Influence of Bottom Ash as a Partial Replacement of Fine Aggregate Along with Glass Fiber for Sustainable Concrete

Mr. Rutik K Kale[1], Dr. Mahesh Raut[2]
[1]Research Scholar, G.H. Raisoni College of Engineering and Management, Nagpur, Maharashtra, India
[2]Assistant Professor, Department of Civil Engineering, G.H. Raisoni College of Engineering and Management, Nagpur, Maharashtra, India

***Abstract*—Concrete remains one of the most widely used construction materials worldwide and is responsible for a considerable portion of global resource consumption and environmental impact. The increasing demand for infrastructure has led to excessive extraction of natural aggregates and higher cement production, both of which contribute significantly to environmental degradation. As a result, there is a pressing need to explore alternative materials and innovative approaches that can reduce the ecological footprint of concrete while maintaining or enhancing its engineering performance. Utilizing industrial by-products such as bottom ash and incorporating advanced reinforcing materials like glass fibers offer promising pathways toward achieving sustainable and high-performance concrete. Although many previous studies have focused on using either bottom ash as a fine aggregate replacement or glass fiber as a strength-enhancing material independently, the present study investigates the combined effect of both. In this research, bottom ash collected from the Koradi Super Thermal Power Station is used as a partial replacement for fine aggregate, and glass fibers are incorporated to evaluate the overall performance of the concrete. The study examines concrete behavior when natural sand is replaced up to 30% with Koradi bottom ash, providing a new perspective on the synergistic potential of these materials for developing durable and sustainable concrete.**

***Index Terms*—Coal Bottom Ash, Glass Fibers, Sustainable Concrete, Mechanical Properties, Durability, fine aggregate, replacement**

I. INTRODUCTION

Concrete remains the most extensively utilized construction material worldwide, and its demand continues to increase due to rapid urbanization and infrastructure development. This growing dependence on concrete places significant pressure on natural resources, particularly river sand, which serves as the primary fine aggregate in conventional concrete. Excessive extraction of river sand has resulted in environmental degradation, riverbank erosion, and ecological imbalance, prompting the need for alternative sustainable materials that can partially or fully replace natural aggregates. One such promising material is coal bottom ash (CBA), an industrial by-product generated in coal-fired thermal power plants. Studies have reported that bottom ash constitutes nearly 15–20% of the total coal ash produced and remains largely underutilized compared to fly ash, leading to large-scale accumulation in ash ponds and landfills [1, 3].

The uncontrolled disposal of bottom ash creates long-term environmental concerns, including soil contamination, groundwater pollution, and deterioration of surrounding ecosystems due to the presence of heavy metals and unburnt residues [2, 20]. Researchers have emphasized that utilizing bottom ash as a fine aggregate replacement not only minimizes disposal-related issues but also contributes to conserving natural sand resources and reducing the carbon footprint of concrete production [4–7, 23]. The physical characteristics of bottom ash, such as its porous structure, low density, and granular morphology, make it suitable for use as a partial sand substitute. However, high replacement levels may influence workability and early-age strength due to higher water absorption and irregular particle shape [7, 12, 19].

Although bottom ash possesses pozzolanic characteristics that can contribute to long-term strength development, concrete containing bottom ash often suffers from brittleness and limited tensile capacity—properties inherent to conventional concrete matrices. To overcome these limitations, incorporating discrete fibers has gained significant attention. Among various fibers, glass fibers have proven effective in improving tensile strength, toughness, crack resistance, and post-cracking ductility due to their high tensile capacity and crack-bridging behavior [14]. However, most previous research has focused either on bottom ash as a sand replacement or on glass fibers as a reinforcement material independently. Only limited studies have explored the combined effect of bottom ash and glass fibers on mechanical and durability properties of concrete, representing a critical research gap.

Considering the availability of a large quantity of bottom ash from power stations such as the Koradi Super Thermal Power Plant, and the proven performance benefits of glass fibers, there is a strong need to examine their synergistic performance in concrete. Therefore, this study investigates the influence of Koradi bottom ash as a partial replacement for fine aggregate along with glass fibers to develop sustainable, durable, and high-performance concrete. The research focuses on analyzing mechanical behavior, durability characteristics, and the optimum replacement ratio that ensures improved structural performance while reducing the environmental impact associated with natural sand extraction and industrial waste disposal. This approach aligns with global sustainability goals and supports the effective utilization of industrial by-products in construction materials [1, 3, 23, 24].

