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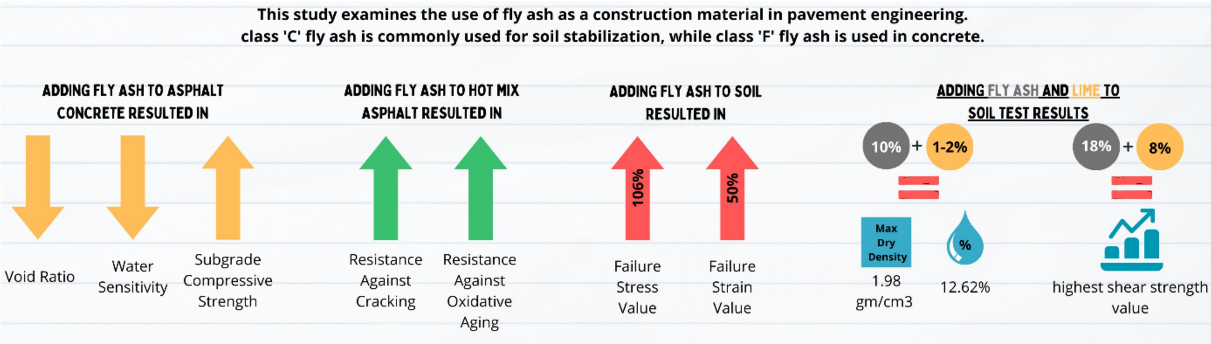
State-of-the-Art Review on Utilization of Fly Ash in Pavement Structures

Uneb Gazder[1], Md Arifuzzaman[2], Marwa Jazi[1*], Madiha Abid[3]
[1]Department of Civil Engineering, University of Bahrain, Bahrain
[2]Department of Civil Engineering and Environmental Engineering, King Faisal University, Saudi Arabia
[3]Department of Urban and Infrastructure Engineering, NED University of Engineering and Technology, Pakistan



ABSTRACT: The use of fly ash in construction has been on the rise, yet its application in pavement construction remains relatively underexplored. This study addresses this gap by critically reviewing 70 years of research on fly ash usage in pavement engineering, offering valuable recommendations. Class 'C' fly ash is employed for soil stabilization, while class 'F' is used in concrete. In both flexible (asphalt) and rigid (concrete) pavements, fly ash primarily functions as a filler material. Fine ash, owing to its fineness, enhances asphalt concrete by reducing void ratios and water sensitivity, as well as easing subgrade compaction while increasing compressive strength. Incorporating fly ash into Hot Mix Asphalt (HMA) enhances resistance to cracking and oxidative ageing. Adding fly ash (up to 25%) significantly boosts soil failure stress and strain values by 106% and 50%, respectively, while a combination of 8% lime and 18% fly ash yields maximum shear strength. A modest amount of lime (1-2%) mixed with 10% fly ash achieves a maximum dry density of 1.98 gm/cm3 at an optimal water content of 12.62%. Additional testing by researchers corroborates and validates the findings of this literature review.

