Review Article

Effective Use of Waste Materials: A Case Study of Utilization of Fly Ash in Flexible Pavement Structures

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Generation of energy through thermal processes is still dominant in many parts of the world. One of the by-products of this process is fly ash, whose safe disposal incurs monetary and environmental costs. To mitigate this issue, the utilization of fly ash as a construction material has been increasing remarkably; however, evaluation and summarization of its use in pavement construction are not very common. This study reviews its utilization in construction from different aspects and attempts to fill the gap within the literature with a critical review of fly ash usage in pavement construction engineering for the last few decades. Further recommendations have also been suggested in this context. Class 'C' fly ash is used for soil stabilization, and class 'F' is used in concrete. A review of the literature found the following results. The application of fly ash in both flexible (asphalt) and rigid (concrete) pavements is common in the form of a filler material. However, this paper only focuses on its use in flexible pavement layers. In the case of flexible pavement, fly ash is used or can be used in surface, base, and sub-grade layers. The surface layer is made up of concrete, wherein it can be used as a mineral filler or as a partial replacement of asphalt. The most common types of tests performed on asphalt concrete are Marshall stability and tensile strength. However, there is a lack of field testing studies on asphalt concrete modified with fly ash. As for the other layers of flexible pavement, fly ash has been used with activators for their stabilization, as these layers are made up of natural compacted materials. Fly ash has shown promising results when used with cement, with both used within a proportion of 10%. The future research areas identified through this review are the modeling of pavement layers modified with fly ash and the standardization of fly ash properties for use in pavement layers.

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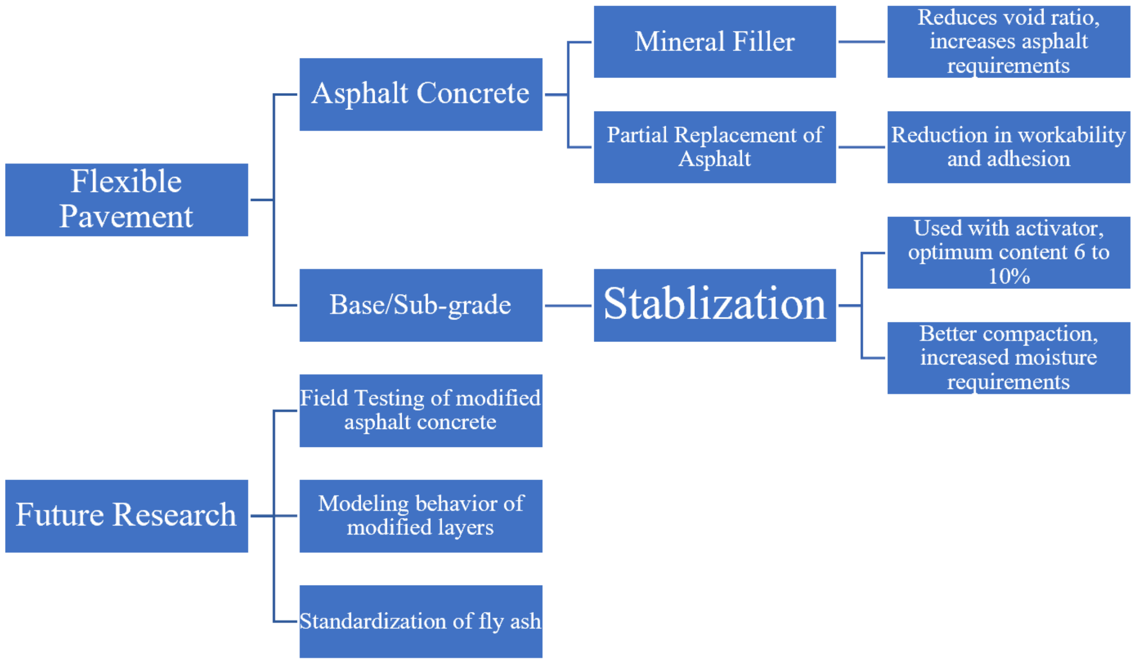
Graphical Abstract



Introduction

Thermal power generation plants fueled by pulverized coal are commonly used in developing, as well as developed, countries. These plants produce fine mineral fly ash and bottom ash as waste materials [1], and the disposal of these residual materials is a major environmental concern. A trade-off must be made between increasing energy production and following stringent air quality standards. In addition, the appropriate disposal of this residue incurs extra costs, and thus affects the financial feasibility of these projects [2]. Hence, it is imperative to identify and explore the possible applications of fly ash, which is cheap and has negative impacts if not utilized. For these reasons, the use of fly ash has been explored by many industries and sectors, including construction, agriculture, and manufacturing [3].

Since fly ash is a pozzolanic material, it has been widely used in civil engineering applications [4]. It has been used in conjunction with traditional materials such as cement concrete, asphalt concrete, and soil [5]. Pandian [6] and Ahmaruzzaman [7] have listed various properties of fly ash that make it suitable for use as a construction material. These properties include its adsorption, low unit weight, high drainage ability, and ease of compaction.

