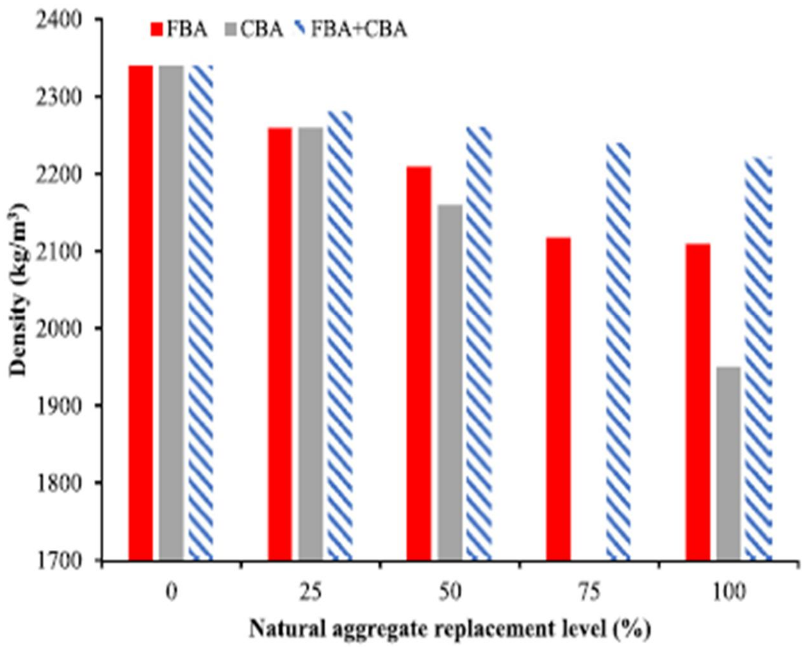


Fig. 3. The effect of CBA on the density [32].

### *F. Mechanical properties*

#### *1) Compressive Strength*

Compressive strength is one of the most important mechanical properties used to evaluate the performance of concrete. The use of coal bottom ash (CBA) as a partial replacement for fine aggregate influences the compressive strength of concrete depending on the replacement percentage and mix design. Several studies reported that at lower replacement levels, the compressive strength of concrete can be comparable to conventional concrete. This is because the fine particles of bottom ash may contribute to better particle packing and improved bonding within the cement matrix. However, at higher replacement levels, the compressive strength generally decreases due to the porous nature and lower strength of bottom ash particles compared to natural sand [10, 22, 23].

Researchers have also observed that an optimum replacement level exists where satisfactory compressive strength can be achieved. In many studies, replacement levels of around 10–30% bottom ash have shown acceptable strength performance, while higher percentages tend to reduce strength due to increased porosity and water absorption. Proper mix design, controlled water–cement ratio, and the use of chemical admixtures can help improve the strength performance of bottom ash concrete. Therefore, although high replacement levels may reduce compressive strength, the appropriate use of bottom ash can produce sustainable concrete with adequate structural performance [10, 22, 23].

In addition, some studies reported that the long-term compressive strength of concrete containing bottom ash may improve due to **pozzolanic reactions and improved microstructure over time**. The presence of fine ash particles can contribute to better filling of voids and densification of the cement matrix during hydration. As a result, concrete with bottom ash can achieve comparable or slightly improved strength at later ages when the replacement level is properly controlled **[10, 22, 23]**.

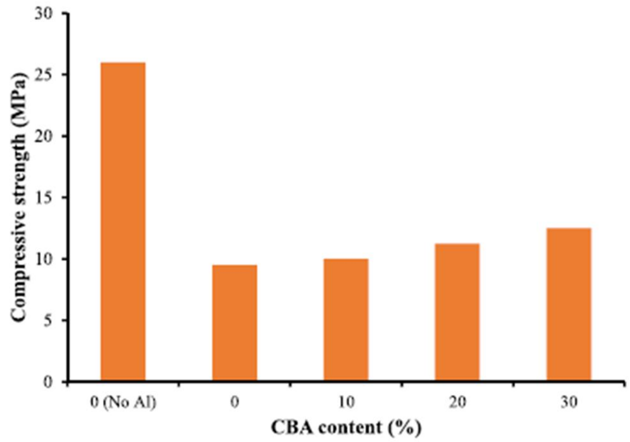


Fig. 4. Compressive strength of concrete mixes comprising CBA [33].