II. LITERATURE REVIEW

Ku Muhammad Firdaus Ku Meh et al. (2022) This study investigated the performance of concrete when coal bottom ash (CBA) was used as a partial sand replacement. The authors examined workability, density, and compressive strength across various replacement levels. Results showed that moderate CBA substitution enhanced mechanical strength due to improved particle packing and reduced porosity. The study highlighted the environmental benefits of utilizing industrial waste, noting that CBA reduces natural sand consumption and landfill demand. Durability assessments indicated stable performance under long-term loading conditions. The findings support the use of CBA as a sustainable construction material for producing eco-friendly concrete with acceptable strength properties.

D'Souza (2017) D'Souza examined the effects of replacing fine aggregate with bottom ash in conventional concrete. The study evaluated slump, compressive strength, and density at different replacement levels. Results indicated that bottom ash improved compressive strength at moderate percentages due to its porous texture and better interlocking behavior. Although workability decreased slightly, strength improvement compensated for the reduction. The research emphasized that bottom ash offers a cost-effective and environmentally friendly alternative to river sand. The study concluded that bottom ash can be efficiently utilized in structural-grade concrete without compromising performance, particularly in regions facing scarcity of natural fine aggregates.

Singh (2016) Singh focused on the environmental impact of river sand mining and the urgent need to find sustainable alternatives for use in concrete. The study described how uncontrolled extraction of sand has led to severe ecological problems such as riverbank erosion, groundwater depletion, and habitat destruction. This has created a scarcity of natural sand and rising costs in the construction industry. Singh emphasized that industrial by-products such as coal bottom ash, quarry dust, and foundry sand present viable substitutes for natural fine aggregates. The research also reviewed experimental findings showing that such by-products can partially replace sand without significantly compromising strength or durability. Importantly, Singh highlighted that the use of these materials contributes not only to environmental conservation but also to industrial waste management. The study provides strong motivation for adopting coal bottom ash in sustainable concrete and aligns with efforts to reduce the ecological footprint of construction.

Ku Meh et al. (2018) Ku Meh et al. carried out experimental research on the potential of coal bottom ash (CBA) as a partial replacement for fine aggregate in concrete. Their study analyzed the physical and chemical properties of CBA, highlighting its porous and angular nature, which influences workability and strength. They found that replacing natural sand with CBA up to 30% could yield compressive strength comparable to conventional concrete, although higher percentages reduced workability and mechanical performance. The study emphasized that proper grading and processing of bottom ash are necessary to achieve consistent results. Additionally, the environmental benefit of reducing landfill disposal was noted as a key advantage. This research provides direct experimental evidence supporting the use of CBA in sustainable construction. It also highlights the importance of optimizing replacement levels to balance environmental gains with mechanical and durability requirements, making it highly relevant to the present study.

Kumar (2018) Kumar explored the combined effect of coal bottom ash and fibers on the mechanical and durability properties of concrete. His study highlighted that bottom ash, when used as a fine aggregate replacement, could reduce workability due to its porous texture but could still achieve satisfactory compressive strength at moderate replacement levels. The addition of glass fibers improved tensile strength, crack resistance, and toughness, offsetting the limitations introduced by bottom ash. Kumar's experiments also revealed enhanced durability indicators, including lower shrinkage and better resistance to water penetration, when both CBA and fibers were incorporated. The study concluded that the synergy between industrial waste utilization and fiber reinforcement could lead to eco-friendly yet high-performance concrete. Kumar's findings are crucial because they demonstrate how fibers can complement CBA, making the overall mix sustainable while maintaining or even improving structural performance, thus supporting the objectives of this research.

Kumar & Singh (2019)Kumar and Singh [6] investigated the durability performance of concrete incorporating coal bottom ash as partial fine aggregate replacement. Their study emphasized durability aspects such as sulfate attack resistance, water absorption, and chloride penetration. Results indicated that moderate replacement levels (10–20%) of CBA could improve resistance to aggressive environments due to pore refinement, while higher levels adversely affected durability because of increased porosity. The research also pointed out the necessity of using admixtures or supplementary cementitious materials to counterbalance negative effects at higher replacement levels. This work extended earlier findings by focusing on long-term behavior rather than just strength properties. The authors concluded that CBA has potential in structural-grade concrete if carefully proportioned and treated. Their findings fill an important knowledge gap by addressing durability concerns, which remain a critical barrier for large-scale adoption of bottom ash concrete in practical construction applications.