Properties of Fly Ash. The properties of fly ash depend on coal composition, combustion conditions, emissions control, by-product storage, handling, and climate. The common size distribution of fly ash ranges between 2µm and 50µm. It consists of three major mineral matrices: glass, mullite-quartz, and magnetic spinel [8].

The main elements of fly ash are aluminum, silicon, and oxygen, with small quantities of Potassium (K), Calcium (Ca), Iron (Fe), Titanium (Ti), and Carbon (C). The bulk density of fly ash is in the range of 0.7gm/cm^3 to 2.45gm/cm^3, which is equal to or higher than ordinary cement [9]. This composition makes fly ash non-reactive and suitable for the replacement of other civil engineering materials like cement.

Classes of Fly Ash. Based upon the proportions of its chemical constituents, fly ash can be classified into class 'C' and class 'F'. Although researchers have not limited themselves to this classification, as will be shown in the proceeding sections, these classes are most widely referred to by researchers. The prime difference between the classes is the proportion of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). Class 'C' contains approximately 60% (38% and 19%), while class 'F' contains 80% (55% and 25%) of these elements. Class 'C' is used for soil stabilization, while class 'F' is used in applications with concrete [10]. The detailed composition of each type of fly ash is shown in Table 1.

Compound	Class C	Class F
SiO_2	20.7	55.23
Fe_2O_3	32.0	10.17
Al_2O_3	9.01	25.95
CaO	27.1	1.32
K_2O	2.51	1.59
Na_2O_{eq}	1.00	1.59
SO_3	1.61	0.18
MgO	2.05	0.31
LOI	2.97	5.25

Table 1. Chemical composition of Class C and F as a proportion of their weights [11]

Seyrek [12] mentioned that class 'C' suits the soil stabilization process because of its rapid hydration property. This helps in gaining strength without any delay or use of an activator, which is not the case with class F, which requires an activator, such as lime [13]. There are other effects reported for the application of this type of fly ash for soil stabilization, which will be discussed in the relevant sections. On the other hand, class F is reported to improve interfacial zone microstructures and reduce the alkalinity of cement concrete [14].

The difference in their composition is due to the process and the primary material from which they are made. Class 'C' is produced by burning anthracite or bituminous coal, while class 'F' is produced from lignite or sub-bituminous coal; the former class exhibits pozzolanic properties, and the latter possesses cementitious properties [15]. This change in properties dictates their applications in different fields of civil engineering.

Applications of Fly Ash. The use of fly ash in concrete started in the very early stages of the 20th century because the production of ordinary Portland cement was expensive and environmentally unsustainable. Consequently, reviews were conducted in the past on evaluating the use of fly ash in concrete, such as that done by Das et al. [16]. These studies emphasized the fact that the use of fly ash increases the workability of concrete as well as its strength and durability. According to Ahmaruzzaaman [17], in addition to the above advantages, fly ash also increases resistance to shrinkage, improves the setting/hardening time for concrete, and can also be used as an air-entrainment admixture in concrete.

A review of the current literature shows that review efforts have already been undertaken successfully with regard to the use of fly ash in concrete structures, which show clear and solid conclusions. However, there is a need to extend the current literature to the use of fly ash in pavement structures, which is an important part of national infrastructure. Moreover, pavements have different load applications, support, and exposure mechanisms, so the findings of the review from concrete structures cannot be applied to them directly. This instigated the idea for the current study. Fly ash is primarily used in pavements as a replacement for mineral filler in asphalt concrete and for the stabilization of the base/sub-grade [18]. These materials are mostly used in infrastructure construction and constitute a major part of project costs. Various properties of asphalt concrete and base/soil materials modified with fly ash have been investigated and compared with conventional materials as well as with other modifications. Hence, it seems important to collect all the available knowledge in this area to increase the awareness of researchers, academicians, industries, and students, as well as to recommend future directions of research.

Research Significance

Considering the wide application of fly ash in civil engineering, it is important to integrate the research efforts carried out in this area. Fly ash is reported to be more frequently used in three materials, namely, cement concrete for buildings and rigid pavements, asphalt concrete, and aggregate or subgrade layers [19]. This study provides a comprehensive review of the use of fly ash in an important area of civil engineering, i.e., flexible pavement construction. Figure 1 shows the main parts of a flexible pavement structure, with which the present study is concerned.

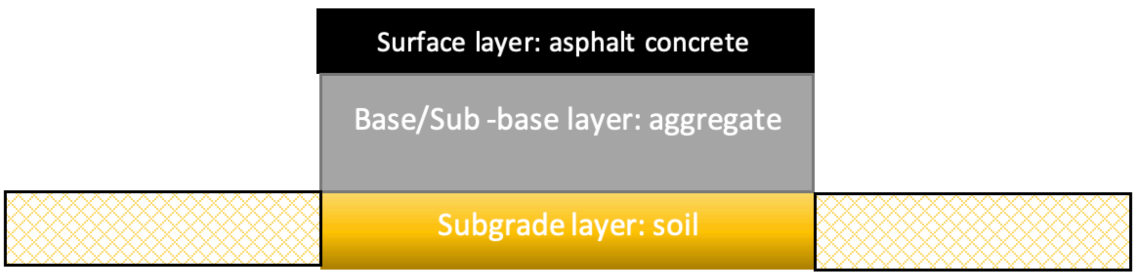


Fig. 1. Flexible Pavement Structure

Based on the review, future applications and research areas pertinent to fly ash for pavements have been recommended. This research is expected to be beneficial for researchers, students, and civil engineering professionals by familiarizing them with the use of this unconventional material. It is also supposed to encourage and initiate future research and use of fly ash in highway construction projects.