الملخص: يَزْدادُ اِسْتِخْدامُ الرَمادِ المُتَطايِرِ فِي البِناءِ، لٰكِنَّ اِسْتِخْدامَهُ فِي بِناءِ الرَصِيفِ غَيْرُ شائِع. يَتَناوَلُ هٰذا البَحْثُ اِسْتِخْدامَ الرَمادِ المُتَطايِرِ فِي هَنْدَسَةِ بِناءِ الرَصِيفِ عَلَى مَدَى 70 عاماً بِنَقْدٍ دَقِيقٍ وَيُقَدِّمُ تَوْصِياتٍ مُهِمَّةً. يُسْتَخْدَمُ الرَمادُ مِنْ الفِئَةِ "C" لِتَثْبِيتِ التُرْبَةِ وَالفِئَةِ "F" فِي الخَرَسانَةِ. يُشِيرُ اِسْتِعْراضُ الأَدَبِ إِلَى أَنَّ اِسْتِخْدامَ الرَمادِ فِي الرَصِيفِ المَرِنِ (الأَسْفَلْتِ) وَالصُلْبِ (الخَرَسانَةِ) يَكُونُ عادَةً كَمادَّةِ حَشْوٍ. يُحَسِنُ الرَمادُ الناعِمَ مِنْ خَصائِصِ الخَرَسانَةِ الإِسْفَلْتِيَّةِ، وَيُقَلِّلُ مِنْ حَساسِيَّتِها لِلماءِ، كَما يَسْهُلُ الضَغْطُ عَلَى التُرْبَةِ السُفْلِيَّةِ وَيَزِيدُ قُوَّتِها الضَغْطِيَّةِ. اِسْتِخْدامُ الرَمادِ فِي الخَلْطَةِ الساخِنَةِ (HMA) يُعَزِّزُ مُقاوَمَتَها لِلتَشَقُّقِ وَالشَيْخُوخَةِ. إِضافَةُ الرَمادِ (حَتَّى 25%) يَزِيدُ بِشَكْلٍ كَبِيرٍ مِنْ قِيَمِ الإِجْهادِ وَالتَشَدُّدِ لِلتُرْبَةِ. الجِيرُ (8%) مَعَ الرَمادِ (18%) يَزِيدُ مُقاوَمَةِ القَصِّ. كَمِّيَّةٌ صَغِيرَةٌ مِنْ الجِيرِ (1-2%) مَعَ 10% مِنْ الرَمادِ تُحَقِّقُ أَعْلَى كَثافَةٍ جافَّةٍ وَمُحْتَوىً مائِيٍّ مِثالِيٍّ. الاِخْتِباراتُ الإِضافِيَّةُ تُؤَكِّدُ نَتائِجَ اِسْتِعْراضِ الأَدَبِ وَتَوْصِياتِهِ.

Keywords: Fly ash, Utilisation of waste material, Pavement layers, Soil stabilization; Stresses and strains

الكلمات المفتاحية: الرماد المتطاير ، واستخدام النفايات ؛ طبقات الرصيف ؛ استقرار التربة، الضغوط و التوتر.

Corresponding author's e-mail: marwah.jazi@gmail.com

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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 (Kumar 2012), 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. 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 (Shannon 2017).

Since fly ash is a pozzolanic material, it has been widely used in civil engineering applications (Ahmed 1991). It has been used in conjunction with traditional materials such as cement concrete, asphalt concrete and soil (Kumar 2012). Ahmaruzzaman (Ahmaruzzaman 2010) has listed various properties of fly ash which make it suitable for use as a construction material. These properties include its adsorption, low unit weight, high drainage ability and ease of compaction.

Data collection and resource distribution: A total of 84 resources are covered by this review paper. Journal articles make up 75% of the resources, while 8% are conference papers, and the remaining 17% comprises books, reports, and theses (Figure 1). In terms of area of application, 52% of references are related to the use of fly ash in soil or pavement layers' stabilization, 29% include investigations on the use of fly ash in asphalt concrete, while the rest of the references discuss general information about fly ash, such as; its constituents, classes and need for its utilization, as shown in Figure 2.

It should be noted that Figures 1 and 2 show the distribution of research reviewed for the current review effort and should not be taken as a measure of the actual magnitude of research done in this area.

Properties of fly ash: The properties of fly ash are dependent upon several factors, including the composition of the parent coal, conditions during combustion, the efficiency of emission control devices, storage and handling of the byproducts and climate. The common size distribution of fly ash ranges between 2µm-50µm. It consists of three major mineral matrices: glass, mullite-quartz, and magnetic spinel (El-Mogazi 1988).

The main elements of fly ash are aluminium, 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 (Matsunaga 2002). This composition makes fly ash non-reactive and suitable for the replacement of other civil engineering materials like cement.

Classes of fly ash

Based on the proportions of its chemical constituents, fly ash can be classified into class 'C' and class 'F.' Although other classification methods are available, this classification will be followed for the purposes of the present review study. The prime difference between the classes is the proportion of silicon dioxide (SiO_2) and aluminium 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 (Guo 2010).

