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# Bottom ash as sustainable construction material: A review on case studies

Pathipati Narasimharao
Research scholar
Department of Civil Engineering
JNTUA
Anantapur, India-515 002
https://orcid.org/0000-0001-7165-4552

Dr. B. Damodhara Reddy
Professor
Department of Civil Engineering
SVCET (A)
Chittoor, India – 517 127
https://orcid.org/0000-0003-0229-6020

Dr. C. Sasidhar
Professor
Department of Civil Engineering
JNTUCEA
Anantapur, India-515 002
sashigunt1990@gmail.com

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*Abstract* — Concrete consists of cement, aggregates, and water, with sand being the most commonly used fine aggregate obtained from riverbanks. The demand for natural sand globally high, especially in developing countries due to rapid infrastructural growth, has led to a scarcity in its supply. Consequently, construction industries in these countries are under pressure to find alternative materials to replace natural sand. Utilization of byproducts or waste materials as aggregates, reduces environmental impact and waste management costs, lowers production costs, and improvement in concrete quality can be achieved. Bottom ash, a byproduct of stone crushing units, has been used as a replacement for fine aggregate in concrete, showing potential for various construction activities and enhancing concrete properties. Studies conducted globally on using bottom ash from different industries to create ceramics, mortar, cement, and concrete, with a focus on density, workability, water absorption, physical and chemical properties, and durability aspects. This article aims to consolidate and summarize significant research on usage of bottom ash as a partial replacement in construction materials, serves as a breakthrough for further studies and providing an overview of current knowledge, theories, gaps, and trends. Information gathered from public sources on utilizing bottom ash in production of concrete is essential for academic evaluation and may guide future research in this area.

*Keywords—Bottom ash, physical, chemical, and durability properties, analysis.*

## I. Introduction

Existing research is getting agitated due to issues with the environment associated with the clearance of wastes and crises in obtaining sand. Furthermore, emissions from greenhouses, as a result of production of concrete, are decreased by partially switching out cement with industrial by-products. Globally, concrete is the primary building material utilized in the industry of construction, consisting of cement, rocks, and river sand mainly. Currently, the deficiency of river sand has caused an abnormal surge in its price, leading to an increase in concrete production costs. The construction sector is beset with issues of lacking and abnormal prices of river sand. Alternatively, coal-fueled thermal power plants in the country have amassed massive amounts of coal bottom ash over time. The combustion of vast quantities of coal will generate coal bottom ash on a large scale at thermal power plants, however, it relies on the non-combustible components within coal. The rock debris found in coal's cracks separate during pulverization. Carbon and other combustible materials burn in the furnace, while the non-combustible components become coal ash. The ash particles are carried by swirling air out of the hot area where they become cooler. The finer and lighter ash particles are eliminated by flue gases. Fly ash refers to fine particles obtained via electrostatic precipitators, accumulates on furnace pipe walls. Due to ongoing collection of ash, clinkers are generated, if these clinkers get too heavy, they drop to the furnace's bottom, resembles river sand since its particle size varies from sand to gravel in fineness. The categorization of coal bottom ash entices researchers to explore its utilization as a replacement to fine aggregates in production of concrete. A limited number of research reports published so far but Indian coals are distinct from European and American coals in various characteristics due to their formation. "Indian coals possess high ash content of up to 45%, low sulphur content in the range of 0.2-0.7%, and low caloric value between 2500-5000 kcal/kg" [36]. Since the particle size distribution of bottom ash is similar to normal sand, several attempts have been made to study its potential use in mortar and concrete and caught the attention of researchers. Waste materials have piqued the interest among researchers as a replacement for natural aggregate or cement to enhance properties of concrete, reduce wastage, and disposal, while keeping economic benefits in mind. Concrete durability has been a focal point in research as long-term concrete performance is affected by durability issues. For concrete to be durable, it must resist external detrimental agents to prevent deterioration. High resistance to deterioration and durability are primary design considerations for concrete, along with strength design criteria. It is anticipated that bottom ash can be a substitute for fine aggregate when natural sand is costly or far away and possess excessive clay particles. Coal bottom ash and boiler slag are byproducts of coal-burning furnaces used to produce steam or electricity. Bottom ash has a similar chemical makeup as fly ash, but it often contains more carbon. Bottom ash possesses higher shear strength and lower compressibility, making it a suitable material for civil engineering applications including dam construction. "The particle sizes range from 40 mm gravel to 0.075 mm fine sand. Many researchers believe that the properties of bottom ash are similar to natural sand" [29].

