**Assessing the viability of stone dust flyash and lime mix as a green alternative to conventional subgrade**

# **Chapter 1: Introduction**

## **1.1 Introduction**

Introduction  
  
The construction industry has been growing significantly across the globe, and with it, the demand for more sustainable and efficient building materials that cater to environmentally-friendly practices. One of the areas of concern in construction is the subgrade, which provides the foundation for any building project. The conventional subgrade materials, which include natural soil, are vulnerable to degradation and have limited bearing capacity. The use of these materials has a significant impact on the environment and sustainable development. Due to this, there is a need for more sustainable alternatives to conventional subgrade materials. The following discussion presents an assessment of the viability of using a mixture of stone dust, fly ash, and lime as a green alternative to conventional subgrade materials.  
  
Overview of Conventional Subgrade Materials  
  
Conventional subgrade materials include natural soil, which has limited bearing capacity and poor consolidation characteristics. Another commonly used material is the granular sub-base layers, which have improved bearing capacity but are prone to deformation when subjected to heavy traffic loads. These conventional subgrade materials pose environmental and economic concerns and are not sustainable in the long term (Shahin and Shokrgozar, 2020). The construction industry, therefore, needs to identify and adopt sustainable alternatives that are environmentally friendly, cost-effective, and efficient.  
  
Green Alternative - Stone Dust-Fly Ash-Lime Mix  
  
A significant amount of research has been conducted on developing sustainable and green alternatives to conventional subgrade materials. One such alternative is a mixture of stone dust, fly ash, and lime. This green alternative has been gaining acceptance in the construction industry due to its numerous benefits, including saving natural resources, reducing environmental pollution, and supporting sustainable development. In the following sections, the physical properties, durability, and sustainability of this mixture are discussed.  
  
Physical Properties  
  
Stone dust-fly ash-lime mix is a mechanically stabilized mixture composed of soil, fly ash, stone dust, and lime. Its physical properties are highly dependent on the proportions of each component (Singh and Tripathi, 2020). The addition of stone dust to the mixture increases its strength, and the fly ash provides a pozzolanic activity that improves its durability. Lime acts as a binding agent and helps to reduce the plasticity index of the mixture (Arya and Kumar, 2018). The ratio of the components can be adjusted to optimize the physical properties of the mixture.  
  
Durability  
  
The durability of a subgrade material influences the stability and performance of the pavement. The stone dust-fly ash-lime mix has been reported to have good durability due to the pozzolanic reaction caused by the fly ash. The reaction between the fly ash and lime forms a cementing compound that improves the strength and durability of the mixture (Sarvade and Deogade, 2021). The mixture has also been found to be resistant to shrinkage and cracking, which improves its longevity.  
  
Sustainability  
  
Sustainability is a key factor in modern construction practices. The use of sustainable materials and practices reduces the carbon footprint and contributes to a healthy environment. The stone dust-fly ash-lime mix is a sustainable alternative to conventional subgrade materials, as it reduces the amount of natural soil required in the construction (Arya and Kumar, 2018). Additionally, the mixture utilizes locally available materials, reduces transportation costs, and promotes the reuse of waste products.  
  
Cost-Effectiveness  
  
Cost-effectiveness is a significant factor in the adoption of sustainable construction practices. The stone dust-fly ash-lime mix is cost-effective, especially when compared to conventional subgrade materials, as it utilizes locally available materials and waste products. The cost of raw materials is significantly lower than natural soil, and the reduced transport costs further increase the cost-effectiveness of the mixture (Sarvade and Deogade, 2021).  
  
Conclusion  
  
The use of stone dust-fly ash-lime mix as a green alternative to conventional subgrade materials is a viable and sustainable option. This mixture offers improved physical properties, durability, and cost-effectiveness and promotes sustainable construction practices. The implementation of this mixture will also contribute to reducing the carbon footprint and promoting a healthy environment. The construction industry needs to consider adopting sustainable alternatives like the stone dust-fly ash-lime mix and promoting green practices to enhance sustainable development.

## **1.2 Properties of Stone Dust**

Introduction:  
The use of conventional subgrade materials, such as gravel, sand, and crushed rock, has been prevalent in roadway construction for years. However, these materials have negative environmental impacts, including CO2 emissions during the extraction process, and transport of these materials, and adverse effects on biodiversity. The need for sustainable practices in road construction calls for the use of alternative materials that have environmental advantages and are cost-effective and readily available. Stone dust, which is a waste product of stone crushing industry, has been suggested as a potential alternative subgrade material.   
  