Fig. 5. Compression Testing Machine (CTM) Used for Compressive Strength Testing

2) Ultrasonic pulse velocity :

Ultrasonic Pulse Velocity (UPV) is a commonly used non-destructive testing method to evaluate the quality and uniformity of concrete. It measures the velocity of ultrasonic waves passing through the concrete, where higher wave velocity generally indicates better quality and denser concrete. Studies have shown that the UPV values of concrete containing coal bottom ash (CBA) increase with curing age, which reflects the improvement in concrete density and internal bonding over time. However, acceptable UPV values are generally observed at lower replacement levels of CBA, while higher replacement levels may slightly reduce the pulse velocity due to the porous nature of bottom ash particles. In some cases, UPV values were reported to decrease by about 5% in mixtures with higher fineness modulus of CBA compared to control concrete, although the concrete still remained relatively uniform and homogeneous [22].

Further investigations on concrete mixtures incorporating CBA have shown that the mechanical and durability properties are influenced by the replacement level and the use of additional materials such as fly ash. Research indicates that **lower replacement levels of CBA can improve the internal structure and mechanical properties of concrete**, while higher replacement levels may reduce the UPV values due to increased porosity. However, the addition of supplementary cementitious materials such as **fly ash** has been found to enhance both **UPV values and compressive strength**, improving the overall quality of the concrete. Moreover, durability properties including **surface abrasion resistance, water absorption, and resistance to chloride** penetration have shown improvement when CBA is used at moderate replacement levels as a fine aggregate substitute **[22]**.

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Fig. 6 Ultrasonic Pulse Velocity Measurement on Concrete Cube

*3) Tensile strength*

Tensile strength is an important mechanical property of concrete that indicates its ability to resist cracking under tensile stresses. The incorporation of **coal bottom ash (CBA)** as a partial replacement for fine aggregate can influence the tensile strength of concrete depending on the replacement level and mix composition. Several studies have reported that at **lower replacement levels of bottom ash**, the tensile strength of concrete can be comparable to or slightly higher than that of conventional concrete. This improvement is attributed to the **better particle packing and improved bonding between the cement paste and aggregates**, which enhances the internal structure of the concrete matrix **[10, 22, 23]**.

However, when the replacement level of bottom ash increases beyond the optimum range, the tensile strength tends to decrease. This reduction is mainly due to the **porous nature and lower strength of bottom ash particles**, which can increase the void content and reduce the bonding capacity within the concrete. Nevertheless, with proper mix design, controlled water–cement ratio, and the use of supplementary materials or admixtures, concrete containing bottom ash can still achieve satisfactory tensile strength while promoting the sustainable utilization of industrial by-products **[10, 22, 23]**.

*4) Rebound Hammer Test*

The Rebound Hammer Test is a widely used non-destructive testing (NDT) method for assessing the surface hardness and estimating the compressive strength of concrete. The test is based on the principle that the rebound of a spring-controlled mass striking the concrete surface is related to the hardness and quality of the concrete. A higher rebound number generally indicates better surface hardness and stronger concrete.

In the present study, the Rebound Hammer Test was conducted on concrete specimens containing different percentages of coal bottom ash (CBA) as a partial replacement for fine aggregate. The test was performed after the specified curing periods in accordance with the procedures recommended by Bureau of Indian Standards IS 13311 (Part 2): 1992. Multiple readings were taken at different locations on each specimen, and the average rebound number was calculated to minimize the effect of local variations.

The results obtained from the Rebound Hammer Test indicated that the rebound number increased with the age of concrete due to continuous hydration and strength development. Concrete mixes containing lower percentages of coal bottom ash exhibited rebound values comparable to those of conventional concrete. However, at higher replacement levels, a slight reduction in rebound number was observed, which may be attributed to the porous nature and lower density of bottom ash particles.

The Rebound Hammer Test provides a quick and economical method for evaluating the uniformity and surface quality of concrete without causing damage to the structure. The findings obtained from the rebound hammer test were correlated with compressive strength results to assess the suitability of coal bottom ash concrete for structural applications. Overall, the test confirmed that concrete containing moderate levels of coal bottom ash possesses satisfactory surface hardness and quality, making it suitable for sustainable construction purposes.


Fig. 7 Rebound Hammer Test Setup for Concrete Specimen

## IV. CONCLUSION

The present investigation demonstrates that coal bottom ash can be successfully utilized as a partial replacement for natural fine aggregate in concrete, contributing to both sustainable construction and effective waste management. The experimental results revealed that the inclusion of bottom ash influences the fresh and hardened properties of concrete due to its porous texture, lower density, and higher water absorption characteristics.

A gradual reduction in concrete density and workability was observed with increasing bottom ash content. This behavior is mainly associated with the lightweight and porous nature of bottom ash particles. Although the reduction in workability was noticeable, satisfactory consistency can be achieved through proper mix proportioning and the use of suitable admixtures.

The mechanical performance of the concrete indicated that mixes containing moderate levels of bottom ash achieved strength values close to those of conventional concrete. Among the replacement levels investigated, the mix containing 20% bottom ash exhibited the most balanced performance in terms of strength, durability, and overall concrete quality. Non-destructive testing results also confirmed the acceptable integrity and uniformity of the modified concrete.