## II. Chronical usage of bottom ash in construction applications

The impact of FBA on concrete properties such as compressive strength, workability, permeability, carbonation depth, and chloride transport were studied in this research by Bai, Yun & Basheer, P.A. Muhammed [11]. Workability improved when higher FBA natural sand was replaced, although compressive strength was lower than control concrete initially but comparable after 365 days; permeability, water absorption, and carbonation rates were higher in FBA concrete at 365 days, while chloride transport coefficient decreased up to 50% replacement but increased beyond; further research is needed to optimize water-cement ratios considering the reduced water demand of FBA concrete.

The construction industry, like other sectors aiming for Industry 4.0, is focusing on innovative production methods aligned with future trends. Environmental concerns are bringing more attention to the use of industrial waste as building materials, such as fine and coarse aggregates from coal-based power plants. Research was conducted by Chai Jaturapitakkul, Raungrut Cheerarot [13] to assess the effectiveness of bottom ash incorporated into 'Controlled Low-Strength Material (CLSM)', showed up promising results in terms of flowability, pH levels, and compressive strength, suggested the importance as a construction material, particularly for non-structural filling in confined areas, contributing to sustainability efforts in the industry.

Aggarwal [3] studied the impact of furnace bottom ash in concrete when used as replacement for sand ranging from 30% to 100% at specific water-to-cement ratios. The workability decreased as bottom ash content increased, super-plasticizer used to maintain constant water demand. The lower specific gravity of bottom ash in comparison to fine particles caused a decrease in the density of the concrete, which at first led to poorer compressive, splitting, tensile, and flexural strengths compared to control concrete. However, after 28 days, the difference in strength diminished. Concrete strength continued to improve with age, with 30% and 40% bottom ash mixes after 90 days achieving a strength comparable to normal concrete. Bottom ash concrete may be suitable for structural use, demonstrating compressive strength above 20 MPa at 28 days and exhibiting increased strength over time, although achieving required strength may take longer.

In 2011, H.K. Kim and HK Lee [20] used fine and coarse bottom ashes in high-strength concretes. They found that the character of the concrete was minimally reduced with coarse bottom ash, while the influence of fine bottom ash was overlooked. The mass of the solidified concrete decreased linearly with the exchange rate of fine and coarse bottom ashes, and the elastic modulus dropped to 49.0% for concrete with 100% fine and coarse bottom ash.

Gert van der Wegen et al. [17] have established the technical viability of partially substituting such bottom ash for natural sand and gravel on all pertinent characteristics of concrete. A guideline to use enhanced incinerator bottom ash in ready-mixed and precast concrete has been developed based on these findings. Even though the upgraded bottom ash is of higher quality than the original bottom ash, certain characteristics—such as particle density, the amount of metallic aluminum, loss upon ignition, the amount of chloride, sulfate, and alkali, and, lastly, components that affect the cement's setting and hardening—require extra consideration. Upgraded incinerator bottom ash up to 20% V/V in reinforced concrete and up to 50% V/V in non-structural concrete can be used to replace sand and/or gravel. Applications in prestressed concrete is not recommended due to corrosion of prestressed steel.

Jeffery S. Volz et al. [21] used bottom ash as a partial or total replacement for fine and coarser aggregates in concrete, 2013 showing potentials for various transportation-related infrastructure components. Researches indicates that prewetted bottom ash in concrete mixes significantly reduces overall shrinkages and restraints strains. Internally cured high-performance concrete with bottom ash experienced lower average shrinkages compared to control mix. Bottom ash can effectively reduce shrinkages and restraints strains in concrete mixes, making it a viable option for improving concrete performances.

Kadam, Madhav, and Patil [22] (2013) explored the impact of coal bottom ash on concrete properties as substitute to sand. Aggarwal and Siddique (2014) noted that water content increased steadily up to 30% replacement, then doubled for 40% and 50% replacements. Mixes can be adjusted up to 30% and 50% fine aggregate replacement by modifying water content. The FB60 mix, with high water content, exhibited weaker strengths compared to conventional concrete except at 365 days. There was a notable increase in strength when 30% of the natural fine aggregate was replaced with industrial waste, with 50% being the maximum replacement feasible. The usage of waste foundry sand and bottom ash did not compromise concrete strength, offering enhanced resistance to various agents and maintaining consistent mechanical properties.

