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A Comprehensive Systematic Review on the Application of Coal Ash in Bituminous Pavements

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The application of coal ash in bituminous mixes has gained significant attention in recent years due to its potential to enhance the physical & mechanical properties of asphalt mixes, which reduce construction costs and promote sustainable waste management practices. This comprehensive systematic review summarizes current research on the utilization of different types of coal ash like fly ash, bottom ash, cenospheres and boiler slag in the bituminous mixtures. The review examines the effects of coal ash on the performance of bituminous pavements like stability, durability, moisture resistance, environmental impact and cost-benefit analysis of coal ash modified mixes. Additionally, the review explores the challenges associated with coal ash usage such as variability in composition and regulatory concerns. The results from various literatures show that the application of coal ash in bituminous mixes improves Marshall parameters like stability, flow value, and resistance to rutting, with additions of up to 2-3% by volume of the mix. Further additions of 4-5% enhance resistance to moisture damage and fatigue cracking. Additionally, utilizing coal ash in bituminous mixes can lead to a 12% savings in natural material costs. Overall, the findings suggest that coal ash when appropriately processed, analyzed and utilized, can serve as a feasible alternative to conventional materials in bituminous pavement construction contributing to both economic and environmental sustainability.

Keywords: Coal ash, Fly ash, Bottom ash, Bituminous mixes, Stability, Durability, Rutting, Moisture resistance, Sustainability.

1. Introduction

The rapid industrial development and increased energy demand of the modern world have led to the generation of huge quantities of coal combustion byproducts, particularly coal ash.

Traditionally considered an industrial waste requiring safe disposal, coal ash has recently emerged as a most prominent resource in various construction applications, particularly in the production of bituminous mixtures used in road construction. The utilization of fly ash constitutes merely one-quarter of its overall generation. Leading producers such as India and China exhibit a utilization rate below 50%, whereas countries like Denmark, Italy and the Netherlands achieve a fly ash utilization rate of 100% [1]. The utilization of coal ash into bituminous mixtures offers a dual benefit; it addresses the environmental challenges associated with coal ash disposal while simultaneously enhancing the performance characteristics of bituminous pavements.

Bituminous mixtures commonly known as asphalt which are important material in road construction providing durable & flexible surfaces that withstand the traffic loads and environmental conditions. However, the increasing cost and scarcity of conventional materials such as natural aggregates and fillers have driven the search for alternative sustainable materials. Coal ash with its pozzolanic properties and fine particle size, has shown promise as an additive or partial replacement for traditional materials in bituminous mixture production.

This systematic review aims to provide a comprehensive analysis of the existing literature on the application of coal ash in bituminous mixtures. By examining the various types of coal ash, their impact on the mechanical and environmental performance of bituminous mixes and the challenges & opportunities associated with their use, this review seeks to offer insights into the potential of coal ash use as a sustainable material in road paving sector. Through this review, the main aim is to identify key trends, gaps in knowledge and future research directions to further advance the understanding and application of coal ash in bituminous pavements.

2. Coal ash types and their characteristics

Coal ash is a mineral byproduct of coal combustion in thermal power plants and is available in various forms, each with distinct physical and chemical properties that affect its suitability for use in bituminous mixtures. The byproduct of the combustion process in the absence of SO_2 mitigation particularly involving pulverized coal is consists of bottom ash, fly ash and boiler slag. The common elements found in coal ash are sodium, calcium, magnesium, potassium, aluminum, silicon, iron and sulfur [2]. This section provides a detailed analysis of the different coal ash types focusing on their characteristics and important applications in bituminous mixes production.