Use of Fly Ash in Asphalt Concrete

Asphalt concrete is used in the top layer of flexible pavement, which is the costliest and the most frequently maintained layer of pavement [20]. This layer is subjected to direct wear and tear from vehicles and the environment [21]. Hence, it has been a subject of study for many researchers. Changes in the configuration of asphalt concrete with indigenous materials have been employed to improve its properties [22][23]. Fly ash has also been tried by many researchers as a replacement for asphalt and mineral fillers. The following sections provide a brief overview of these research efforts.

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Fly Ash as Mineral Filler. Many researchers have investigated the use of fly ash for Hot Mix Asphalt (HMA), mainly as a mineral filler. For example, Henning [24] investigated the effects of using fly ash from different sources and made a comparison with hydrated lime as the mineral filler. The comparison was made based on air-void ratios and resistance to water. He concluded that the use of fly ash, irrespective of its source, gives better results in terms of the tested parameters as compared to lime.

Rosner et al. [25] compared fly ash with other fine materials, including lime, Portland cement, and chemical anti-strip agent. They found that the addition of fly ash at 6% of the aggregate weight gives the best performance. It was also observed that the addition of fly ash reduces the asphalt requirement and the voids in the mineral aggregate. Moreover, the addition of fly ash for strip resistance (moisture damage) was comparable to that of any other anti-strip agent used in their study.

Ali et al. [26] conducted a study to evaluate the effects of using different percentages of fly ash. The comparison was made of mechanical properties and pavement performance in terms of water damage, stripping, and rutting. These researchers concluded that fly ash can improve the mechanical properties of asphalt concrete in terms of resilient modulus and moisture damage. However, no significant improvement was observed in terms of resistance to pavement distress and the present serviceability index. In addition, they predicted that pavement resistance to cracking will deteriorate over the long term (10 years).

Asi and Assa'ad [27] conducted a study to evaluate the use of fly ash in different proportions. They based their results on the mechanical properties of HMA, including Marshall stability, tensile strength, and resistance against pavement failures such as fatigue, creep, and stripping. It was found that the use of fly ash has a positive effect on strength and water sensitivity. Moreover, the best results for its mechanical properties were obtained at 10% replacement. However, it was also reported that the filler should be replaced by 50%-100% fly ash to show significant performance against pavement failure.

Tapkin [28] conducted a study to evaluate the effects of using different types of fly ash as a filler in asphalt concrete. He used type 'C' as well as type 'F' fly ash from three different sources. He compared specimens of asphalt concrete using both types of fly ash, Portland cement, lime, and calcareous aggregates. The comparison was made based on mechanical properties, namely Marshall stability, flow, and fatigue life of asphalt concrete. He concluded that the use of class 'F' fly ash with a coarser particle size, compared to that of other fillers studied, provided the best results in terms of all the above parameters.

Another study by Reyes-Ortiz et al. [29] determined the response of HMA in terms of tensile strength and energy parameters. These researchers conducted experiments by replacing mineral filler with fly ash, cement, and lime. This study concluded that the replacement of filler with lime yielded the best results in terms of strength as well as energy. However, the use of fly ash produced better tensile strength in specimens than cement. They also recommended exploring the use of energy parameters for field implementation in determining optimum asphalt content. Sobolev et al. [30] found that the use of fly ash as a mineral filler has been reported to result in higher resistance against cracking and oxidative ageing.

Modarres and Rahmanzadeh [31] used natural coal waste from a coal washing plant as the mineral filler in HMA. Stability, resilient modulus, and tensile strength of the samples were tested. Standard samples with lime as the mineral filler, samples with fly ash as filler, and samples with equal amounts of lime and fly ash as the filler were prepared. Fly ash was tested as part of this study and was reported to show pozzolanic properties; therefore, it can be categorized as class 'C' even though it was not reported as such by the authors of the study. The study showed that samples with fly ash had better characteristics than the other samples in terms of stability, resilient modulus, and tensile strength. However, the use of fly ash with lime, in equal proportions, showed high water resistance. Adding to that, they mentioned that the preparation of coal waste ash may incur extra costs if prepared solely for this purpose. This further reinforces the point that fly ash produced from coal-powered thermal plants is economically more feasible.

Muniandy et al. [32] examined the effect of different by-product waste fillers, including ceramic waste dust, fly ash, limestone dust, and steel slag, on the engineering characteristics of fine mastics and stone mastic asphalt. The study showed that adding these fillers to stone mastic asphalt improved its properties. It was observed that using a filler size proportion of 50/50 yielded the best results in terms of stability, Marshall quotient, and resilient modulus. Although the research concluded that ceramic waste dust and steel slag were the most effective fillers, fly ash still had a good impact.