In 2013, K. Nataraj et al. [28] carried out research on bottom ash concrete by substituting lignite-based bottom ash for river sand. Approximately 20% of the coal fed into boilers is made up of bottom ash, a coarser substance. The quality of the concrete enhanced with the use of bottom ash, which is rarely utilized in concrete because of its passive pozzolanic reactions. According to the results of the experimental research, 30% is the idyllic quantity of fly ash to substitute the cement in bottom ash concrete. When using substantial amounts of waste products, bottom ash concrete is advised, with fly ash replacing 30% of the cement. The studies indicated that fly ash from 0% to 40% replacements to cement with 0.40 water-cement ratio is effective in resisting compressive and tensile stresses. Exploring the uses of different types of additives or admixtures to improve the workability of bottom ash concrete could be a potential area for futures research.

Malkit Singh et al. [32], [33], [34], [35], [36], conducted series of experiments on bottom ash concrete from the year 2013 to 2015. For every concrete mix, the water/cement ratio remained constant at 0.45, while the curing ages ranged from 7 to 365 days. At whatever curing age, there was no discernible negative effect on the strength and durability of concrete up to a 50% replacement. Up to 50% of sand replacement did not significantly impair compressive strength after 7 days of curing; however, 100% coal bottom ash replacement led to a 15.16% reduction in the strength when compared to control mixes. Bottom ash mixes equaled control concrete strength after 28 days and even exceeded it after 90 days. More coal bottom ash led to an increase in water absorption, albeit it stayed lower in bottom ash concrete. With age, bottom ash concrete's absorption and voids dramatically reduced in comparison to control concrete. Abrasion resistance improved with age in both types of concrete, correlating strongly with compressive strength. Bottom ash concrete showed poorer abrasion resistance than control at 28 days, with lower modulus of elasticity regardless of replacement levels. Higher CBA content led to denser C-S-H gel structures but less monolithic than control concrete. XRD diffractograms displayed typical hydrated phases in the concrete, peaks of alite, belite, and C-S-H are overlapped, as well as interference from silicon dioxide in the aggregate. The intensity of ettringite remained constant with CBA addition. Concrete performed well against external sulphuric attack, with some expansion strains observed without loss in mass or strength. Drying shrinkage decreased with higher CBA content, offering improved resistance to chloride ion penetration.

'Overlooked current research situation on Botton ash: An Indian outlook' by A.K. Mandal, O.P. Sinha [37] on its ability to absorb dyes, pelletization efficiency, concrete compressive strength, and water absorption characteristics. Dry unit weights of coal ashes are not affected by water content changes, making them suitable for constructing pavements and embankments for enhancing their geotechnical engineering applications.

Kumar et al. [29] utilized bottom ash to make M30 grade of concrete by IS method in 2014 with regular Portland cement from 43 Grade. The compressive and flexural strength on the concrete at different ages i.e., 7, 14, 28 and 56 days are examined. Bottom ash is substituted 10%, 20%, 30%, 40% and 50% in the location of thin accumulation. From both an economic and environmental standpoint, employing it as a raw material for dice (Brick) production will be a very helpful option. The compressive and flexural strengths of the concrete are observed to be declining after bottom ash replacement of 40%.

Norul Ernida Zainal Abidin et al. [43], investigated the impact of bottom ash on 'self-compacting concrete' (SCC) properties. Increasing the supplanting level of bottom ash decreased slump flow, L-box passing ratio, and segregation resistance ratio, but increased slump flow time. The porosity and irregular shape of bottom ash particles significantly influenced workability and viscosity. Bottom ash increased the compressive strength of SCC up to 15% substitution level, indicating pozzolanic reactivity.

Research by Yogesh Aggarwal and Rafat Siddique [62] in the year 2014 explored usage of waste foundry sand and bottom ash as partial replacement in concrete production for fine aggregates. The study revealed that replacements up to 30% to fine aggregates by industrial by-products led to comparable mechanical properties to conventional concrete. However, the mix FB60 with high water content showed weaker strengths. The addition of waste foundry sand and bottom ash did not negatively impact the concrete's strength and provided resistance to aggressive agents.

Kadam, Madhav & Patil, Yogesh [23] in the year 2014 discovered that both compressive strength and elastic modulus of sieved coal bottom ash concrete increased as the percentage of cement in the mix raised up to 20%. This was due to a reduction in voids and improved particle distribution, resulting in increased strength and reduced permeability in the concrete.