Patel et al. (2020) Patel et al. studied the mechanical behavior of concrete when natural fine aggregates were partially replaced with coal bottom ash. Their work involved compressive, split tensile, and flexural strength testing at varying replacement levels. The results showed that concrete with 20% replacement of sand by CBA exhibited strength comparable to conventional concrete. Beyond this limit, a decline in workability and strength was observed. The authors attributed this to the porous and irregular texture of bottom ash particles. However, they emphasized that pre-treatment methods like washing and grading could improve performance. The study also underlined the cost-effectiveness and environmental benefits of utilizing industrial by-products in construction. Patel et al. recommended the use of CBA in non-structural and partially structural applications, depending on performance requirements. Their findings support the sustainable use of waste materials while recognizing the need for further optimization in mix design.

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.

Ali & Khan (2021) Ali and Khan focused on the environmental and economic impacts of using coal bottom ash in concrete production. Their study emphasized the dual benefits of reducing natural sand consumption and minimizing industrial waste disposal. They performed a lifecycle cost analysis that revealed substantial savings when CBA was used at 15–20% replacement levels. Mechanically, the mixes showed comparable compressive strength and satisfactory durability performance. The study stressed that widespread adoption of bottom ash in construction could significantly reduce the ecological footprint of the concrete industry. Furthermore, the authors pointed out challenges such as variability in ash quality depending on its source, necessitating proper characterization before use. Their findings provide both technical and economic justification for incorporating CBA in concrete, aligning with sustainable development goals while demonstrating its feasibility in real-world 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

Researchers studied the influence of bottom ash as a partial replacement for fine aggregate along with glass fiber reinforcement on the properties of concrete. Two sets of concrete specimens were prepared: the first set with conventional concrete, and the second set with partial replacement of fine aggregate by bottom ash combined with glass fibers. Cubes of size 150 × 150 × 150 mm and cylinders of size 150 mm diameter × 300 mm height were cast using a concrete mix designed for M25 grade, with a proper ratio of cement, sand, and coarse aggregate. Glass fibers were added in specific proportions to enhance tensile strength and crack resistance, while bottom ash was used at varying replacement levels to evaluate its effect on workability, strength, and durability.

After casting, the specimens were cured for 28 days under standard conditions. Following the curing period, the cubes and cylinders were subjected to several tests, including compressive strength, split tensile strength, and flexural strength tests. The experimental study also evaluated durability parameters such as water absorption, density, and crack resistance.

The methodology involved the following steps:

1 . Preparation of concrete mixes with partial replacement of fine aggregate by bottom ash and incorporation of glass fibers.
2. Casting of cube and cylinder specimens according to standard dimensions.
3. Proper curing of specimens for 7, 14, 28, 56 days.

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

Analysis of results to determine the optimal bottom ash replacement and glass fiber content that provide a balance of strength, durability, and sustainability.

The study aimed to investigate the synergistic effect of bottom ash and glass fibers in concrete, focusing on sustainable material utilization and improved mechanical performance. Observations from this study provide insights into developing eco-friendly concrete with reduced dependency on natural aggregates and enhanced structural properties.

3.1 EXPERIMENTAL PROGRAMME

The coal bottom ash (CBA) employed in the present study was collected from the Manjung Thermal Power Plant located in Perak, Malaysia, as illustrated in Fig. 1. Prior to its use, the collected CBA was oven-dried at 110 °C for a duration of 24 hours in order to minimize the moisture content that could influence the experimental outcomes. After drying, the material was passed through a 5.0 mm sieve to eliminate oversized particles, as shown in Fig. 2. The processed CBA was subsequently considered as a partial replacement for fine aggregate (sand) in concrete. Accordingly, a detailed investigation of the physical characteristics of the CBA particles was carried out to evaluate their suitability for use in concrete mixtures.

The particle size analysis indicated that both coal bottom ash (CBA) and natural sand satisfied the grading requirements, with their distributions lying within the specified upper and lower limits. The results demonstrated that the CBA particles predominantly fall within the coarse-to-medium sand range, showing a grading pattern comparable to that of the natural sand used in this study, in accordance with BS 882:1992. Furthermore, the median particle size (d50) of the CBA was found to be 1.10 mm, whereas the corresponding value for river sand was 0.88 mm. This indicates that approximately 50% of the CBA particles were relatively coarser compared to river sand. Overall, the findings suggest that coal bottom ash obtained from the Manjung Power Plant exhibits particle size characteristics similar to those of natural sand, highlighting its potential suitability as a partial or complete replacement for fine aggregate in concrete production.