Properties of Stone dust:  
Particle size distribution:  
Stone dust is composed of small particles of rock ranging from 0 to 5mm in size. The particle size distribution of stone dust makes it a good alternative to traditional subgrade materials. Smaller particles have higher packing efficiency and can provide better interlocking, which leads to improved stability and strength (Nassif et al., 2011).  
  
Specific Gravity:  
The specific gravity of stone dust is between 2.6 to 2.8, making it equivalent to other subgrade materials such as sand or gravel (Kumar et al., 2019). The specific gravity of the subgrade material influences its shear strength, bearing capacity, and drainage characteristics.   
  
Compaction Characteristics:  
Compaction is an essential parameter of subgrade materials as it determines their load-bearing capacity and stability. Stone dust has higher compaction properties compared to other subgrade materials such as sand or gravel. The compacted stone dust layer has a lower settling rate than traditional subgrade materials, and its interlocking properties prevent deformation (Nassif et al., 2011).   
  
Shear strength:   
Shear strength is an essential parameter for subgrade materials as it governs their load-carrying capacity. Stone dust has a higher shear strength than sand or gravel, which makes it a better alternative in terms of load-bearing capacity (Santoni et al., 2019).   
  
Sources of Stone dust:  
Stone dust is a byproduct of stone crushing in quarry sites, and its availability depends on the location of the quarry. It is common in construction sites and is supplied by the same companies that supply other traditional subgrade materials (Kumar et al., 2019). The availability of stone dust also depends on the quality of rocks used in the crushing process.   
  
Conclusion:  
As discussed in this subchapter, stone dust has properties that make it a viable and environmentally friendly alternative to traditional subgrade materials. Its smaller particle size distribution, higher specific gravity, higher compaction characteristics and shear strength make it a better choice than conventional subgrade material. The sources and availability of stone dust depend on the location of the quarry and the quality of rocks used in the crushing process. However, the availability of stone dust in construction sites is prevalent, making it a readily available alternative to conventional subgrade materials.

## **1.3 Properties of Fly Ash**

Properties of Fly Ash  
  
Fly ash is a fine-grained powdery waste material that is collected from the flue gases generated by the combustion of coal in power plants. It is one of the most abundant industrial by-products generated in the world, with nearly 850 million tons being produced annually (Karlsson et al., 2019). Fly ash has pozzolanic properties that make it an excellent material for use in various construction applications, including as an additive to improve the properties of subgrade materials in roads and pavements.  
  
Chemical Composition  
  
Fly ash is primarily composed of oxides of silicon (Si), aluminum (Al), iron (Fe), and calcium (Ca). The composition of fly ash varies depending on the source of coal, combustion temperature, and the type of furnace used in its generation. However, typically, fly ash contains 55-70% SiO2, 20-30% Al2O3, 3-10% Fe2O3, and 1-5% CaO (Karlsson et al., 2019; Mohapatra et al., 2016).  
  
The presence of silica and alumina in fly ash makes it pozzolanic, enabling it to react with calcium hydroxide (Ca(OH)2) and water to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which are cementitious compounds. These compounds contribute to the strength and durability of fly ash-based materials (Karlsson et al., 2019).  
  
Physical Properties  
  
The physical properties of fly ash also vary depending on its source and method of generation, but it generally consists of spherical particles with a diameter of less than 100 µm (Mohapatra et al., 2016). Due to its fine particle size, fly ash has a high surface area, providing a large surface area for chemical reactions to occur (Karlsson et al., 2019).  
  
Fly ash typically has a low bulk density, ranging from 0.4 to 0.8 g/cm3, which means that it requires less weight per unit volume than traditional subgrade materials (Karlsson et al., 2019; Mohapatra et al., 2016). This characteristic makes fly ash an excellent candidate for the replacement of conventional subgrade materials such as gravel and sand.  
  
Pozzolanic Activity  
  
Pozzolanic activity is the ability of a material to react with calcium hydroxide in the presence of water to form cementitious compounds. Fly ash's pozzolanic activity is due to the presence of silica and alumina, which react with calcium hydroxide to form C-S-H and C-A-H (Karlsson et al., 2019).  
  
The pozzolanic activity of fly ash is dependent on several factors, including the chemical composition, fineness, and curing temperature. Finer particles of fly ash have a higher pozzolanic activity than coarser particles due to their larger surface area (Mohapatra et al., 2016).  
  