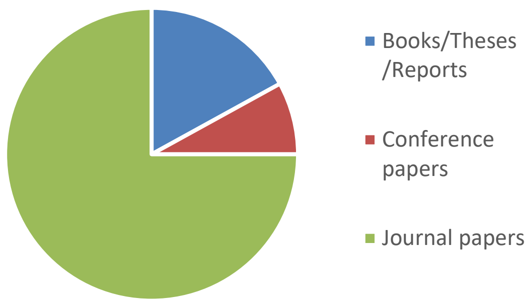

Figure 1. Source distribution

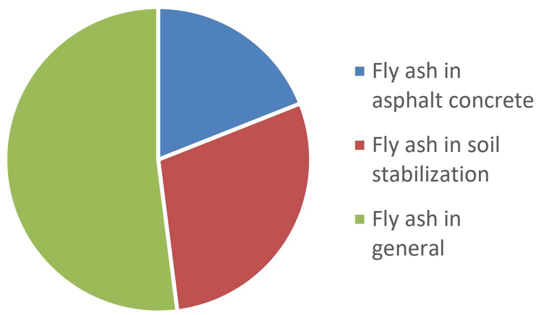

Figure 2. Topic distribution

The difference in their composition is due to the process of their production and the primary material from which they are made of. 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 (Barbour, 1991). This change in the properties dictates their applications in different fields of civil engineering.

Applications of fly ash: The use of fly ash in concrete started in the 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. A review of the current literature shows that sufficient knowledge is already available on the use of fly ash in concrete structures, and the conclusions are clear. 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/subgrade. 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 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 conducted in this area. Fly ash is reported to be more frequently used in three materials (Yan 2012), namely, cement concrete, asphalt concrete and soil. This study provides a comprehensive review of the use of fly ash in a critical area of civil engineering, i.e., pavement construction. Based on the review, future applications and research areas pertinent to fly ash for pavements have been recommended. This research will be beneficial for researchers, students, and civil engineering professionals by familiarizing them with the use of this unconventional material.

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. This layer is subjected to direct wear and tear from vehicles and the environment. Hence, it has been a subject of study for many researchers. 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.

Fly ash as mineral filler: Many researchers have investigated the use of fly ash for Hot Mix Asphalt (HMA) as mineral filler. For example, Henning (Henning 1974) investigated the effects of using fly ash from various 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 in comparison with lime.

Rosner et al. (Ronser 1986) explored the use of fly ash as a replacement for aggregates in asphalt concrete. These researchers 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 aggregate weight gives the best performance. It was also observed that the addition of fly ash reduces the asphalt requirement and the voids in 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. (Ali 1996) conducted a study to evaluate the effects of using different percentages of fly ash as a mineral filler in asphalt concrete. 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 would deteriorate over the long term (10 years).

Asi and Assa'ad (Asi 2005) 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 with 50%-100% fly ash to show significant performance against pavement failure.

Tapkin (Tapkin 2008) conducted a study to evaluate the effects of using distinct 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 and the flow and fatigue life of asphalt concrete. He concluded that the use of class 'F' fly ash with 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. (Reyes 2011) determined the response of HMA in terms of tensile strength and energy parameters. These researchers conducted experiments by replacing mineral fillers 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. (Sobolev 2013) provided a brief overview of the benefits gained by using fly ash as a filler in HMA. It was found in this study that this particular use of fly ash has been reported to result in higher resistance against cracking and oxidative ageing.

Modarres and Rahmanzadeh (Modarres 2014) Used natural coal waste from a coal washing plant as the mineral filler in HMA. The stability, resilient modulus, and tensile strength of the samples were assessed. 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 evaluated 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.

R Muniandy, E Aburkaba and R Taha (R Muniandy 2013) examined the effect of different byproduct 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 the ceramic waste dust and steel slag were the most effective fillers, fly ash still had a good impact.

Experimental research done by Mirkovic, Tosˇic and Mladenovic (Mirkovic 2019) tested asphalt samples consisting of three distinct types of fly ash with 25%, 50%, 75%, and 100% of 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 could be obtained with the addition of fly ash. Moreover, the stability of asphalt improved after the addition of fly ash by 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 them suitable for rut-resistant asphalt surface courses.

K. Onyelowe, Onyia and others (Kennedy 2020) studied the effect of utilizing fly ash as a modifier and crushed waste glasses 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.

Use of Fly Ash in Asphalt Concrete as a Replacement of Asphalt and Fine Aggregates: Churchill and Amirkhanian (Churchill 1999) extended the use of fly ash by using it as a replacement for fine aggregates. Fly ash was used from various 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 premise that it is available at a low cost and does not affect the soil's properties in terms of its metallic components.

Suheibani (Suheibani 1986) investigated another application of fly ash, which he termed an "asphalt extender". He used fly ash as a replacement for asphalt in HMA in varying proportions (10%-40% of asphalt weight). Another dimension of this study was an investigation of the effect of using varied 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. (Sobolev 2013) also proposed a modified asphalt mix referred to as asphalt. 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 increased 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 did 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.).