The study further highlights that the physical characteristics of coal bottom ash, such as its particle grading and surface texture, make it suitable for use as a fine aggregate substitute. While its porous structure increases water demand, it can also contribute to improved particle interlocking and bonding within the concrete matrix when used at appropriate replacement levels.

Based on the findings, it can be concluded that coal bottom ash is a viable alternative material for partial replacement of natural sand, particularly up to a replacement level of 20%. Its utilization not only conserves natural resources but also reduces the environmental impacts associated with the disposal of thermal power plant waste. Therefore, the adoption of coal bottom ash in concrete production offers a practical approach toward sustainable and eco-friendly construction.

Further studies may focus on long-term durability behavior, the combined effect of bottom ash and fiber reinforcement, and the development of optimized mix design procedures for wider field applications.

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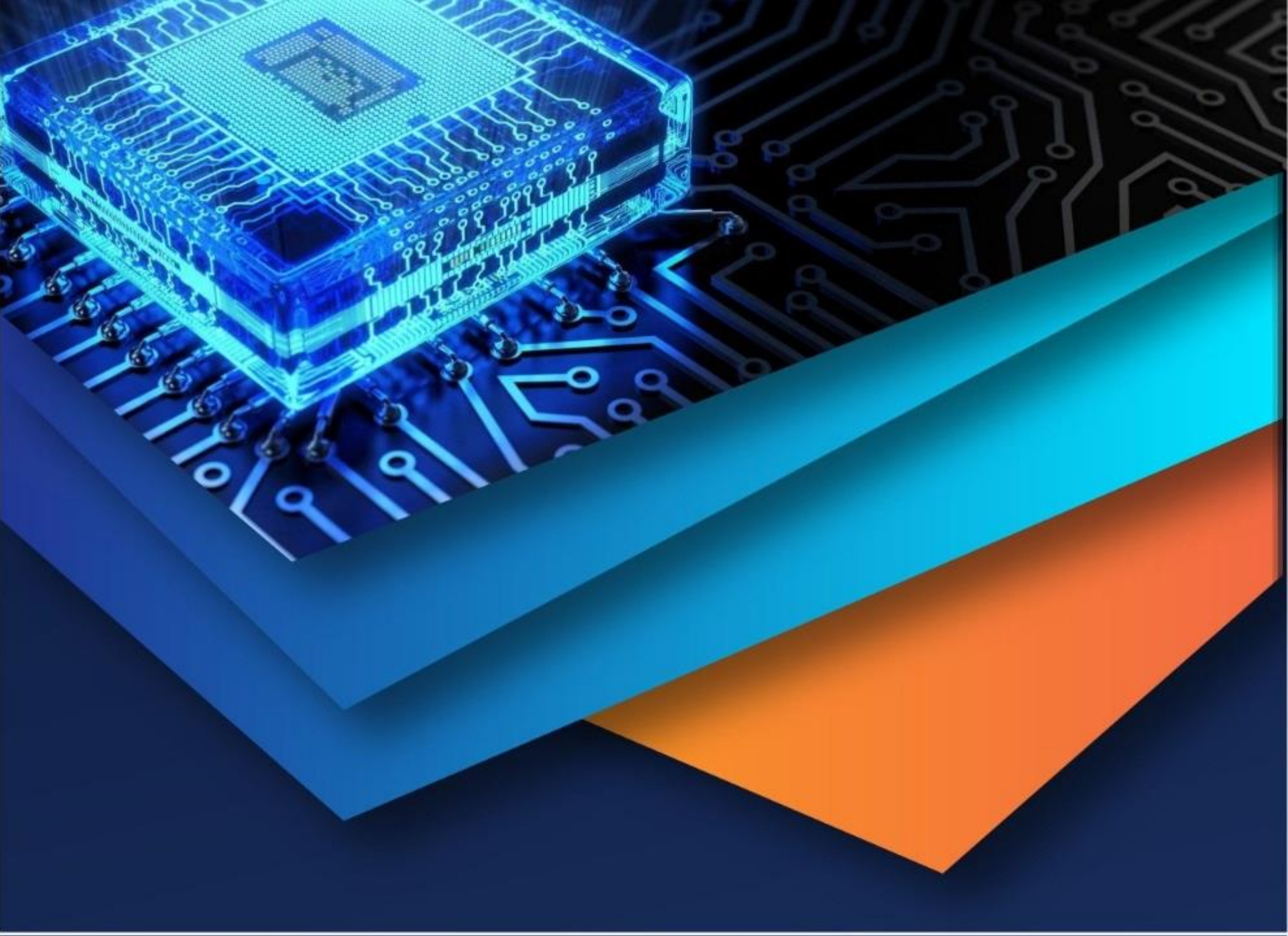

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