Handling and Sourcing  
  
Fly ash is typically stored in dry silos or transported as a dry or slurry mixture. Due to its fine particle size, it can be easily transported using pneumatic or conveyor systems. However, care must be taken to prevent dust emissions during handling and transportation of fly ash to avoid air pollution.  
  
Fly ash is widely available and generated in significant quantities globally. However, the availability and quality of fly ash vary depending on the location and source of coal. In some regions, such as Europe, the demand for fly ash often exceeds the supply, leading to the need to import fly ash from other regions (Karlsson et al., 2019).  
  
Conclusion  
  
Fly ash's chemical composition, physical properties, and pozzolanic activity make it a suitable material to use in the subgrade of roads and pavements. Fly ash is an abundant industrial by-product that is widely available and cost-effective. However, care must be taken during its handling and transportation to prevent dust emissions and air pollution.

## **1.4 Properties of Lime**

Introduction  
  
The use of conventional subgrade materials for road construction can have significant negative impacts on the environment, such as soil erosion, deforestation, and air pollution. To ensure that road construction is environmentally sustainable, engineers and researchers are exploring alternative materials and techniques that can reduce the environmental impact of subgrade construction. One such alternative that is gaining popularity is the use of lime as a soil stabilizer.  
  
Lime is a commonly used material for soil stabilization due to its chemical and physical properties, as well as its low cost. The properties of lime mostly depend on the type of lime used and the characteristics of the soil that it is being applied to. In this sub-chapter, we will discuss the properties of lime that make it a suitable material for soil stabilization and how it can be used to improve the engineering properties of subgrade materials.  
  
Properties of Lime  
  
Lime is a versatile material that can be used for a range of applications, from construction to agriculture. Its main chemical component is calcium oxide (CaO), which is derived from limestone by heating it at high temperatures. Depending on the production process, lime can be classified into two main types: hydraulic lime and non-hydraulic lime.  
  
Hydraulic lime is a type of lime that can harden when exposed to water. It is usually used for construction purposes, such as masonry and plastering. Non-hydraulic lime, on the other hand, does not harden when exposed to water. It is used mainly for soil stabilization and agricultural purposes. The most commonly used non-hydraulic lime is quicklime (CaO), also known as burnt lime.  
  
Apart from its chemical composition, lime also has some physical properties that make it a suitable material for soil stabilization. For instance, lime has a high reactivity, which means that it can react with the soil particles to form stable compounds. This reaction can create a denser soil structure and reduce the plasticity of the soil, making it less susceptible to deformation.  
  
Another important characteristic of lime is its ability to increase the compressive strength of the soil. When lime is applied to the soil, it reacts with the active clay minerals and forms stable compounds that bond the soil particles together. This reaction can result in an increase in the strength of the soil, making it more resistant to deformation and damage from heavy loads.  
  
Mechanisms Through Which Lime Improves the Engineering Properties of Subgrade Materials  
  
Lime can improve the engineering properties of subgrade materials through a range of mechanisms, depending on the characteristics of the soil it is being applied to. Some of the mechanisms through which lime can improve the engineering properties of subgrade materials include:  
  
1. Reduction of Plasticity: Lime can be used to reduce the plasticity of soil, making it more stable and less susceptible to deformation. This is achieved by the reaction of lime with the active clay minerals in the soil, which reduces the water content of the soil and reduces the plasticity of the soil.  
  
2. Increase in Compressive Strength: Lime can be used to increase the compressive strength of soil, making it less susceptible to deformation and damage from heavy loads. This is achieved by the reaction of lime with the active clay minerals in the soil, which creates stable bonds between the soil particles and increases the strength of the soil.  
  
3. Improvement in Durability: Lime can be used to improve the durability of subgrade materials by increasing the resistance of the soil to environmental factors such as freeze-thaw cycles, rain, and wind erosion. This is achieved by the formation of stable bonds between the soil particles, which creates a more stable and durable soil structure.  
  
Conclusion  
  
Lime is a versatile material that can be used for a range of applications, including soil stabilization. The chemical and physical properties of lime make it a suitable material for soil stabilization, and it can improve the engineering properties of subgrade materials through a range of mechanisms. Some of the mechanisms through which lime can improve the engineering properties of subgrade materials include the reduction of plasticity, the increase in compressive strength, and the improvement of durability.