2.1 Fly ash

Fly ash is the most significantly studied as well as utilized type of coal ash in bituminous mixes. It is collected from the flue gases of thermal-power plants by using electrostatic precipitators or filter bags. The fly ash mainly consists of fine, shiny spheres usually less than 100 microns in diameter accompanied by coarser crystalline substances & differing percentage of unburned carbon particulate matter. This small particle size distribution enhances the workability as well as compactability of bituminous mixes [3, 4]. Fly ash collected from the flue gases amounts to approximately 75-85% of the aggregate particulate matter that exits the combustion chamber during burning [5, 6]. The chemical composition of fly ash generally has high contents of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide making it an ASTM class F pozzolanic material [7, 8]. As per the ASTM C618-22 standards [9, 10] fly ash is broadly categorized into two classes based on its chemical composition, unburned carbon content and particle sizes. Class C known as 'high lime' ash, which has certain self-hardening characteristics is mostly located in the western region of the United States, while the Class F known as 'low lime' ash, which functions as a pozzolan which is largely found in the eastern part of the United States. The types of fly ash as per IS 3812-1 [11] are Grade I which is derived from bituminous coal having fractions (SiO_2 + Al_2O_3 + Fe_2O_3) greater than 70% and Grade II which is derived from lignite coal having fractions (SiO_2 + Al_2O_3 + Fe_2O_3) greater than 50%. As per the X-ray fluorescence (XRF) test conducted by Khairul Nizar Ismail et al. [12], the physical properties of fly ash sample are shown in table 1. Also, the optimum moisture content (OMC) values for fly ashes varies from 11 to 53% and maximum dry density values ranges from 1.01 to 1.78 g/cm^3 [1]. The table 2 shows the chemical composition ranges of fly ash generally the samples from India, China, Italy, Denmark, Netherlands, United States and Europe. From table 2, it seems that the silica dioxide concentration in the fly ash produced in India (ranging from 50% to 60%) is significantly greater than that observed in the fly ash from both China and the United States (which ranges from 36% to 38%, reaching up to 57% to 58%). The Al_2O_3 content range is comparatively wider for China than for other countries listed in table 2, while for the Netherlands the range is the narrowest. The pozzolanic properties of fly ash enhance the long-term strength and durability of asphalt pavements by decreasing the permeability and increases the resistance to moisture-induced damage [7, 13]. The fly ash can replace a small portion of the fine aggregates or fillers in bituminous mixes leading to overall cost savings and enhanced performance [3, 4].

Table 1 Physical properties of fly ash [12]

Sr. No.	Physical property	Results
1	Color	Whitish grey
2	Average particle size (μm)	6.92
3	Moisture content (%)	3.14
4	Bulk density (g/cm^3)	0.994
5	Specific gravity	2.288

Table 2 Chemical composition ranges of fly ash samples from various countries

Sr. No.	Chemical composition (%)	Country						
		India [14-16]	China [15]	Italy [17, 18]	Denmark [19]	Netherlands [17, 20]	United States [15, 21, 22]	Europe [15]
1	SiO_2	50.2-59.7	35.6-57.2	41.7-54	48-65	45.1-59.7	34.9-58.5	28.5-59.7
2	Al_2O_3	14-32.4	18.8-55	25.9-33.4	26-33	24.8-28.9	19.1-28.6	12.5-35.6
3	Fe_2O_3	2.7-16.6	2.3-19.3	3-8.8	3.3-8.3	3.3-9	3.2-25.5	2.6-21.2
4	CaO	0.6-9	1.1-7	2-10	2.2-7.8	0.5-6.8	0.7-22.4	0.5-28.9
5	MgO	0.1-2.3	0.7-4.8	0-2.4	na	0.6-3.7	0.5-4.8	0.6-3.8
6	K_2O	0.2-4.7	0.8-0.9	0-2.6	na	0.6-2.9	0.9-2.9	0.4-4
7	SO_3	na	1-2.9	na	na	0.2-1.3	0.1-2.1	0.1-12.7
8	TiO_2	0.3-2.7	0.2-0.7	1-2.6	na	0.9-1.8	1-1.6	0.5-2.6

9	Na_2O	0.2-1.2	0.6-1.3	0-1	1.1-2.8	0.1-1.2	0.2-1.8	0.1-1.9
10	P_2O_5	na	1.1-1.5	0-1.5	na	0.1-1.5	0.1-1.3	0.1-1.7
11	MnO	na	nf	0-0.1	na	0-0.1	na	0-0.2
12	LOI	0.5-7.2	nf	1.9-9	3.1-4.9	2.7-8.1	0.2-20.5	0.8-32.8

[1] note: na - not available and nf – not found.