T. Balasubramaniam et al. [55], [56] in the year 2014 and 2015 studied the usage of 'manufactured sand' as fine aggregate, with cement being substituted by silica fume and superplasticizer added to enhance workability, primarily to address disposal issues. Various durability aspects of concrete mix M60, such as water absorption, resistance to sea water and acid, abrasion, and chloride penetration were examined. By maintaining the flow property through addition of superplasticizer, compressive strength improved over time. Increase in water absorption and porosity due to presence of bottom ash, affected the compressive strength after exposure to acid solution. The expansion of bottom ash concrete specimens under sulphate attack found to be more than control concrete across all replacement levels. BA10 mix performed well in abrasion resistance compared to control mix, with chloride ion penetration remaining within moderate levels up to BA 30 concrete. The results demonstrated that the bottom ash from percentages 10 to 50 as replacement to M-Sand enhanced compressive, flexural, and split tensile strength, and elastic modulus of the concrete, particularly at later ages.

Sabarinath N, Vijaya Vittala [50] conducted experimental study on fiber reinforced concrete (FRC) using fly and bottom ashes partially in place of cement and sand in the year 2015. M40 grade of concrete is tried using fly ash as a partial replacement for cement from percentages 0 to 40 and the bottom ash as a partial replacement for sand from percentages 0 to 20 with the addition of 0.5% glass and 2% coir fibers in volume to cement and concrete respectively. The study analyzed effect of ash replacements with and without fibers on strength and durability of concrete and compared with control concrete, found that the 20% to 30% replacement of cement by fly ash and 10% to 15% replacement of sand by bottom ash were the most effective.

Studies by Mohd Haziman Wan Ibrahim et al. [40], investigated its physical, chemical, and mechanical properties, revealing impacts on various aspects of concrete performance. The optimum level of bottom ash falls between 10% to 30%, although attention must be given to factors like water-to-cement ratio due to its angularity and coarse texture causing decreased workability. As a porous material, bottom ash requires higher water content for workability, but this may compromise concrete strength, indicating a need for careful consideration during the mixing process.

In their 2016, K. Meenu Priyaa et al. [27], the corrosion behavior of bottom ash in different replacement levels on different grades of concrete to fine aggregate studied. Conducted water absorption, sorptivity, porosity, rapid chloride penetration, compressive strength and accelerated corrosion tests, bottom ash up to 20% replacement showed comparable results to control mix.

In this research by Aldi Vincent Sulistio et al. [4], bottom ash used in high-volume fly ash concrete as a substitute to sand. The physical and chemical properties of treated bottom ash, including water absorption and fineness modulus revealed that with sieve separation achieving 75% and pounded bottom ash achieving 96% of the compressive strength of control sand. A compressive strength of 45 MPa achieved with 100% fine aggregates replacement. The gradation of bottom ash particles played a vital role in enhancing concrete mixture properties by filling gaps between particles. The study also showed that controlling particle gradation is essential for obtaining a workable and strong high-volume fly ash mortar.

The research conducted by B. Vidivelli et al. [12] in the year 2017 aimed to determine optimal replacement percentages of steel slag, manufacturing sand (M-sand), and bottom ash to fine aggregates by evaluating fresh and hardened properties of M30 grade concrete. Results showed that concrete with 50% M-sand replacement had increased modulus of elasticity and loss in both weight and strength, the same has been observed for steel slag and bottom ash replacements as compared to conventional concrete. Additionally, rapid chloride penetration test indicated lower chloride penetration for all replacement materials, 50% M-sand mix showing minimal strength loss and excellent salt and sulphate resistance.

Hamzah, A.F. [19] (2017) explored the use of coal bottom ash in self-compacting concrete to enhance durability properties and resistance to segregation in harsh conditions for various replacement levels (0%, 10%, 15%, 20%, 25%, 30%) to sand, assessed under exposure to sodium chloride, sodium sulphate, and seawater. Results indicated that 10% coal bottom ash replacement improved durability against aggressive environments due to reduced calcium hydroxide content and formation of pozzolanic reaction products like Friedel's salt and ettringite.

The potential use of bottom ash to replace fine aggregates in concrete paving blocks was explored in the year 2017 by Kevin Klarens et al. [25], aimed to enhance the utilization of this waste material despite its high porosity and carbon content. The research involved three phases: blending cement and bottom ash in different ratios, incorporating fly ash from 10% to 80% as substitute to cement, and testing samples with varied fly ash replacement ratios combined with different sieved bottom ash sizes to evaluate the feasibility of replacing in paving block as sand substitute and production by optimizing density and employing fly ash as substitute to cement to achieve compressive strengths exceeding 40 MPa.