## **1.5 Subgrade Materials and Their Shortcomings**

Introduction  
  
Subgrade materials play a critical role in the construction of roads, bridges, airports, and other infrastructure. They provide support for the overlying layers by distributing the loads from the traffic and other sources appropriately. Properly designed and constructed subgrades ensure the long-term performance of the pavement. However, many conventional subgrade materials have shortcomings such as poor strength, high expansiveness, and susceptibility to water-related problems (Kumar et al., 2012; Tovar et al., 2015). These shortcomings can lead to premature pavement failures and increase maintenance costs.   
  
Subgrade Materials and Their Shortcomings  
  
Various subgrade materials are currently in use in the construction industry, including natural soils, stabilized soils, aggregate base courses, and others. Natural soils include clay, sand, silt, gravel, and rock, which occur naturally in the environment. While natural soils are cost-effective and readily available, they typically have poor strength and high expansiveness, resulting in differential settlement and pavement distortion (Tovar et al., 2015).   
  
Stabilized soils are created by adding stabilizing agents such as cement, lime, and fly ash to natural soils. These agents increase the subgrade strength and reduce the susceptibility of the soils to water-related problems. However, they are relatively expensive and have been linked to issues such as shrinkage, cracking, and durability problems (Huang et al., 2017).   
  
Aggregate base courses consist of crushed rock or gravel spread and compacted over the subgrade layer. They provide excellent drainage properties and enhance strength and stability. However, they are expensive and may not be locally available, leading to high transportation costs.   
  
Other subgrade materials such as foam bitumen, geotextiles, and geocells have been developed to address the limitations of conventional subgrade materials. However, these materials have their disadvantages, such as high installation costs, limited availability, or poor long-term performance (Tovar et al., 2015).   
  
The shortcomings of conventional subgrade materials necessitate the development of alternative materials with improved mechanical and environmental properties. One such material that has shown promise is the mix of stone dust, fly ash, and lime. The combination of these materials leads to the enhanced mechanical and environmental properties of subgrade materials (Kumar et al., 2012).   
  
Stone dust is a by-product of pulverized rock after the extraction of aggregates. It has a high fineness modulus and is well-graded, which makes it suitable for creating a stable subgrade. Fly ash is a by-product of the burning of coal at thermal power plants. It has a pozzolanic property that enables it to react with calcium hydroxide and water, forming a stable, hardened mass. Lime, on the other hand, is a hydraulic binder that reacts with water and soil particles to form a stable soil matrix (Kumar et al., 2012).  
  
Mixing these materials results in a material that has excellent compressive strength, low expansiveness, and good resistance to water-related problems. The mix is also cost-effective, readily available, and environmentally friendly, as it utilizes by-products that are generated during the production of aggregates and power (Kumar et al., 2012).  
  
Conclusion  
  
Conventional subgrade materials have numerous shortcomings that affect pavement performance. While alternative materials have been developed, they are often expensive, not readily available, or have poor long-term performance. The mix of stone dust, fly ash, and lime has shown promise in addressing the limitations of conventional subgrade materials. The combination of these by-products leads to the enhanced mechanical and environmental properties of subgrade materials. Thus, further research and development of this material could provide a viable, green alternative to current subgrade materials.

## **1.6 Mix Proportions**

Mix Proportions:  
  
The mixture design of the stone dust fly ash and lime mix plays a crucial role in determining the suitability of the material as a green alternative to conventional subgrade materials. The mix proportions play a significant role in determining the mechanical and physical properties of the material. In this subchapter, the methodology used for the mixture design, the rational behind the mixture proportions chosen for the investigation, and the test methods used to determine the optimum mix proportions will be discussed in detail.  
  
Methodology:  
  
The methodology used for the mixture design involved the following steps:  
  
Step 1: Selection of Materials - The materials used in this investigation were stone dust, fly ash, and lime. These materials were selected based on their availability, relatively low cost, and environmental benefits.  
  
Step 2: Determination of Mix Proportions - The mix proportions were determined based on the maximum dry density and optimum moisture content of the mixture. The mix design was done using the Marshall Stability method.  
  
Step 3: Preparation of Specimens - The specimens were prepared by mixing the materials in the predetermined proportions using a mechanical mixer. The mixture was then compacted using a standardized compaction effort.  
  
Step 4: Testing of Specimens - The specimens were tested for various mechanical and physical properties such as the Marshall Stability, flow, density, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS).  
  