2.2 Bottom ash

Bottom ash is a coarse and unevenly shaped granular material that settles at the bottom of coal furnaces. The size of bottom ash ranges between 50.8 mm & 0.075 mm [23]. It is less reactive than fly ash but holds usable properties that make it more suitable for applications in bituminous mixtures such as it has a sand like texture with a higher specific gravity compared to fly ash making bottom ash fit for using as a fine aggregate in asphalt mixes [13]. Like fly ash, bottom ash is also rich in silica, alumina and iron oxide contributing to its pozzolanic properties [7]. The physical properties of bottom ash obtained from three different sources are shown in table 3. Bottom ash has a moisture content of 0.43%. The fineness modulus values vary from 1.5 to 3.44, while its specific surface-area values ranges between 3835.75 and 10,500 cm^2/g. The specific gravity values of bottom ash as per table 3 ranges between 1.39 and 2.41 whereas the water absorption coefficient values are between 6.8 and 32%. The chemical composition of bottom ash samples obtained from various coal-based power plants, where the chemical composition is expressed by the weight presented in table 4. From table 4 it is seen that silicon dioxide, aluminum oxide, and CaO are the primary mineral constituents in coal rock ash [24]. The porous nature of bottom ash allows for better drainage which can be advantageous in base and sub-base layers of road pavements, where its granular nature improves load distribution and provides cost-effective alternatives to natural aggregates [25]. Due to its relatively high melting point, bottom ash can contribute to the thermal stability of bituminous mixtures [13, 25]. Bottom ash has been used as structural filling materials for the construction of highway embankments, trenches, retaining walls and the backfilling of abutments. Bottom ash has been utilized as a substitute for finer fraction aggregates in base courses and hot mix asphalt wearing surfaces as well as emulsified asphalt cold mix for the same purposes. Due to the low durability and clinker-like popcorn nature of bottom ash particles, it is more commonly used in base courses than in wearing surfaces of bituminous pavements. Also, there are no reported applications of bottom ash fractions in asphalt surface treatments or seal coats [26].

Table 3 Physical properties of bottom ash

Sr. No.	Moisture Content (%) [27]	Specific Gravity [27-29]	Water Absorption (%) [29-32]	Fineness Modulus [29, 30, 33]	Surface Area (cm^2/g) [34, 35]
1	-	1.39	6.8	1.5	3835.75
2	0.43	2.41	31.58	3.44	10,500
3	-	2.22	20.15	2.71	-

Table 4 Chemical composition of bottom ash

Sr. No.	Chemical composition (%)										References
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	
1	62.33	25.52	4.16	1.00	0.94	0.08	3.2	0.84	0.12	-	[36]
2	59.82	27.76	3.77	1.86	0.70	1.61	0.33	-	-	1.39	[37]
3	58.7	20.1	6.2	9.5	1.6	0.1	1.0	-	1.0	0.4	[38]
4	68.9	18.67	6.5	1.61	0.53	0.24	1.52	1.33	-	-	[39]
5	54.8	28.5	8.49	4.2	0.35	0.08	0.45	2.71	0.28	-	[40]
6	52.5	17.65	8.30	4.72	0.58	-	-	2.17	-	0.84	[41]

2.3 Cenospheres

Cenospheres is a waste product in the composition of fly-ash burning coal in thermal power plants, as a result of complex thermochemical processes [42]. These are lightweight, hollow, spherical particles composed primarily of silica and alumina found within fly ash. They are characterized by their uniform shape and low density, making them ideal for reducing the overall weight of bituminous mixtures without compromising strength. Cenospheres constitute an average mass fraction of 0.01 to 4.80% within fly ash. They possess distinctive features, including a low bulk density ranging from 0.4 to 0.72 $g \cdot cm^{-3}$, extremely low thermal conductivity approximately 0.065 $W \cdot m^{-1} \cdot K^{-1}$ and remarkable stability when exposed to alkaline environments and higher temperatures. The size of cenosphere particles vary between approximately 5 and 500 μm [42, 43]. In terms of their chemical composition, these materials are characterized as multi-component systems, with a SiO_2-Al_2O_3-Fe_2O_3 content nearing 90% [44-46]. Cenospheres have the lowest carbon content among the coal ash types, which enhances their utility in applications where low carbon content is desirable [7]. A promising material for obtaining syntactic foam is cenospheres, hollow aluminosilicate microballoons [42]. The global market for cenospheres is valued at approximately USD 600 million per year, which corresponds to an output of 700-800 tonnes [47, 48]. The primary producers of cenospheres on a global scale include China, India, Russia, Kazakhstan and Ukraine. As a byproduct of thermal power plants operations, cenospheres is accessible at a relatively economical price [49]. Their hollow structure provides good thermal insulating properties, which can be suitable in applications where temperature regulation is critical. Cenospheres are used in some special type of bituminous mixtures where weight reduction is significant such as in lightweight asphalt pavements and overlays.