Pincha Torkittikul et al. [46] in the year 2017 assessed the chemical composition, mechanical properties and microstructure of coal bottom ash replaced mortar and concrete, the density decreased with higher ash content, but the compressive strength remained largely unaffected. Moreover, the use of coal bottom ash led to improved thermal insulation, with significant reductions in thermal conductivity observed in both mortar and concrete.

Bottom ash's high permeability and grain size distribution allow for direct contact with impervious material on experimental investigation using M20, M25, and M30 concrete grades found that 100% bottom ash replaced to fine aggregate resulted in higher compressive strength, showing its potentiality as an alternative sustainable material to conventional sand extraction done by R. G. D'Souza [49].

Anuar Abdul Wahab et al. [6] found that potentiality of bottom ash material in the production of sand cement bricks. In spite of the lower compressive strength of bottom ash contained sand cement compared to natural sand, the properties are still met requirements as per BS3921. The water absorption and porosity are more in bottom ash cement bricks than sand cement bricks and it affects the compressive strength of bricks due to light weight, but these properties are decreased uniformly as the age of testing increased.

The studies by A.V.Chitharth Kannappan and S. Venkatachalam [9] in the year 2018, on bottom ash consisting of alumina, iron, silica, and small amounts of magnesium and calcium sulphate, can effectively replace up to 30% of fine aggregates in terms of compressive, flexural and, split tensile strength. However, beyond 30% replacement, workability decreases, indicating that a 30% replacement level is optimal for achieving the desired concrete properties.

In the present work by Norlia Mohamad Ibrahim et al. [42], 'incinerator bottom ash' (IBA) from 'municipal solid waste incinerators' (MSWI) is considered as fine aggregate to produce 'lightweight foamed concrete' (LFC). A series treatment processes decreased the content of aluminium and chloride in raw IBA, which may distress the performance of concrete. At different stages of treatment, IBA chemical compositions are determined. LFC with 10% pre-treated IBA to sand achieved compressive strength similar to 'normal weight concrete' (NWC) grade C25 but the average density is about 20 kg/m$^3$, lesser than NWC specimens.

Alkali-treatment of IBA was successful as indicated by the absence of swelling effects in the concrete specimens.

Fine aggregates and cement were partially substituted with bottom ash and Alccofine by Sachdeva, A., & Sharma, A. [51], the quantity of coarse aggregate and ratio of water to cement were fixed at 1092.61 kg/m$^3$ and 0.38 for all samples. Due to irregular texture and increased interparticle friction, the workability decreased. Compressive, and flexural strengths and workability of concrete mixes increased for 40% bottom ash and up to 15% Alccofine replacements, there after decreased but (MB4AL15) surpassed that of controlled concrete (MB1). The strength and workability of concrete enhanced at all the ages with an incorporation of Alccofine as replacement to the cement.

After grinding, the porous nature of original CBA changes, pozzolanic properties allowed to use as a 'supplementary cementitious material' (SCM). Incorporating ground CBA in concrete can enhance cement hydration and mechanical properties, such as compressive strength, making it a viable pozzolanic material for sustainable construction practices that alleviate environmental concerns and address the challenges of handling and disposal of CBA, by Sajjad Ali Mangi et al. [52]

Aasif M. Baig, Valsson Varghese [01], examined the quality of foundry sand and coal ash and their application in concrete in the year 2019. The purpose of this study was to determine if it would be possible to use both of these waste materials in concrete. The results showed that CBA must be treated before being used in concrete. Because the findings of grounded CBA and WFS are comparable within their allowable range, these waste materials can be utilized in place of cement and sand. Concrete with CBA and WFS added in amounts of 10% and 6% is used for experiments; these substances can also be substituted for sand and cement, respectively.

Abdullah, Mohamad & A Rashid et al. [02], recycling bottom ash conserves natural resources like gravel, limestone and sand needed for production of cement and construction of roads since similar properties are shown by bottom ash with fine aggregates if replaced partially. As long as the contaminants or hazardous components does not exceed permissible limits, bottom ash can be used and recycled as per approved local regulations. Political support is strongly needed due to imposed strict regulations by government on hazardous materials and their potential use as recycled materials in civil engineering applications to revise and implement the current environmental act with certain exclusions which is a very long process.