Experimental research done by Mirkovic et al. [33] tested asphalt samples consisting of three distinct types of fly ash with 25%, 50%, 75%, and 100% mineral filler substitution. The study focused on determining the samples' volumetric composition, stability, flow, water sensitivity, and resistance to permanent deformation. It was concluded that an adequate volumetric composition can be obtained with the addition of fly ash. Moreover, the stability of asphalt improved after the addition of fly ash up to 16%, while the flow decreased to 40%. The maximum stability recorded was 11.8 kN with 75% filler substitution using fly ash class F. The results also indicated that the effect becomes more detectable at higher temperatures, and accordingly, the researchers recommended the use of fly ash as a filler in warmer climates. Further, the samples showed good resistance to permanent damage, making it suitable for rut-resistant asphalt surface courses.

Onyelowe et al. [34] studied the effect of utilizing fly ash as a modifier and crushed waste glass as fillers on the mechanical properties of asphalt pavement. During the study, three different samples – asphalt, asphalt mixed with fly ash, and asphalt mixed with fly ash and crushed waste glass - were prepared and analyzed according to the Marshall stability test's procedure. The results obtained indicated that at 15% weight addition of fly ash and 8% of crushed waste glass, the stability of asphalt increased from 216 N/mm^2 to 224.2 N/mm^2. In addition, the researchers concluded that when fly ash was added to asphalt, enhanced rheological and performance characteristics were detected at a lower cost and with less unfriendly environmental effects.

Other Uses of Fly Ash in Asphalt Concrete. Churchill and Amirkhanian [35] extended the use of fly ash by using it as a replacement for fine aggregates. Fly ash was used from different sources and in different proportions of fine aggregate. Short-term tensile strengths and tensile strength ratios of the samples were obtained. In addition to using fly ash, a comparison was also made with samples prepared with hydrated lime. It was found that the use of fly ash had a detrimental effect on the short-term strength of the pavement. However, these researchers advocated the use of fly ash, based on the premises that it is available at low cost and does not affect the soil properties in terms of its metallic components.

Suheibani [36] investigated another application of fly ash, which he termed as "asphalt extender". He used fly ash as a replacement for asphalt in HMA in varying proportions (10%-40% of asphalt weight). Another dimension to this study was an investigation of the effect of using different sizes of fly ash in the specimens. He concluded that, although all gradations of fly ash are suitable replacements for asphalt, medium-sized particles presented the best results. Sobolev et al. [30] also proposed a modified asphalt mix referred to as ASHphalt. Class 'C' as well as class 'F' fly ash were used as replacements for asphalt binder. The replacement percentages were 5% and 60%. The stiffness of samples with varying percentages and types of fly ash was observed. It was concluded that the usage of fly ash increases the stiffness of samples. Moreover, it was further claimed in their research that the use of fly ash as a replacement for asphalt binder in the mix does not affect its workability. Hence, this modification can be applied in the field using standard construction techniques. In addition, a change in pavement elastic modulus at 10% replacement of asphalt binder was also reported. They recommended further exploration in terms of stiffness and strength by varying the percentages of replacement at smaller intervals (between 5% to 60%, such as 10, 20, 30, etc.).

Al-Osta et al. [37] studied the effects of heavy fuel on asphalt concrete as a mineral filler as well as a binder replacement. The former was replaced by 50%, while the latter was replaced by 3% and 5%. They observed that the use of this type of fly ash improves stiffness and fatigue. However, it was recommended to use an anti-stripping agent with the modified mixes to avoid moisture damage.

Wahhab et al. [38] investigated the effects of chemically treated fly ash in asphalt concrete. These researchers observed that the said modification improved split tensile strength (11%), resilient modulus (25%), fatigue life (1400%), and caused a reduction in rutting (55%).

FHWA Standards. The use of fly ash in asphalt concrete pavements has been realized by researchers as well as transportation organizations. This is the reason that the Federal Highway Authority (FHWA) has periodically developed, reviewed, and published standards for the application of fly ash in asphalt concrete pavements. The first report in this regard was published in 1986, which contributed to the increase in fly ash usage in pavement construction.

An extension of this effort was published in 2003 in report FHWA-IF-03-019. This report specifies the use of fly ash in pavement from all aspects, including HMA, stabilized soils, joint fillings, and concrete slabs. In addition, this document discusses the testing, handling, and mixing procedures for the use of fly ash in pavement construction [39].

The results of further experimental work conducted by FHWA were published in 2012 in report FHWA-RD-97-148. It was prepared because of experiments performed on different types of fly ash by FHWA. This report focused on the use of fly ash as a mineral filler in HMA. It reported that the use of fly ash as a mineral filler provides resistance against stripping and delays the hardening of asphalt concrete. The report also stated that normal design and construction procedures are applicable to asphalt concrete pavements modified with fly ash as a mineral filler [39].