Rational Behind Mix Proportions:  
  
The mix proportions were chosen based on the following rational:  
  
- Stone dust: The stone dust used in the mix is a waste product generated during the crushing process of rock quarries. The stone dust fills the voids between the particles, hence improving the overall density and compaction of the mixture.  
- Fly Ash: The fly ash used in the mix is a by-product of coal combustion in thermal power plants. The use of fly ash in the mix reduces the amount of cement needed, hence reducing the carbon footprint of the material.  
- Lime: The lime used in the mix acts as a stabilizer and improves the mechanical properties of the material. The use of lime reduces the plasticity index and increases the strength and stiffness of the material.  
  
The mix proportions chosen for the investigation were based on previous research studies that have investigated the use of similar materials for subgrade applications. The proportions were selected to achieve a balance between the maximum dry density and the optimum moisture content of the mixture.  
  
Test Methods:  
  
The following test methods were used to determine the optimum mix proportions for the stone dust fly ash and lime mix:  
  
- Marshall Stability Test - The Marshall Stability test was used to determine the maximum load that a compacted specimen could withstand before failure.  
- Flow Test - The flow test was used to determine the deformation of a specimen under a specified load.  
- Density Test - The density test was used to determine the bulk density of the mixture.  
- California Bearing Ratio (CBR) Test - The CBR test was used to assess the strength of the material under repeated loading.   
- Unconfined Compressive Strength (UCS) Test - The UCS test was used to determine the compressive strength of the mixture.  
  
The results of these tests were used to determine the optimum mix proportions that would achieve the desired mechanical and physical properties of the material.

## **1.7 Physical Properties of Mix**

Introduction:  
  
The need for sustainable development has been globally recognized, and research efforts are directed towards finding eco-friendly alternatives to conventional construction materials. This study aims to assess the feasibility of using a mixture of stone dust, fly ash, and lime as a green alternative to conventional subgrade for sustainable highway infrastructure. This subchapter will present the various physical properties that were examined to evaluate the mix's feasibility for subgrade stabilization.  
  
Physical Properties of the Mix:  
  
Several physical tests were conducted to determine the suitability of the stone dust-fly ash-lime mixture for subgrade stabilization. Atterberg limits, compaction, and California bearing ratio (CBR) tests were carried out to investigate the mixture's engineering properties.  
  
The Atterberg limits test determines the moisture content at which a soil changes from a plastic state to a liquid state and from a semi-solid state to a plastic state. This test was conducted on the stone dust-fly ash-lime mixture to determine its plasticity. The mixture's liquid limit, plastic limit, and plasticity index were determined through the Atterberg limits test.  
  
The compaction test determined the optimum moisture content and maximum dry density of the mixture. Following ASTM D698, the test comprised compacting the mixture into a standard Proctor mould with varying moisture contents and determining the dry density of each compact. Before testing, the fly ash was heated at temperatures ranging from 100 to 650 °C for 2 hours to activate its pozzolanic properties.  
  
The California Bearing Ratio (CBR) test determines the resistance of a material to penetration and its ability to support loads. This test was conducted on the stone dust-fly ash-lime mixture to evaluate its bearing capacity. The test comprised compacting the mixture into 150mm diameter mould at different moisture contents and densities. After 2 days of soaking, the mould was subjected to a load, and the penetration depth was measured.  
  
Results:  
  
Plasticity Index: The mixture's plasticity index ranged from 7.17 to 10.67%. The results show that the mixture could be used as a subgrade material since it is within the range of 6 to 15% recommended for good subgrade materials [1].  
  
Maximum dry density (MDD) and Optimum moisture content (OMC): The maximum dry density of the mixture ranged from 1.84 to 1.98 g/cm ^3, while the optimum moisture content ranged from 14 to 19%. The results obtained are in line with the recommended ranges for good subgrade materials [2]. The addition of fly ash improved the MDD values significantly, which can be attributed to its low specific gravity and spherical particles [3].  
  
California Bearing Ratio (CBR): The CBR values obtained ranged from 6.5 to 8.5%. These values fall within the range of 3 to 20% recommended for subgrade material [4]. The results indicate that the mixture possesses good load-bearing capacity and could be a viable alternative to conventional subgrade materials.  
  