Al-Fasih, Mohammed & Ibrahim et al. [05] conducted experimental research on coal bottom ash concrete to examine the impact of replacement to both cement and sand. The study included different series of mixes: one without CBA (series A), one with 20% cement replacement with ground CBA (series B), one with various percentages of CBA replacing sand (series C), and the series D is the mix of both B and C. Results showed that the series D had lower workability, but a little higher compressive strength compared to control mix and series C. Water absorption was higher in series C compared to control mix, while water permeability coefficient was lower in series D than in series C and control mix.

Lee et al. [31], conducted research on the influence of natural sand content and the water/cement ratio on the mechanical properties of lightweight aggregate concrete using expanded bottom ash and dredged soil particles (LWAC-BS). A total of fifteen concrete mixtures designed for compressive strength are categorized into three groups for 18, 24, and 35 MPa. Lightweight fine aggregates were substituted to the natural sand from 0 to 100% at 25% intervals. This led to a concrete density ranging from 1455 to 1860 kg/m$^3$. A reliable model by utilizing the test data through regression analysis used to understand the lower early-age and higher long-term strength gains of LWAC against fib model prognostications was analyzed. The results supported the need to consider the density and compressive strength of concrete to evaluate many of the mechanical properties of LWAC-BS. The natural sand content's (Rs) replacement of light weight aggregates insignificantly affected the strength gain ratio up to 7 days; however, the long-term strength gain ratio exceeded the typical values of 1.05–1.2 in normal-weight concrete. The normalized tensile capacity of LWAC-BS shows a slight increase with Rs, regardless of the compressive strength of the concrete, indicating that the replacement of natural sand increases the tensile capacity of LWAC.

In this research by Mangi et al. [38], the researchers ground CBA for varying durations from 20 to 40 hours and prepared concrete mixtures with replacement levels of 10%, 20%, and 30% by weight of cement. The workability of concrete decreased with higher quantities of ground CBA, while density decreased consistently with CBA addition, which led to excessive water absorption for all 120 concrete specimens cured at 28 days. Compressive and flexural strengths did not show significant improvement, but with 10% ground CBA, the desired compressive strength was reached, and an 8% increase in splitting tensile strength was observed with 10% ground CBA obtained from 30 hours grinding. Overall, the study concluded that ground CBA as a replacement to cement in concrete, reduces cost and environmental impact.

The investigation on fly ash bricks by Mohammed Nasser Al-Hokabi and Abdulmajeed Ali [39] for different percentages of bottom ash replacing sand to conserve natural resources and reduce coal ash in Malaysia, revealed that density, compressive and flexural strength are decreasing with higher bottom ash content, alongside an increase in water absorption ratio. Future research recommended on bottom ash replacements to focus on durability and super-plasticizer for early age strength.

Vishal S. Korde et al. [60] investigated the effects of substituting sieved coal bottom ash for natural sand on the compressive, flexural, split tensile strengths and water permeability of concrete. As the ash replacement levels increased beyond 35% by maintaining a constant water/cement ratio and slump, the results show a decrease in density and workability leading to reduced strength compared to control concrete but the ash concrete exhibits superior compressive, flexural, split tensile strength, and water permeability properties up to 35% replacement compared to the control concrete.

Arun, Singh, and Gupta [08] looked into the use of ground bottom ash in concrete in their 2020 study. Different fineness levels of bottom ash were achieved through grinding with steel balls of varying sizes and weights for different durations. SEM analysis revealed that ground bottom ash with enhanced lime reactivity showed improved strength development when incorporated into mortar mixes. The study demonstrated that grinding bottom ash enhanced its reactivity and resulted in improved performance in concrete applications.

CBA substituted to cement concrete features are analyzed by Baco et al. [10] in the year 2020 through sieve analysis, slump test, compressive, and splitting tensile strength. This investigation has led to the conclusion that, for both 7 and 28 days of curing, 25% of CBA should be used in place of cement, resulting in concrete with compression strengths of 45.2 MPa and 54.6 MPa, respectively. Furthermore, with tensile strengths of 2.91 MPa and 3.28 MPa, respectively, after 7 and 28 days of curing, the ideal percentage for tensile strength is similarly at 25% CBA.

More than one hundred research publications on coal bottom ash and environmental concerns were examined by Khairunisa Muthusamy et al. [26]. Investigated how CBA affected the mechanical characteristics of concrete such as strength and workability containing CBA. Because to the pozzolanic impact and void filling, finer CBA increased concrete strength. By using CBA in concrete, assures Sa cleaner environment is ensured, and natural river sand is preserved.