Effects of Fly Ash on Asphalt Concrete. Fly ash has been used more commonly as a mineral filler in asphalt concrete, and its other uses in this regard include being a replacement for fine aggregate and asphalt binder. The following observations can be made based on the above review:

1. Fly ash has a positive impact on the void ratio and water sensitivity of asphalt concrete, and the use of coarser particles may also increase its strength when used as a replacement for asphalt binder.

2. When used as a replacement for fine aggregate, fly ash does not show promising results in terms of its strength.
3. Fly ash may prove to be beneficial in the rehabilitation of asphalt concrete pavements by stabilizing the existing pavement course with fly ash using the cold-in-place method.

Another potential issue that has been discussed in the literature is the changes in construction techniques required to incorporate the modification of asphalt concrete with fly ash. In that respect, Zoorob and Caberera [40] discussed in detail the design and procedure for the construction of HMA pavements with fly ash as a filler. FHWA standards can also be referred to in this regard. However, it has been observed that fly ash modification does not require drastic changes in terms of construction techniques.

Use of Fly Ash in Base Layers

Base layer(s) play an important role in providing the required strength to the pavement and in the distribution of vehicle loads to the subgrade. Hence, they are considered during the mechanistic-empirical design of flexible pavements [41]. Arora and Aydilek [42] used class F fly ash for the stabilization of the base layer. They used cement and lime as the activators, with fly ash, due to its lack of self-cementing ability, which would be vital for stabilization purposes. Their study was conducted on sandy soils with a fly ash content of 40%. They measured the strength of samples in terms of resilient modulus, California Bearing Ratio (CBR), and unconfined compressive strength. Their study found that the strength of the soil increases with cement content up to 5%. Lime treatment had a detrimental effect on the strength of samples, although samples with lime treatment survived the freeze-thaw cycles.

Lav et al. [43] used class F fly ash, mixed with cement, as an aggregate-free base layer. They found that these layers should not have a cement content of less than 8%, while the pavement thickness should not be less than 300mm; otherwise, these layers should be used as a sub-base. They found an increase in dynamic modulus and pavement thickness with respect to the increase in cement content. The maximum cement content was 10%, while the maximum thickness was found to be 500mm.

Saride and Jallu [44] used three different types of fly ash with reclaimed asphalt pavement base layers. Their samples consisted of virgin aggregates, a liquid alkaline activator ($Na2SiO3:NaOH$), and fly ash. They found that the optimum proportion of elements in the alkaline solution is highly dependent upon the reactive potential of fly ash. Their study also attempted to recalibrate the layer coefficients for the base layer with the mixtures prepared in their research.

Barstis and Metcalf [45] conducted a field study on the comparison of lime fly ash stabilized base layers with traditional base layers. Pavement cores were cut to obtain the samples at different stations, and their thicknesses and dynamic moduli were compared. They found that the variation in these parameters for the stabilized layers was higher and attributed it to the compaction effort. They suggested increasing the compaction effort to 100% of the standard Proctor value.

Cetin et al. [46] pointed out an important issue with the use of high-carbon fly ash, which is the leaching of metals. They conducted field tests on pavements in which fly ash was used with an activation agent (lime kiln dust). They found that an increase in the content of fly ash, the activation agent, and the pH value has a significant effect on leaching heavy metals.

Pai et al. [47] used a steel-slag, fly ash, and lime mix in proportions of 75:19:6 in the base layer of the pavement, which was tested in the field. Firstly, an unconfined compressive strength test was used in the lab for determining the stiffness and, consequently, the required thicknesses of the base layer with this material. Thicknesses of 150 and 250mm were employed in the field and tested using a falling weight deflectometer. A comparison was made between the proposed mixture of steel-slag, fly ash, lime, and wet mix macadam. It was found that the proposed mix increased the service life by 2.6 times and reduced the cost by 15%, in comparison to the wet mix macadam.

Nguyen and Phan [48] used cement and fly ash in base layers in varying proportions. 8% and 10% cement contents were used, while fly ash varied from 2 to 6% with 8% cement content. They used unconfined compressive strength and splitting tensile tests, along with non-destructive techniques, to observe the behavior of the base layer. A sample with 8% cement content and 2% fly ash was found to have a tensile strength of 0.45MPa, which is enough to be used as a base layer according to local Vietnamese standards. However, they also found that compressive strength, tensile strength, and elastic modulus further increased when cement content was increased to 10% without the use of fly ash.

Khan et al. [49] have used over-burnt clay as the base layer in pavement, which was stabilized through cement and fly ash. They found that a cement content of 6% (of aggregate-fly ash mix) gives suitable strength and durability to be used as a base layer, while if this content is 7%, then it can be used as a sub-base.

Fly ash has also been used to stabilize base layers for the construction of new pavements and for the rehabilitation of old ones. Crovetti [50] identified the need for using fly ash as a stabilizer in Cold-in-Place Recycled Asphalt (CIPR) for pavement rehabilitation. In a similar study, Wen et al. [51] utilized class 'C' fly ash to develop a stabilized base course for the rehabilitation of asphalt pavement. They mixed fly ash with CIPR for this purpose. Deflection under repetitive loading was observed for the pavement structure obtained with this base. Then, layer coefficients were back-calculated using the deflection values, and it was found that a fly ash-stabilized and recycled base has a better layer coefficient than crushed aggregate material.