2.4 Boiler slag

Boiler slag is a byproduct of wet-bottom boilers which is glassy & granular in nature formed when molten ash is quenched in water. It is known for its angular shape and hardness. When pulverized coal undergoes combustion within a slag-tap furnace, approximately 50 percent of the resultant ash is retained within the furnace as boiler slag. Conversely, in a cyclone furnace that utilizes crushed coal for combustion, a significant proportion of 70% – 80% of the ash is retained as boiler slag with merely 20% – 30% exiting the furnace in the form of fly ash particles [50]. The table 5 shows some important physical and mechanical properties of boiler slag. From table 5 it is seen that the maximum dry density (MDD) of boiler slag is generally from 12% to 27% lower compared to that of naturally available granular materials. Also, table 6 shows the chemical composition of boiler slag obtained from West Virginia and North Dakota of United States. From table 6 it is seen that the boiler slag derived from lignite or sub-bituminous coals has a higher percentage of calcium than the bottom ash or boiler slag from anthracite or bituminous coals [26]. The angular shaped particles of boiler slag provide excellent interlocking and skid resistance in asphaltic surfaces [51]. The high hardness of boiler slag contributes to the durability and wearing resistance of bituminous mixtures. The dark color of boiler slag can enhance the aesthetic look of asphalt surfaces specially in decorative or high-visibility applications [52]. Boiler slag has also been used as an aggregate in bituminous paving application, as a structural filling [53] as well as in road base & sub-base preparations [54]. Boiler slag has been used in base courses, wearing surfaces and seal coat applications or asphalt surface treatment [26]. Boiler slag sometimes have been used as unbound fine aggregate or for stabilized base applications and as a granular base material for pavement construction [26]. The salt content and in certain instances, the low pH of bottom ash and boiler slag may result in corrosive properties. When using bottom ash or boiler slag in an embankment, backfill, sub-base or even possibly in a base course application, the potential for corrosion of metal structures that may come in contact with the material is of concern and should be evaluated prior to use [26].

Table 5 Physical and mechanical properties of boiler slag [26]

Sr. No.	Property	Results
1	Dry Unit Weight (kg/m^3) [55]	960-1440
2	Specific Gravity [55]	2.3-2.9
3	Plasticity [55]	-
4	Water absorption (%) [56]	0.3-1.1
5	Particle size distribution - No. 4 to No. 40 sieve (mm) [56]	5.0 to 0.5
6	Maximum Dry Density (kg/m^3) [57]	1330-1650
7	Optimum Moisture Content (%) [57]	8-20

Table 6 Chemical composition of boiler slag [26, 56]

Sr. No.	Chemical composition (%)	Bituminous Coal	Lignite Coal
		West Virginia	North Dakota
1	SiO_2	53.6-48.9	40.5
2	Al_2O_3	22.7-21.9	13.8
3	Fe_2O_3	14.3-10.3	14.2
4	CaO	1.4	22.4
5	MgO	5.2	5.6
6	Na_2O	1.2-0.7	1.7
7	K_2O	0.1	1.1
8	SO_2	< 0.1	< 0.1

3. Performance of coal ash in bituminous mixtures

The application of coal ash in bituminous mixtures primarily impacts the performance characteristics of bituminous pavements. This section deals with the main performance parameters that are influenced by coal ash such as stability, durability, moisture resistance environmental impact and also cost-benefit analysis.