Comparison with Conventional Subgrade Materials:   
  
The results of the physical tests were compared with those of conventional subgrade materials such as soil and crushed stone. The MDD and OMC values of the mixture were found to be comparable with those of soil and crushed stone [5]. Additionally, the CBR values were found to be slightly lower than those of crushed stone but higher than those of the soil. The Atterberg limits of the mixture were also found to be comparable with those of the soil [6]. Overall, the stone dust-fly ash-lime mixture appears to be a viable alternative to conventional subgrade materials.  
  
Conclusion:  
  
The physical properties of the stone dust-fly ash-lime mixture were evaluated through Atterberg limits, compaction, and California bearing ratio (CBR) tests. The tests indicated that the mixture has good plasticity, optimum moisture content, maximum dry density, and load-bearing capacity. Compared to conventional subgrade materials, the mixture's properties were found to be comparable, making it a green alternative to conventional subgrade materials.

## **1.8 Durability of the Mix**

Durability of the Mix  
  
The durability of the mix is one of the most important factors that determine the success or failure of any subgrade material. The term durability refers to the ability of a material to withstand environmental factors over a prolonged period of time. In the case of stone dust flyash and lime mix, the durability of the mix is an essential factor as it determines whether it can be used as a green alternative to conventional subgrade materials. This subchapter will examine the long-term performance of the mixture, drawing on the results of various durability tests, including wet and freeze-thaw cycling tests to determine the suitability of the mixture for the intended use.  
  
Wet Cycling Test  
  
The wet cycling test is an important aspect in determining the durability of the stone dust flyash and lime mix. The purpose of this test is to simulate the effect of moisture on the mix over time. The test involves subjecting the mix to a series of wet and dry cycles. The samples are first soaked in water for a specific time period, after which they are allowed to dry. The test is then repeated several times to simulate the effect of moisture on the mixture over time.  
  
In a study conducted by Rana et al. (2018), the researchers evaluated the durability of a stone dust and flyash blend concrete mix using the wet cycling test. The researchers observed that the mix demonstrated good durability when subjected to the wet cycling test. The study concluded that the mixture had a higher resistance to moisture penetration compared to conventional subgrade materials.  
  
Freeze-thaw Cycling Test  
  
The freeze-thaw cycling test is a crucial test in determining the durability of the mix as it simulates the effect of temperature fluctuations on the material. The test involves subjecting the samples to a series of cycles where they are frozen and thawed repeatedly. The test is carried out to determine the ability of the mix to withstand the effects of temperature changes over time.  
  
In a study conducted by Ahmed et al. (2018), the researchers evaluated the durability of flyash-lime stabilized crushed stone dust as a subgrade material using the freeze-thaw cycling test. The researchers observed that the mixture demonstrated good durability under freeze-thaw cycling. The study concluded that the mixture could be used as a sustainable alternative to conventional subgrade materials.  
  
Chemical Durability Test  
  
The chemical durability test is used to evaluate the resistance of the mix to chemical attacks such as acidity, alkalinity, and sulfate attacks. The test is important as it simulates the effect of chemicals on the mixture over time. The test involves subjecting the samples to different chemical solutions and measuring their resistance to the chemical attack.  
  
In a study conducted by ASTM (2004), a series of chemical durability tests were conducted on lime-flyash treated soils to determine the suitability of the material for subgrade construction. The results of the tests indicated that the mixture had a high resistance to chemical attacks, making it an ideal alternative to conventional subgrade materials.  
  
Conclusion  
  
In conclusion, the long-term performance of stone dust flyash and lime mix is critical in determining its viability as a green alternative to conventional subgrade materials. The durability of the mixture is tested using a series of tests, including wet cycling, freeze-thaw cycling, and chemical durability tests. The results of these tests indicate that the mixture demonstrates good durability and can be used successfully as a sustainable alternative to conventional subgrade materials.

## **1.9 Sustainability Evaluation**

Introduction:  
  
The development and growth of urban and rural infrastructure depend on sustainable and resilient transportation networks, and roads are a major component of this infrastructure. In the construction of roads, subgrade materials play a crucial role in providing strength and support to the overlying pavement layers. However, the materials used for subgrade construction are not always environmentally sustainable and may incur substantial environmental costs. In recent years, there has been a growing concern about the environmental impact of subgrade materials and, therefore, a need to develop more sustainable and eco-friendly options. This subchapter presents a comparative analysis of the environmental impacts of conventional subgrade materials and the Stone dust, fly ash, and lime mix. This will provide insight into the environmental benefits of the green alternative in terms of carbon footprint, energy consumption, and resource depletion.  
  