The above review clearly shows that researchers have essentially used activators with fly ash for the stabilization of base layers. The content of fly ash and activators has been under 10%, and cement has generally been the preferred activator in this case. The use of fly ash, with an activator, has been reported to increase the layer modulus and, consequently, provide an economical and long-lasting design.

Use of Fly Ash in Soil Stabilization and Improvement

Soil is an integral foundation material for civil infrastructure and is mainly categorized as coarse-grained (sand and gravel) or fine-grained (silt and clay) [50]. The evaluation of soil properties provides a practical understanding of its stability and durability. Infrastructure assets such as buildings, pavements, dams, bridges, and retaining walls exert pressures on soil. These structures are built on different strata of soil, and this causes stability and strength issues. Pavement layers are based on several types of soils from subgrade to base, and it is necessary to densify the base and sub-base layers of soil to produce strong pavements. Stabilized soils are composite materials in which natural soil is reinforced with other materials to enhance its engineering properties [51]. In contrast, the construction of infrastructures on clayey soil leads to consolidation and affects the shearing strength of the soil, due to which the structures may fail, or their durability may be affected [52]. Similarly, earthen embankments experience erosion due to permeable layers of soil. It is necessary to stabilize the soil to control these issues [53].

Several ways exist to stabilize the soil, including grouting, injection, soil reinforcement, and the application of geotextiles [53]. Soil can be chemically stabilized with lime, cement, and/or fly ash used in isolation or in combination [54]. The use of cement in soil compaction is a more expensive method than the use of lime and fly ash. Amiralian et al. [55] reported that the effects of lime on soil compaction parameters were not sufficient compared to other binders such as fly ash. Therefore, it can be said that fly ash gives appropriate results for soil compaction and strength in contrast to lime and cement at a lower cost. Fly ash is a by-product of coal combustion and exhibits more cementitious characteristics. Fly ash also has high fineness, which decreases the porosity and pore size and increases the compressive strength. Therefore, fly ash is now being widely used as an additive material in soil to improve the soil's mechanical properties.

Reasons for Using Fly Ash in Soil. Fly ash, a by-product of coal burning, can enhance the stability of bases or sub-grades in backfills, as well as reduce lateral earth pressures. It can also improve slope stability in embankments [56]. Over the years, different researchers, including [57][58], have conducted various studies on the use of fly ash for soil stabilization. These studies demonstrate the efficacy of fly ash in stabilizing fine-grained soils. However, the geotechnical properties of fly ash for stabilization with soil or other binding materials can vary widely. Bose [59] found that fly ash shows promise in enhancing the engineering properties of expansive soil. Similarly, Takhelmayum et al. [60] have proven that the addition of fly ash can enhance soil strength.

Effects of Fly Ash in Soil. Several studies have been conducted on fly ash and soil composites, and most of the researchers observed the effect of fly ash with different types of soil. For example, Takhelmayum et al. [60] showed improvement in the strength characteristics of soil with the addition of coarse fly ash. Consoli et al. [61], Phani-Kumar and Sharma [62], and Senol et al. [63] reported the effectiveness of fly ash in improving the properties of soil. These studies highlight the fact that there is a vast scope for the utilization of fly ash as an additive in the improvement of the geotechnical properties of soil. The literature review below presents a brief account of recent studies on soil stabilization and improvement using fly ash. However, there has been concern shown over the leakage of mobile metals in fly ash to the soil. Cement-chelated solidification has been recommended as an effective approach to immobilize these heavy metals [64].

Sharma et al. [65] observed that the addition of fly ash increases the maximum dry density and decreases the optimum moisture content. This trend continues up to a certain fly ash content, which was referred to as the "optimum fly ash content," and then reverses beyond this optimum level. Based on unconfined compressive strength tests, Brooks [56] found that failure stress and strain increased by 106% and 50%, respectively, with the addition of fly ash from 0% to 25%.

Sumesh et al. [66] analyzed the use of fly ash to minimize environmental pollution issues in certain civil engineering projects, such as the construction of highway embankments and pavements, and the backfilling of retaining walls. The results from unconfined compression tests demonstrated that the percentage increase in fly ash content in fly ash-soil mixtures leads to a decrease in dry density due to the low specific gravity of fly ash. Moreover, the addition of cement to soil-fly ash mixtures increases the unconfined compressive strength (UCS) and the brittle behavior of these mixes.

Okonta et al. [67] conducted research on mixing residual sand with lime and fly ash by performing UCS tests and California bearing ratio (CBR) tests on the soil samples. Sand samples were collected from the coastal plain and identified that the coastal soil was weak and unconsolidated. The main objective of this study was to investigate the durability of compacted lime and fly ash as a replacement for fines. The maximum dry density of sand was 18.08 mg/m3 at 10.2% moisture content, and the addition of lime and fly ash led to an increase in the optimum moisture content and a decrease in dry density. These researchers concluded that 8% lime with 18% fly ash was adequate for maximum shear strength values. Moreover, the CBR of the stabilized mix was found to increase when the content of lime and fly ash increased.