Fig. 1. Coal bottom ash (CBA) produced by Manjung Power Plant, Perak, Malaysia (Source: Ku Meh et al., 2016). [1]

Fig. 2. Particle size distribution of coal bottom ash (CBA) aggregate.(Source: Ku Meh et al., 2016). [1]

3.2 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.

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.

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

3.3 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].

3.4 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 $SO_3 \leq 5\%$ and LOI $\leq 6\%$, 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.

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.

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	–

IV. RESEARCH GAP

Although bottom ash has been widely investigated as a supplementary cementitious material, its application as a fine aggregate replacement remains significantly underexplored. Most existing studies focus primarily on its pozzolanic behavior, leaving a limited understanding of how bottom ash, when used as a granular fine fraction, influences the overall grading, density, and microstructural packing of concrete.

Furthermore, the effect of bottom ash on the fresh properties of concrete—such as workability, bleeding, and setting characteristics—has not been comprehensively established. Due to its porous texture and irregular particle shape, bottom ash may alter water demand and rheological behavior; however, systematic experimental evidence on these aspects is still insufficient.

A major research gap also exists in the long-term durability performance of bottom-ash-modified concrete. Critical durability parameters—including resistance to sulfate attack, chloride penetration, carbonation depth, and permeability—have not been thoroughly examined under aggressive environmental exposures. The absence of long-term data creates uncertainty regarding the suitability of bottom ash concrete for structural and durability-sensitive applications.

Moreover, there is a lack of studies exploring the combined incorporation of bottom ash with other sustainable or performance-enhancing materials such as alkali-resistant glass fibers. The interaction between bottom ash's porous morphology and the crack-bridging ability of glass fibers has not been adequately evaluated, creating a gap in understanding their synergistic influence on mechanical and durability properties.

Another significant gap concerns the identification of an optimum replacement level of bottom ash that ensures a balanced improvement in strength, workability, and durability. The findings reported in literature vary widely, indicating the need for more controlled and standardized experimental investigations to determine an ideal replacement percentage for practical applications.

Finally, although non-destructive testing methods such as Surface Hardness Test, Ultrasonic Pulse Velocity (UPV), and Electrical Resistivity provide valuable insight into microstructural integrity and durability potential, their application in evaluating bottom-ash-based concrete remains limited. Expanding the use of such techniques would help develop a more accurate assessment framework for understanding the real-time performance of concrete containing bottom ash.

V. CONCLUSION

Based on the experimental findings, the incorporation of bottom ash as a partial replacement for fine aggregate has shown promising potential for sustainable concrete production. The study confirms that the density of concrete decreases with increasing bottom ash content, which is attributed to the lower specific gravity and porous nature of bottom ash particles. The high water absorption capacity of bottom ash also leads to a reduction in workability;

however, this limitation can be effectively managed through the use of suitable chemical admixtures.

Mechanical performance results indicate that concrete mixes containing 10% and 20% bottom ash exhibit compressive strength values comparable to those of conventional concrete. Among the tested proportions, the 20% replacement level demonstrates optimum performance, offering a favorable balance between strength, durability, and material efficiency. Evaluations further support the structural integrity and quality of bottom-ash-modified concrete.

The findings align with previous literature, which highlights that bottom ash possesses particle characteristics similar to natural sand, including comparable grading and favorable interlock behavior. Its rough texture and porous structure contribute positively to bond formation but also influence water demand. Despite these challenges, the presence of calcium-rich compounds in bottom ash enhances strength when optimally used.

Overall, the study concludes that bottom ash can effectively serve as a partial fine aggregate substitute, particularly at replacement levels up to 20%. This not only maintains satisfactory mechanical and durability properties but also supports sustainable waste utilization. The use of bottom ash reduces the environmental burden associated with thermal power plant waste disposal and decreases dependency on natural river sand. Further research is recommended to explore long-term durability, fiber reinforcement synergy, and standardized mix design approaches to enhance the practical application of bottom-ash-based concrete in the construction industry.

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