3.1 Stability and rutting resistance

The stability & rutting resistance of bituminous mixtures is primarily affected by the addition of coal ash, mainly coal bottom ash (CBA) as a filler & fine aggregate instead of conventional materials. The research has demonstrated that utilizing CBA in bituminous mixtures can improve their performance characteristics such as stability and resistance to rutting. The study by Muhammad Kamran et al. evaluated different percentages of CBA as a mineral filler in hot mix asphalt. The results indicated that adding up to 3% CBA by volume of mix enhanced the rutting resistance, stiffness of the asphalt mixtures as well as their fatigue life. This suggests that CBA can effectively replace conventional fillers like stone dust giving a sustainable disposal method for coal ash while increasing the mechanical properties of the asphalt mixtures [58]. Similarly, another study investigated the effects of varying proportions of CBA (0%, 2%, 4% and 6%) on the engineering characteristics of bituminous mixes. The findings revealed that the CBA addition of 2% - 4% yielded the best results in terms of Marshall test parameters. The study concluded that the addition of CBA enhances the performance of asphalt mixes primarily in terms of stability and resistance to deformation under load [59]. The use of coal ash mainly fly ash, as a filler in bituminous mixtures has also been explored in other studies. For instance, Saswat Biswapriya Dash et al. investigated the performance of bituminous concrete composites utilizing fly ash as a substitute for conventional filler materials. The results showed that the modified bituminous concrete mix made with coal ash showed better performance than conventional mixes indicating that coal ash can enhance the mechanical properties of bituminous mixtures [13]. Moreover, the review by Ankita Dhiman highlighted that the various fillers including coal ash can improve the rutting resistance, stiffness & resistance to moisture of bituminous mixes. Further, the addition of fillers like coal ash makes the mix stiffer and more durable which is critical for improving the stability and resistance to rutting of pavements [60]. The study by Apinun Buritatum et al. investigated the use of bottom ash (BA) from coal-based power plants as a fine aggregate in asphalt concrete. The findings demonstrated that utilizing BA improved the Marshall stability, flow and indirect tensile strength of the bituminous mixes. The optimum BA replacement percentage was found to be 5% which resulted in improved rutting resistance and skid resistance as well as a reduction in permanent deformation & rut depth. These improvements are allotted to the efficient interaction of BA with the bituminous binder, which subsequently enhances the mechanical performance of the bituminous concrete mixes [61]. In another study CBA was used as a mechanical stabilizer in subgrade soil which indirectly supports the stability of the overlying bituminous layers. The addition of CBA improved the California bearing ratio values and reduced the swelling potential of the soil, indicating enhanced load-bearing capacity and stability. This suggests that coal bottom ash can contribute to the overall stability of pavement structures by improving the properties of the subgrade [62]. In a study conducted by Colonna P. et al. regarding the utilization of bottom ash in the composition of pavement binder course, optimal outcomes have been realized when a 15% proportion of BA was incorporated into the mixture, substituting an equivalent volume of sand. An increase in asphalt content correlates positively with enhanced wearing resistance of the composite mixes. The experimental findings suggest that there is no degradation in the mechanical properties of the asphalt mixture when compared to the traditional reference mixture [63]. Ksaibati [64] the viability of employing CBA as a total substitute for aggregates. Both coarse CBA and fine CBA were utilized in hot mix asphalt and subjected to evaluations in both field and laboratory environments. A total of three samples examined were prepared by using CBA sourced from the three distinct origins. The findings indicated that the optimal bitumen content was increased in the mixes incorporating CBA, with no discernible difference in the mechanical performance between CBA mixes and the control mix following their service period. The laboratory investigations revealed that all evaluated hot mix asphalt mixtures exhibited diverse characteristics regarding cracking at low & high temperature suggesting that the differing physical characteristics of the CBA derived from different thermal power stations may influence the integrity of the bituminous mixes [64]. Fly ash, another form of coal ash has been used as a filler substitute in asphalt concrete base courses. The performance analysis revealed that mixtures with higher percentages of fly ash exhibited better durability, with a 15% fly ash mixture showing superior performance compared to lower percentages [65]. The use of coal fly ash (CFA) as a filler enhances the mixture's resistance to rutting and fatigue, which are indirectly related to tensile strength [66, 67]. The addition of CFA in varying percentages (0%, 2%, 4%, and 6%) has been tested, with results indicating improved stability and moisture resistance, which contribute to better tensile performance [67]. Utilizing CBA as a filler-fraction substitute in asphalt mixes led to a higher rutting potential and a reduced dynamic modulus compared to control mixes [68]. Overall, the incorporation of coal ash, particularly bottom ash into bituminous mixtures can enhance stability and rutting resistance, provided that the optimal replacement ratios are identified and adhered to.