Osta et al. (Al-Osta 2016) studied the effects of heavy Fuel on asphalt concrete as a mineral filler as well as 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. (Wahhab 2015) 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%), and 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 of fly ash usage in pavement construction.

An extension of this effort was published in 2003 in the report FHWA-IF-03-019. This report specifies the use of fly ash in the 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 (FHWA 2003).

The results of further experimental work conducted by FHWA were published in 2012 in the report FHWA-RD-97-148. It was prepared as a result of experiments performed on several 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 (FHWA 2012).

Effects of Fly Ash on Asphalt Concrete: Fly ash has been used more commonly as 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. The main reason behind this behaviour is the increase in asphalt content when fly ash is added to the asphalt concrete mix. This is necessitated to maintain the workability of the mix.
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 which 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 Cabrera (Zoorob 1997) discussed in detail the design and procedure for the construction of HMA pavements with fly ash as 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 SOIL STABILIZATION AND IMPROVEMENT

Soil is an integral foundation material for civil infrastructure and is categorized as coarse-grained (sand and gravel) or fine-grained (silt and clay). 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 pressure on the soil. These structures are built on different strata of soil, and this causes stability and strength issues. For example, 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.

Soil can be chemically stabilized with lime, cement and/or fly ash used in isolation or in combination (Brooks 2009).

In this regard, the following findings have been drawn from the review of the previous literature:

Amiralian et al. (Amiralian 2012) reported that fly ash gives appropriate results for soil compaction and strength in contrast to lime and cement at a lower cost. They also reported that fly ash is a byproduct of coal combustion and, therefore, exhibits more cementitious characteristics. Fly ash also has high fineness, which decreases the porosity and pore size and increases the compressive strength.

Reasons for Using Fly Ash in Soil: Fly ash can be used to stabilize bases or sub-grades in backfills to reduce lateral earth pressures and in embankments to improve slope stability (Dermatas 2003).

Studies of the utilization of fly ash for soil stabilization have been conducted in the past by several investigators (Mitchell 1981; Edil 2006) who have demonstrated the effectiveness of fly ash for the stabilization of fine-grained soils.

Bose et al. (Bose 2012) reported that fly ash has good potential for improving the engineering properties of expansive soil, and Takhelmayum et al. (Takhelmayum 2013) showed improvement in the strength characteristics of soil with the addition of fly ash.

Effects of Fly Ash on Dry Density and Moisture Content of Soil: Several studies have been conducted on fly ash and soil composites, and most of the researchers observed the effect of fly ash on different types of soil. For example, Takhelmayum et al. (Takhelmayum 2013) showed improvement in the strength characteristics of soil with the addition of coarse fly ash. Brown (Brown 2001), and Edil et al. (Edil 2006) reported the effectiveness of fly ash in improving the 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 the mobile metals in fly ash into the soil. Cement-chelated solidification has been recommended as an effective approach to immobilize these heavy metals (Tang 2017).

Many studies have found that the content of fly ash in the soil increases the optimum moisture content and decreases maximum dry density. The decrease in maximum dry density is due to the low specific gravity of fly ash (Sumesh; Santos 2011; Pandey 2014; Li 2014). The trend has been reported for a variety of soil samples and test conditions in the above-mentioned studies. However, there have been some exceptions reported in other studies, which are presented below in more detail.

Sharma et al. (Sharma 2008) 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 "optimum fly ash content," and then reverses beyond this optimum level. On the basis of unconfined compressive strength tests, Brooks (Brooks 2009) found that failure stress and strain increased by 106% and 50%, respectively, with the addition of fly ash from 0% to 25%.

Amiralian et al. (Amiralian 2012) 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 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%).

Kumar and Neetesh-Kumar et al. (Kumar 2014) made a series of attempts to utilize fly ash in highway embankments which contained locally-available fly ash. The Standard Proctor test and permeability tests were conducted. 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.

Effects of Fly Ash on Permeability and Strength of Soil: Okonta et al. (Okonta 2011) 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 as being weak and unconsolidated. 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. (Hu 2016) have also stated the positive impacts of mixing fly ash-lime with soil in conditions of sulfate attack. The study led to the conclusion that the mixed soil improves in strength upon reaction with sulfate. Choudhry et al. (Choudhry 2014) also conducted a study by mixing waste plastic strips with fly ash and stated positive results on CBR and the secant modulus of soil.