Hu et al. [68] have also stated positive impacts of mixing fly ash-lime with soil in conditions of sulfate attack. The study led to the conclusion that mixed soil improves in strength upon reaction with sulfate. Choudhry et al. [69] also conducted a study by mixing waste plastic strips with fly ash and stated positive results on the CBR and secant modulus of soil.

Santos et al. [70] gave a brief overview of the properties of fly ash in soil mixtures for embankments. Tests were conducted on soil, including compaction, permeability, and UCS. They found that the addition of fly ash increased the water content at optimum moisture content, while the dry density and permeability decreased. Based on these results, it was recommended to use fly ash for the stabilization of embankments.

Ramaji [71] studied the effectiveness of fly ash with lime for soil stabilization. A series of Standard Proctor tests was conducted according to ASTM D698 (2000) to find the maximum dry density and optimum moisture content using lime and fly ash at different percentages. In their research, yellow sand samples from Baldivis, western USA, were collected. The lime used in this study was hydrated. The study concluded that the use of fly ash is much more effective than that of lime only. With increased amounts of fly ash, lime, or both, the dry density increases, but the optimum moisture content also increases compared to that of pure sand.

Bose [59] reported that fly ash has good potential for improving the engineering properties of expansive soil. Amiralian et al. [72] analyzed the results of methodological research on soil stabilization with the use of lime and fly ash. The results of their study suggested that a mixture of lime and fly ash might be far more effective than the use of either lime or fly ash alone to enhance soil properties.

Amiralian et al. [55] conducted a study to evaluate the effects of lime and fly ash in soil stabilization. They performed Standard Proctor tests and investigated the moisture-density relationship of sandy soil with lime and fly ash. Their research showed that the addition of fly ash to sand increases the natural moisture content and the dry density. It was concluded that lime and fly ash induced a noticeable change in the moisture-density relationship. In addition, the results showed that a combination of 1% to 2% lime with 10% fly ash gives the maximum value of dry density (1.85 gm/cm3) with the optimum percentage of water content (12.62%).

Sharma and Singh [73] investigated the use of fly ash with locally available clayey soil. Experimental testing was performed to evaluate the mechanical properties, which included Proctor testing, UCS testing, and permeability testing. They reported that the UCS and CBR of soil increase substantially with the addition of 20% fly ash and 8.5% lime. It was also found that the maximum dry density decreases from 1.913 gm/cm3 to 1.761 gm/cm3 when the fly ash content changes from 10% to 25%. This decrease in density was related to the lower specific gravity of fly ash compared with that of clayey soil and sand. On the other hand, the optimum moisture content was found to increase because of the large surface area of generally round-shaped fly ash. The UCS value was found to increase to 290.68 kN/m2 for the most appropriate clay-sand-fly ash mix. However, the UCS of the final appropriate composite mix of clay-sand-fly ash was less than the UCS of the optimum clay-sand mix. The reasons for this decrement may be the lower specific gravity and lower maximum dry density of fly ash in comparison to those of clay and sand. The coefficient of permeability of the most appropriate mix (i.e., clay: sand: fly ash 63:27:10) obtained in this study was found to increase to 1.688e-6 cm/s from 1.44x10-7 cm/s because of the spherical shape of the fly ash particles.

Kumar and Neetesh-Kumar [74] made a series of attempts to utilize fly ash in highway embankments that contained locally available fly ash. The Standard Proctor test and permeability tests were carried out. The Standard Proctor test was performed for maximum dry density and optimum moisture content. The researchers reported that the maximum dry density increased when the fly ash content increased, while the optimum moisture content decreased. Further investigations showed that the increment in fly ash content decreased the coefficient of permeability.

Pandey et al. [75] stressed that the use of fly ash is necessary to avoid environmental pollution; they used class 'F' fly ash for compaction and unconfined compression tests. Soil and fly ash were blended in varying weights, while maintaining the cement proportion at or below 2% of the total mass. Red soil for these tests was collected from the premises of Bangalore University. The maximum dry density of red soil with 10% fly ash was 17kN/m3 and was reduced to 16.4kN/m3 for red soil mixed with 30% fly ash. The decrease in maximum dry density is due to the low specific gravity of fly ash. Based on the test results, the addition of fly ash decreases the diffused double layer thickness of the mixture, and hence the water-holding capacity of the soil mixture decreases.

A similar study was conducted by Li et al. [76] on the optimization of fly ash-soil mixtures for highway embankment construction. The tests performed were compaction, permeability, and UCS. They found that as the fly ash content increases, the maximum dry unit weight decreases and the optimum water content increases. The UCS of fly ash-soil mixtures increases with increased fly ash content.

Diallo and Unsever [77] investigated the impact of adding 2% lime and various percentages of fly ash to clay soil. The soil was initially classified through sieve and hydrometer analysis as well as Atterberg Limit tests. Following that, the normal compaction test was performed to determine the optimum water content and maximum dry density. Besides, unconfined compression tests were used to obtain the strength of the samples after 3 days, 7 days, and 28 days of curing. During the study, it was observed that after adding 15% of fly ash, the plasticity of the soil was completely lost. Adding to that, the study concluded that adding fly ash to the clay soil caused the strength of the soil to increase. The maximum unconfined strength, with a value of 38.99 kg/cm2, was recorded when 73% of soil was mixed with 2% of lime and 25% of fly ash. The researchers also mentioned that the strength increased as the curing time increased.