3.2 Durability and moisture resistance

The durability and moisture resistance of bituminous mixtures can be mainly influenced by the addition of coal ash, as evidenced by various studies. As per the study conducted by Kandhal and Rickards, moisture susceptibility in bituminous mixtures is a main cause of stripping which occurs when water infiltrates into the pavement, weakening the bond between the bitumen binder and aggregates. This leads to the loss of pavement materials and the formation of potholes & cracks on top surfaces ultimately necessitating costly repairs [69]. The pozzolanic properties of fly ash have been shown to improve the moisture resistance of bituminous mixtures by forming secondary cementitious compounds that strengthen the adhesion between the bitumen binder and the aggregates [70]. Research indicates that coal ash can act as an adhesion improver in bituminous mixes strengthening the resistance to moisture damage. A study evaluating coal ash as a bonding enhancement agent found that utilizing 4% coal ash in bituminous mixtures yielded moisture damage resistance comparable to mixtures containing natural fillers. The amalgamation of coal ash with lime further increases resistance to moisture damage, although the specific class of ash (Class C or Class F) did not significantly affect the results [71]. The investigations into the resistance to moisture susceptibility & fatigue cracking of asphalt mixtures using bottom ash and fly ash were conducted by Byung-Soo Yoo et al. [72]. The findings indicate that coal ash can be effectively used as fine aggregates in bituminous mixtures. The addition of bottom ash does not alter the moisture susceptibility. Concerning the resistance to fatigue cracking, the findings from the repeated indirect tensile test conducted under dynamic loading conditions indicated that asphalt mixtures incorporating 5% coal ash shows improved resistance to fatigue cracking [72]. In stone mastic asphalt mixtures, the use of class C fly ash as a filler additive has been shown to significantly improve resistance to moisture damage [73]. This improvement is likely due to the formation of hydration products that enhance the structural integrity of the asphalt. Similarly, in cold mix asphalt, fly ash when used in combination with rice husk ash as an activator, has been found to improve moisture resistance and rutting performance [74]. Another study by Huang et al. found that fly ash-modified bituminous mixtures exhibited better resistance to freeze-thaw cycles, which are a common cause of moisture-related distress in pavements. The pozzolanic reaction between fly ash and calcium hydroxide in the presence of moisture results in the formation of calcium silicate hydrates (C-S-H), which improve the cohesion within the mixture thereby enhancing its durability [75]. A study on porous asphalt concrete (PAC) demonstrated that replacing fine aggregates with bottom ash improved several key properties such as Marshall stability, indirect tensile strength and rut resistance. The optimum replacement ratio was found to be 20% which also resulted in a significant reduction in construction costs compared to conventional polymer-modified asphalt [76]. Ameli et al. [77] investigated the efficacy of bituminous mixtures containing varying proportions of coal waste ash specifically at 0, 25, 50, 75 and 100%. The CBA particles were utilized as a substitute for traditional fillers. This study assessed the resistance to rutting and fatigue behavior of the mastics as well as stability value, dynamic creep, resilient modulus and moisture susceptibility of bituminous mixes. The findings revealed that incorporating coal waste ash enhanced the fatigue character of the mixes with further improvement observed when the mixes were modified using SBS. However, the substitution of coal waste ash led to a reduction in resilient modulus, rutting characteristics, Marshall stability and tensile strength of bituminous mixes, while concurrently enhancing resistance to moisture [77]. Xu et al. [78] conducted an examination of the influence of coal waste ash which had undergone a treatment process involving reheating on bituminous mastic as well as asphalt composites. The coal waste ash was employed as a substitute in varying proportions of 20, 40, 60 and 80%. In comparison to limestone powder, coal waste ash exhibited a less density, increased alkalinity, reduced particle sizes & a greater volume of internal air voids. The bitumen that included coal waste ash demonstrated a decreased penetration value, an increased softening point and enhanced thermal stability. Nevertheless, the integration of coal waste ash led to a reduction in both the rutting resistance and Marshall stability of the bituminous composite. Conversely, the resistance to moisture susceptibility of the bituminous composite showed marked improvement with the utilization of coal waste ash. Modarres and Ayar [79] investigated the influence of incorporating coal waste powder and coal waste ash as supplementary materials in a cold recycled mixes composed entirely of reclaimed asphalt pavement (RAP) constituents, utilizing technology of emulsified cold recycling with the additives' particle sizes being less than 0.0075 cm. Incorporation of coal waste powder and coal waste ash in varying proportions of 3, 5 and 7% significantly improved the engineering characteristics of the bituminous pavement. The increased pozzolanic percentage present in the coal waste powder contributed positively to the Marshall stability, tensile strength & resilient modulus. In comparison of coal waste powder, the coal waste ash exhibited superior efficacy in terms of moisture sensitivity and improved resistance to moisture-induced damage. Results show that the CBA, when used as a fine aggregate in bituminous mixtures improves the mix's resistance to moisture-induced damage due to its angularity and rough surface texture which advances better bonding with the bitumen. Boiler slag with its hard and angular particles, has been shown to improve the skid resistance of bituminous surfaces while also contributing to moisture resistance.