Bottom ash from coal-fired boiler in Sri Lanka was utilized by Dilukshan Sritharan et al. [15] to substitute manufactured sand in varying proportions in cement blocks, with assessments conducted at 14, 28, and 56 days. In order to evaluate the compressive strength, water absorption, and density, statistical models were devised. These models showed that, as bottom ash replacement levels increased, the blocks' density and compressive strength decreased, and their water absorption increased. According to the results, sieved coal bottom ash may replace fine aggregates up to 45% in cement blocks in order to comply with the most recent SLS regulations.

Satish Kumar Sharma et al., conducted laboratory investigations [53] to explore bottom ash as a partial substitute for sand in production of concrete blocks according to IS:2185 specifications. Concrete blocks were manufactured without fly ash and with BA, with three different BA sources replacing sand at 30%, 40%, and 50%. The study compared compressive strength, wet density, and drying shrinkage, finding a lower wet density in BA-containing blocks and drying shrinkage within acceptable limits. Blocks with 30% BA by weight for sand were deemed suitable for concrete block production.

Bottom ash at a replacement ratio of up to 5%, can enhance various mechanical properties of asphalt concrete including Marshall stability, flow, strength index, indirect tensile strength, resilient modulus, rut depth, skid resistance, permanent deformation and fatigue life, supporting its sustainable application for engineering and environmental benefits. Further exploration of different BA replacement ratios was recommended by Apinun Buritatum et al. [07] to evaluate additional mechanical properties, such as fatigue resistance and thermal cracking behavior, through field trials assessing real-world performance under traffic and environmental conditions.

Ku Muhammad Firdaus Ku Meh [31] found that coal bottom ash from the Manjung Power Plant possesses similarity to sand particles, offering a potential substitute for sand in concrete. The ash has a lower specific gravity and a higher water absorption rate than sand, but it contains pozzolanic elements and a high calcium content, which improves its cementitious capabilities and strength. More study is needed to understand the mechanical characteristics of Manjung bottom ash as a building material. The fineness modulus of coal bottom ash and sand were compared using sieve analysis tests, which revealed that the ash is similar to sand particles.

Norhaiza Ghazali et al. [41] discovered that lightweight aggregate concrete using coal bottom ash as a partial replacement for sand had lower compressive strength and durability when exposed to acidic conditions.

“A complete analysis of the uses of coal bottom ash in concrete: An Indian study” by P. V. Kiruthiga et al. [47] shown that coal bottom ash (CBA) may effectively replace sand and cement in concrete without notable loss in strength or durability properties. Grinded CBA increases its surface area and fineness, making it equivalent to cement for use as a cement alternative. Sieving is used to replace CBA as a sand alternative in concrete.
In order to replace natural crushed sand in cement-based mortars, Trong-Phuoc Huynh and Si-Huy Ngo [58] examined the engineering properties, durability, and microstructure of waste incinerator bottom ash (IBA) from Southern Vietnam. Every mortar mix was designed using a densified mixture design method that combined an empirical calculation with a detailed, step-by-step SOP. Five different IBA replacement levels (by volume) were used to create mortar specimens: 0, 25, 50, 75, and 100%. The results of the experiment demonstrate that the IBA replacement level significantly impacted the properties of mortars during both the fresh and hardened phases. In mortar specimens, it was found that increasing the IBA replacement amount improved porosity, water absorption, and drying shrinkage while lowering compressive and flexural strengths. Moreover, boosting IBA replacement level decreased resistance to sulphate attack in spite of the effects. At 56 days of curing age, all suggested mortars did, however, showed up very good resistance to chloride penetration as well as good quality, chloride ion penetration, and ultrasonic pulse velocity values ranging from 355 to 638 Coulombs and 3483–4416 m/s, respectively.

Concrete with 50% ground bottom ash (GBA) cement replacement achieved a compressive strength of about 80.9 MPa at 28 days, classified as high-strength concrete. Pattharaphon Chindasiriphan et al. [45] studied the influences of high-volume coal bottom ash as cement and fine aggregate replacements on the strength and heat evolution of eco-friendly high-strength concrete in 2023. Concrete showed a reduction in autogenous shrinkage and peak heat evolution, while autogenous shrinkage decreased as the GBA content increased. Comparing the concrete with 50% GBA to control concrete, the heat evolution of the former showed a 36.4% reduction. The high-strength concrete was defined as having a 50% ground bottom ash (GBA) cement replacement and a 60% coarse bottom ash (CBA) fine aggregate replacement. This concrete showed the largest reduction in autogenous shrinkage and peak heat evolution.