Banaszkiewicz et al. [78] studied the feasibility of utilizing fly ash in treating benzene-contaminated soil. Fly ash (30%) and Portland cement (70%) were added in amounts of 40, 60, and 80% of the soil's mass. The soil samples' compressive strength and capillary water absorption were tested, and the concentration of benzene was supervised during the study period. It was confirmed that adding fly ash and cement reduced the benzene emissions, and the average compressive strength for each of the samples was recorded as 0.57MPa (40%), 4.53 MPa (60%), and 6.79 MPa (80%) (Fig. 2). In addition to that, the capillary water absorption of the samples varied between 15-22% dm.

Effects of Fly Ash on Resilient Modulus of Soil. Resilient modulus is one of the important properties of soil in the context of the design of flexible pavements. Therefore, there have been several studies in which the effects of fly ash on the resilient modulus of soils have been investigated.

Wei et al. [79] observed the stabilization of a silty clay soil with the addition of fly ash. They observed the damage to resilient modulus under Freeze-Thaw cycles. They observed that the unmodified soil experiences a continuous decrease in modulus with every cycle, while those modified with fly ash become stable after the loss of the initial cycle. The reason could be the fact that fly ash provides better resistance to damage in the microstructure.

Hanandeh et al. [80] observed and modeled the effects of fly ash on four different types of soils, and it was shown that the quantity of fly ash has a positive impact on improving the resilient modulus. They varied the fly ash content from 0 to 15%. In another study, the effects of activated fly ash (class F) were reported to have a positive impact on increasing the resilient modulus of naturally expansive soil. However, this trend was observed with activated fly ash when it was mixed within the range of 6 to 10%. A proportion of fly ash below 6% was found to reduce the resilient modulus [81].

With regard to the use of fly ash with organic soils, Tastan et al. [82] reported that the increase in fly ash generally improves the resilient modulus of these soils. However, the improvement would depend upon the soil characteristics and the amount of CaO content, so that lower CaO content would result in less improvement in modulus.

The effect of fly ash on improving the resilient modulus of clayey soils was found to be less than that of cement kiln dust and hydrated lime. The former was more effective at lower percentages (up to 6%), while the latter showed better results at higher proportions (10 to 15%). In both cases, the effect of mixing fly ash was not better than the above-mentioned additives [83].

Senol et al. [84] applied class C fly ash on low plasticity clay soil within a range of 0 to 20%. They found a constant increase in the resilient modulus with the increase in fly ash content. They also advocated the use of fly ash since it does not require any activator and can reduce construction delay.

Bin-Shafique et al. [85] compared pavements designed with stabilized subgrade and the conventional cut-and-fill approach. They used class C fly ash from two different sources. Both pavements were monitored through field tests, and it was found that the unconfined compressive strength and CBR increased with the increase in fly ash, while it did not have a significant impact on the resilient modulus and thicknesses.

Summary and Recommendations

This review study focused on the exploration of existing frontiers of research for the use of waste materials, with a focus on the application of fly ash in pavement structures, to act as a basis for future directions of research. To date, the application of fly ash has mainly been used as a mineral filler in asphalt concrete and as a soil/layer stabilizing material in pavement structures. The application of fly ash in pavement structures is found to be convenient since no major changes in construction techniques are required. Further findings from this review study, with relevant recommendations, are summarized below.

- It was found that the use of fly ash provides better moisture resistance, resilient modulus, and resistance to fatigue damage. However, some studies recommend the use of coarser particles to improve the strength of asphalt concrete with fly ash, warranting modified aggregate gradation curves.
- The advantages of using fly ash as a replacement for asphalt are inconclusive, and further investigations will be required before its use can be recommended.
- The most common and successful use of fly ash has been for the stabilization of aggregate base and sub-grade layers. In these cases, it has been used in conjunction with an activator. Less than 10% content of fly ash and cement has been found to increase the strength parameters of soil/base layers and improve resistance to swelling and moisture damage in expansive soils. However, the use of fly ash increases the moisture/binder content requirements to achieve optimum density.
- More effort is required to model the behavior of pavement structures/layers with the use of fly ash so that appropriate specific guidelines can be developed for the use of fly ash in pavements.
- It was also found that field testing of asphalt concrete with the addition of fly ash has been seldom found in the literature, which could be considered an area of future research.
- Another potential area of research is the standardization of fly ash, in terms of contents and compositions, for use in different layers of pavement. This will enable the generalization of trends from different studies.

Statements and Declarations

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study. All information reviewed is available in the cited references.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: U. Gazder, M. Abid; data collection: U. Gazder, M. Arifuzzaman, M. Abid; analysis and interpretation of results: U. Gazder; draft manuscript preparation: U. Gazder, M. Arifuzzaman. All authors reviewed the results and approved the final version of the manuscript.

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