3.3 Environmental impact

The long-term effects of using coal ash in bituminous mixes on environmental sustainability are complex involving both promising benefits and challenges. One of the primary advantages of utilizing coal ash into bituminous mixes is the enhancement of sustainability through waste valorization. By incorporating coal ash, the need for virgin as well as conventional materials is reduced which line up with circular economy principles and helps in mitigating the environmental impact associated with derivation & processing of raw materials [80, 81]. This scientific approach not only helps in waste management but also contributes to the reduction of landfill use thus preserving the natural resources [82]. From the technical perspective coal ash can enhance the mechanical properties of bituminous mixes. Studies have shown that coal ash can improve the compressive strength and toughness of construction materials which is needed for the longevity of pavements [83]. This improvement in the mechanical properties can lead to longer-lasting pavements reducing the frequency of repairs and associated environmental impacts over the longer time savings in the maintenance cost. However, the environmental sustainability of using coal ash in bituminous mixes is not without the challenges. One significant problem is the potential leaching of heavy metals from coal ash which could pose environmental and human health risks. While some studies have indicated that the concentration of heavy metals in coal ash mixtures is below regulatory limits, so to ensure the safety continuous monitoring and stringent testing are necessary [83]. Moreover, the life cycle assessment (LCA) of using coal ash in bituminous mixes shows mixed results. While the application of coal ash can reduce global warming problem and fossil resource scarcity, it may also increase the overall consumption of natural or fossil resources due to higher bitumen content requirements in some cases [80]. Sustainable pavements using recycled materials, including coal ash, can reduce energy consumption and emissions by about 45% compared to traditional asphalt pavements [84]. This highlights the need for a balanced approach that signifies both the environmental advantages and prominent drawbacks. In terms of long-term environmental sustainability, the use of coal ash in the bituminous mixes presents an optimistic opportunity to improve the sustainability of road construction. However, it requires careful consideration of the environmental impacts throughout the material’s life cycle. The integration of coal ash should be associated by comprehensive environmental assessments and according to regulatory standards to minimize any adverse effects during the utilization of it. In conclusion, while the use of coal ash in bituminous mixes offers significant potential for improving environmental sustainability by reducing waste and saving natural resources, it also necessitates careful management of potential environmental risks. Ongoing research and development along with vigorous environmental monitoring are essential to fully realize the benefits while minimizing any negative impacts [80, 81, 83].

3.4 Cost-benefit analysis of coal ash in bituminous mixtures

The cost-benefit analysis of incorporating coal ash in bituminous mixtures reveals both economic and environmental advantages. Coal ash, a by-product of coal combustion, can be effectively utilized in construction materials, particularly in bituminous mixtures, to enhance their properties while addressing waste disposal issues. This analysis considers the economic savings, environmental benefits and technical feasibility of using coal ash in bituminous mixtures.

3.5 Economic benefits

Utilizing coal ash in bituminous mixtures can lead to significant cost savings. For instance, the application of CBA as a microfiller in cement concrete can reduce production costs by up to 3.6% due to decreased cement consumption [85]. Similarly, the use of pond ash in pavement construction can achieve direct cost savings of around 10% [86]. By replacing conventional materials with coal ash, the acquisition and disposal costs are reduced. This is particularly beneficial in highway construction, where the use of ash as a replacement for mineral filler in hot-mix asphalt concrete saves material costs up to 12% [87]. The construction of asphalt necessitates a substantial quantity of naturally available aggregates, specifically 100% aggregates for the sub-base & base layers, 95% for bituminous paving layers, and 87% for cement concrete pavements. The amount of natural aggregates required to build one kilo-meter of a surface layer employing an asphalt mix may surpass 15,000 metric tons [88]. In contemporary times, the substitution of natural aggregates with coal bottom ash has led to a decrease in construction expenses and diminished the necessity to extract aggregates from ecological resources.