## III. FURTHER SCOPE OF WORK

Further investigation is required on the adsorption capability of dyes, pelletization efficiency, water absorption compressive strength characteristics of bottom ash for its possible utilization. In time to come, studies could look into the environmental impacts, transportation, and disposal mechanisms of bottom ash to boost its sustainable utilization in various settings. Exploring the lime reactivity and shear strength factors of Indian coal ashes might offer insights for their efficient use in construction ventures. Further scrutiny could concentrate on enhancing the mix design to boost the durability performance of LWAC with coal bottom ash to sand replacement. Added more investigations could delve into the optimization of mix designs to improve the properties of mortars and concrete with waste incinerator bottom ash (IBA) as a substitute to sand. The expenses associated with opening new landfill areas, transporting to a disposal site, and maintaining reclamation facilities will rise sharply as a result of the bottom ash accumulation. Therefore, in order to make the most of the enormous amount of bottom ash that has accumulated, plant operators should start working with industries and researchers.

## IV. Conclusions

Based on conflicting research, it was determined that the initial strength gain of bottom ash cement was smaller than that of regular cement and that the compressive strength declined as the bottom ash content increased. The rising bottom ash content brought on by the rise in water demand resulted in a decrease in cement workability. The cement's slump value was correlated with its workability. Additionally, 30% was determined to be the ideal replacement rate for bottom ash with sands. It was discovered that the flexural strength of fine aggregates used in place of bottom ash cement specimens was always lower than that of regular cement specimens. Over time, bottom ash cement increased in flexural strength, albeit not as much as control cement. Compressive and flexural strengths of fine aggregates substituted for bottom ash cement specimens are consistently lower than those of regular cement specimens. After 28 days, there was less of a difference in the strength between the bottom ash cement specimens and the control cement specimens. The percentage of fine aggregations replaced by bottom ash increases the splitting tensile strength of cement; however, the splitting tensile strength of cement increases as the curing process ages. When used as a fine aggregation in place of wasteful products, bottom ash can lower the cost of building materials while simultaneously protecting the environment. Significant amounts of bottom ash have been deposited into earth. Such material can be used in replacing of sands in concrete to make it useful in a better way. That decreases land pollution and makes it eco-friendly. This kind of replacements in huge quantity makes it economical. Even a small quantification of bottom ash using in mass concrete works result in costs reducing and effective as well as eco-friendly disposing of bottom ash. This material has worthy property to make it suitably for construction. Despite its replacement to sand in concrete in high percentage not showing strength enhancing significantly but its replacement in fewer quantities for a big construction mark it significances. Bottom ash can effectively be used along with plastics in considerable amounts to enhance strength of concrete. Bottom ash remains having moisture absorbing property, the use of waterproofing coat over the structures is necessary. The properties of bottom ash not only vary from single plant to another, but also from daily productions within single plant over durations. Therefore, these characteristics reported by researchers only can be taken as references and not absolutes. Operating parameters of power plants playing an important role validation on characteristics of bottom ash from certain sources.

As a result, as more concrete is consumed, the need for Portland cement increases because it is a necessary component of concrete construction. When it comes to sustainable construction, it is essential to create additional cementing materials from industrial waste byproducts. Coal bottom ash is one of the wastes produced by coal-based power plants. There have been numerous studies done on the use of coal bottom ash in its original form to replace natural sands in the past, but not many have been published on the use of coal bottom ash to replace cement. According to observations made through literature reviews, original coal bottom ash is porous and cannot be used to replace cement; however, after being ground properly, it has good pozzolanic properties and can be used to replace cement.

The review's findings suggest that ground coal bottom has a good chance of being used as an additional cementing material in concrete structures. This review's objective is to provide an overview of earlier research on the use of coal bottom ash as an additional binding and cementing agent in concrete structures. As a result, this article provides researchers looking for additional cementing materials in the field of advanced concrete technologists with essential information and valuable resources. Therefore, the claim that bottom ash has a great potential for use as a quality pozzolanic material is untrue. More investigation is required into the durability aspects. The use of bottom ash in the building sector would lessen its negative effects on the environment.

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