Ramaji et al. (Ramaji 2012) studied the effectiveness of fly ash with lime for soil stabilization. A series of Standard Proctor tests were 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.

Amiralian et al. (Amiralian 2012) 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.

Sharma et al. (Sharma 2013) 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 increased substantially with the addition of 20% fly ash and 8.5% lime. 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-6cm/s from 1.44x10-7cm/s because of the spherical shape of the fly ash particles.

Fly ash has also been used to stabilize base layers for the construction of new pavements and for the rehabilitation of old ones. Crovetti (Crovetti 2000) 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. (Wen 2003) utilized class 'C' fly ash to develop a stabilized base course for the rehabilitation of asphalt pavement. It was found that fly ash-stabilized and recycled base has a better layer coefficient than crushed aggregate material.

Diallo and Unsever (Mamadou 2019) investigated the impact of adding 2% lime and various percentages of fly ash to clay soil. 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/cm^2 was recorded when 73% of the 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, Marcinkowski and Pasiecznik (Kamil 2022) 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. 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%).[81]

Effects of Fly Ash on Soil Properties

Three important geotechnical properties of soil have been evaluated in laboratory tests with varying proportions of fly ash, including the moisture–density relationship, permeability and compressive strength. Past research shows that these three laboratory tests are necessary to evaluate the performance of fly ash in soil. Soil compaction and density have been analyzed using the Standard Proctor test, the falling head test has been used for the permeability testing of fine-grained soil, and UCS tests have been used to find the shear strength of cohesive soil. The above studies highlight the following observations:

1. The addition of fly ash improves the compressive and shearing strength of soils. It has been noted in the testing of different soils that fly ash enhances

their strength properties and it controls the shrinking and swelling properties of expansive soils.
2. With the addition of fly ash, the soil becomes denser and compacted. The air voids present in the soil in its natural state are reduced because of the smaller grain size of fly ash. This, in return, makes the soil less permeable.

EXPERIMENTAL RESULTS AND DISCUSSIONS

To validate the conclusions of the literature review and further extend the understanding of the use of fly ash, experimental studies were conducted. The following sub-sections show the results and their discussion of these studies.

Table 1. Results of the Marshall test

Fly ash % (by weight of asphalt)	Asphalt% + fly ash (by weight of sample)	Flow (cm)	Stability (kg)	Air voids (%)
0	4.2%	0.36	621	4.36
10	4.5%	0.38	635	4.26
20	5.0%	0.43	626	3.53
30	6.0%	0.40	692	4.21

Experimental study for HMA

An experimental study was done by the authors to verify the effects of fly ash on HMA, and the results are shown in Table 1. In this study, fly ash was used as a replacement for asphalt in HMA at varying percentages from 10% to 40% by weight of asphalt. Fly ash was obtained from Matrixx Company, belonging to type F. It conformed to the standard specification, ASTM C 618 A, as mentioned by the supplier. The detailed chemical properties of this fly ash are available online on the supplier's website. A comparison was made between the batches of varying fly ash proportions and the control sample, which was made of traditional materials, i.e., asphalt and aggregates. Marshall testing was performed on all the samples according to the standard specified by the American Society of Testing and Materials (ASTM) number D1559-89.

The optimum asphalt content was determined for all proportions of fly ash (0% for the control sample to 40%). Marshall stability, flow and air voids were measured and compared for samples with optimum asphalt content. The results are shown in Table 1.

Table 1 shows that the addition of fly ash results in an increase in the Marshall stability, which shows the strength of the sample. On the other hand, it also contributes to the increase in the flow (deformation at failure) values of the samples. These trends can be seen in Figure 3. The results are consistent with the observations of the literature review and indicate an increase in strength. However, a comparison of the flow value, which indicates resistance to deformation, was not found in previous research.