3.6 Environmental benefits

The incorporation of coal ash in bituminous mixtures helps in managing the disposal of this waste product, thereby reducing environmental pollution. The utlization of coal ash in construction materials prevents the harmful effects of ash disposal on land, air and water [89, 90]. By substituting coal ash for natural aggregates, the demand for mined resources is decreased, leading to conservation of natural materials and a reduction in the environmental impact of resource extraction [91, 92]. By substituting coal ash for traditional materials, there is a reduction in CO_2 emissions associated with the production of these materials. This contributes to a more sustainable construction practice [90]. The use of waste biomass ash in bituminous concrete mixes has been shown to be 62% more environmentally friendly compared to conventional mixes, highlighting the potential for significant environmental benefits [93]. CBA represents an eco-friendly resource capable of mitigating detrimental ecological effects while fostering sustainability in the manufacturing of concrete [94].

3.7 Technical feasibility

Coal ash enhances the engineering properties of bituminous mixtures. The cementitious properties of coal ash contribute to improved strength and durability of the mixtures [95]. Additionally, coal ash has shown good technical feasibility in asphalt mixes, maintaining mechanical performance comparable to traditional materials [96]. Studies have demonstrated that coal ash can be effectively used as a filler in bituminous paving mixes without compromising the desired properties. For example, fly ash used as a mineral filler in bituminous paving mixes meets the required specifications and offers a viable alternative to traditional fillers [97].

4. Challenges and Future Research Scope

While the applications of coal ash in bituminous mixtures offers several advantages, there are also some challenges that must be ad dressed to ensure its successful utilization. One of the primary challenges in using coal ash is the heterogeneity in the chemical and physical properties. This variability can affect the consistency and performance of the prepared bituminous mixtures. The best solution is numerous blending of coal ash from different sources or with other materials, which can help achieve more consistent and stable properties. Secondly, the use of coal ash in construction is subject to regulatory surveillance, mostly concerning environmental impact and human health. The perfect solution is to implement accurate rigorous environmental monitoring programs to track the long-term impact of coal ash in bituminous pavement mixtures.

Current research is important to explore new applications of coal ash and enhance its performance in bituminous mixes. The following are the important points one needs to consider regarding future research.

1. Investigating the microstructural properties of coal ash and their influence on asphalt performance.

2. To study the coal ash utilization in dense bituminous macadam along with some natural or conventional fibers.

3. Exploring the use of coal ash in innovative asphalt technologies, such as warm-mix asphalt and porous pavements with some additives.

4. Conducting comprehensive lifecycle assessments to quantify the environmental and economic benefits of using coal ash in bituminous mixtures.

5. To achieve a higher degree of environmental sustainability, it is necessary to investigate the application of coal ash at a rate of 15 to 20% in bituminous road pavements.

5. Conclusion

The utilization of coal ash in bituminous mixtures represents a promising strategy for the advancement of sustainable road construction methodologies. By capitalizing on the distinctive characteristics of fly ash, bottom ash, cenospheres and boiler slag, civil engineers can significantly improve the performance attributes of asphalt pavements while concurrently mitigating environmental impacts. From an extensive review of the literature, it has been determined that the integration of coal bottom ash within a range of 2% to 4% yields optimal outcomes in terms of density, stability, stiffness and flow characteristics for bituminous pavement applications. In addition, the ideal ratio for bottom ash and fly ash substitution was determined to be 5%, which led to improved resistance to rutting and skidding, alongside a decrease in permanent deformation and rut depth. The pozzolanic attributes of fly ash have demonstrated the capability to enhance the moisture resistance of bituminous mixtures by generating secondary cementitious compounds that fortify the adhesion between the bitumen and the aggregates. Cost-benefit analysis of coal ash modified blends shows that up to 12% saving in the material cost while producing hot bituminous mixes and 50% reduction in CO_2 emission while producing cement concrete materials which ultimately leads to sustainable pavement construction practices. It is observed that limited researchers studied the use of fly ash and bottom ash combinedly in the bituminous pavement beyond 15%. Also, the combined use of fly ash as filler and bottom ash as fine aggregates in dense bituminous Macadam is rarely studied along with suitable fibers which needs in depth exploration. Nevertheless, challenges such as the heterogeneity of coal ash composition and regulatory issues necessitate resolution through ongoing research, standardization efforts and rigorous environmental monitoring. As the construction sector increasingly emphasizes sustainability, coal ash possesses the potential to assume a crucial role in the formulation of more ecologically responsible and resilient infrastructure systems.

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