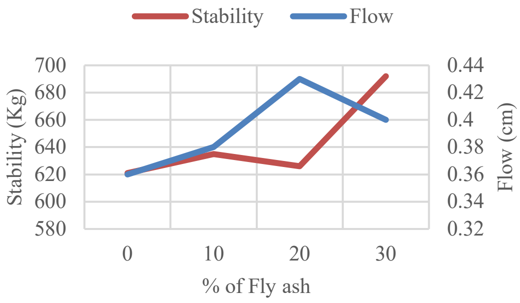

Figure 3. Comparison of Marshall Parameters from authors' study

Experimental study for soil stabilization

Another study was conducted by the authors on the reinforcement of Sabkha soil (found vastly in the Kingdom of Bahrain) by the addition of fly ash and silica fumes in different proportions. Class C fly ash was used in this study. Initially, cement was also considered for this study, but it was later decided to use fly ash and silica fumes as both are waste products and can be acquired cheaply in Bahrain. The cost difference was approximately 6BD (16 USD) per ton in comparison to cement.
As mentioned in the preceding sub-sections, most of the studies have focused on determining the effects of adding fly ash on the dry density and permeability of the soil. Therefore, it was decided that this study would focus on the strength characteristics of the soil. This study is also found to be the first to compare fly ash and silica fume for the stabilization of soil.

Table 2. Results of direct shear test

Type of Soil	Maximum Shear Force (KN)	Maximum Shear Stress (KN/m^2)	Strain (%)
Sabkha	103.20	28667	3.33
Sabkha Soil+5% fly ash	169.20	47000	3.75
Sabkha Soil+10% fly ash	353.60	98222	3.75
Sabkha Soil+30% fly ash	109.20	30333	2.50
Sabkha Soil+10% Silica fume	90.00	25000	2.92
Sabkha Soil+20% Silica fume	102.40	28444	2.08

Two types of tests were performed for these samples, namely unconfined compression test and direct shear test. The maximum shear strain observed in the unconfined compression test did not show any significant changes with the modifications. However, the results of the direct shear test were more conclusive and are hereby presented in Table 2.

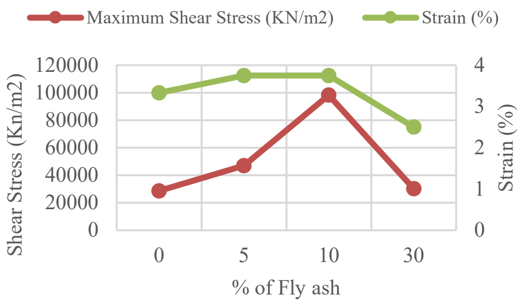

Figure 4. Shear stress and stains from the authors' study.

From the data presented in Table 2 and the trends shown in Figure 4, the following conclusions can be made. Fly ash is a better option for the stabilisation of Sabkha soil compared to silica fume. The addition of fly ash by 10% is the optimum proportion to attain maximum shear stress, after which the properties of soil deteriorate with an increase in fly ash proportion. The results of this study reinforce the findings of the previous research done in this field. The unconfined compression test was found to be the most employed test for testing the strength of the soil, which was found to be inconclusive in this study. Although the direct shear test has been rarely used for such tests, it was found to be efficient for this study.

Another observation of this study was that the addition of 10% fly ash produced stronger samples than the addition of 30%. The same observations have been found in other previous studies where an optimum proportion of fly ash is found for different soils (Tang 2017, Hu 2016).

SUMMARY AND RECOMMENDATIONS

This review study focused on an exploration of the existing frontiers of research for the application of fly ash in pavement structures to function as a basis for future directions of research. To date, the application of fly ash has been as a component of 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, with relevant recommendations, from this review study are summarized below.

- The use of fly ash as a mineral filler in asphalt concrete. It was found that the use of fly ash provides better moisture resistance, resilient modulus, and resistance to fatigue damage in almost all the studies. However, some studies recommend the use of coarser particles to improve the strength of asphalt concrete with fly ash.
- Very few studies have been found in which fly ash was used as a replacement for asphalt binder in asphalt concrete. These studies have reported better resilient modulus but a loss of the tensile strength of asphalt. A local experimental study also found that fly ash can increase the stability (compressive strength) of asphalt concrete with higher flow values, which is due to the better resilient modulus.
- The most common and successful use of fly ash has been for soil stabilization, where it has been used to stabilize sub-grades as well as aggregate layers. This application has been found to increase the strength parameters (including compressive and shear strengths) 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. The above-mentioned advantages can be primarily attributed to the increased fineness of fly ash.
- Fly ash cannot be considered a complete replacement for asphalt due to a lack of binding abilities in comparison with it.
- There are no models available to predict the strength of composites with fly ash; a trial-and-error procedure is adopted for every different case. Hence, more effort is required to model the behaviour of pavement structures/layers with the use of fly ash.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this article.

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