Sustainability Evaluation:  
  
The sustainability evaluation of the stone dust, fly ash, and lime mix as an alternative to conventional subgrades was compared based on three sustainability criteria including the carbon footprint, energy consumption, and resource depletion.  
  
Carbon footprint:  
  
The intense production and transportation activities of conventional subgrade materials such as gravel and crushed stone typically contribute to greenhouse gas emissions, therefore, increase carbon footprint [1]. In contrast, the production and transportation of fly ash, stone dust, and lime are usually less energy-intensive, and these materials release lower amounts of carbon dioxide as compared to conventional subgrade materials [2]. For example, the production of cement, which is a major constituent of conventional subgrades, releases 0.93 kg of CO2 for every kg of cement produced, while fly ash production releases only 0.2 kg of CO2 for every kg of fly ash [3]. Similarly, some studies have reported that the CO2 emissions associated with the production of aggregate are significantly higher than the production of stone dust [4]. Thus, using the Stone dust, fly ash, and lime mix in subgrade constructions can reduce the carbon footprint and promote environmental sustainability.  
  
Energy consumption:  
  
The energy consumption required for the production and transportation of conventional subgrade materials is typically high because these materials need to be processed and transported over longer distances [5]. On the other hand, Stone dust, fly ash, and lime tend to have lower energy consumption because they are usually produced locally, or from byproducts of other industries with a ready supply and are readily available [2]. For instance, fly ash is one of the waste materials generated by thermal power plants, and the reuse of this material in the Stone dust, fly ash, and lime mix can reduce the amount of energy required for their production [6]. Similarly, stone dust is a by-product of quarries and can be obtained without additional energy requirements. Thus, the use of the Stone dust, fly ash, and lime mix in subgrade constructions can substantially reduce energy consumption and promote environmental sustainability.  
  
Resource depletion:  
  
Another critical sustainability criterion for subgrade materials is their resource depletion. Conventional subgrades such as gravel and crushed stone require significant amounts of natural resources, particularly aggregate, which is a finite resource. The excessive exploitation of natural resources can result in environmental degradation and depletion of natural resources [7]. In contrast, Stone dust, fly ash, and lime are typically produced from by-products of other industries and can be obtained without exploiting finite natural resources. For example, fly ash is a by-product of coal-fired power plants, which would otherwise be sent to landfills, while stone dust is a waste product generated by quarries and is readily available without damaging the environment [2, 3]. Therefore, the use of Stone dust, fly ash, and lime mix in subgrade construction can reduce the impact of the subgrade on natural resources and promote environmental sustainability.  
  
Conclusion:  
  
The environmental impacts of the Stone dust, fly ash, and lime mix as a green alternative to conventional subgrade materials have been evaluated based on carbon footprint, energy consumption, and resource depletion. The results of this comparative analysis have shown that the Stone dust, fly ash and lime mix have significant environmental benefits, save energy, reduce carbon footprint, and prevent the depletion of natural resources. These materials have the potential to provide a sustainable alternative for subgrade construction, which may reduce environmental degradation and foster sustainable infrastructure development.

## **1.10 Cost-effectiveness Evaluation**

Introduction:  
  
In recent years, environmental concerns have led to the development of sustainable construction materials and methods. The use of green alternatives for subgrade stabilization is one of the methods that have been developed. The use of stone dust, fly ash, and lime mix could be used as a cost-effective alternative to conventional subgrade materials. The cost-effectiveness of the green mix will be evaluated and compared to the costs of conventional subgrade materials available.  
  
Cost-Effectiveness Evaluation:  
  
In assessing the cost-effectiveness of the green mix, it is essential to look at both the material costs and the construction costs. The material cost of the green mix is compared to the conventional subgrade materials. The construction costs of the two alternatives are also compared.  
  
Material Costs:  
  
Stone Dust: Stone dust is a waste product of the stone crushing industry, and it is readily available at low costs. According to Raman et al. (2017), the cost of stone dust per ton ranges from $1 to $2.5. This makes it an affordable material for subgrade stabilization.  
  
Fly Ash: Fly ash is a waste product from coal-fired power plants. It is a commonly used material for stabilizing subgrades. According to Mishra et al. (2018), the cost of fly ash varies from $3 to $7 per ton. This makes it slightly more expensive than stone dust.  
  
Lime: Lime is also a commonly used material in subgrade stabilization. According to Sarkar et al. (2018), the cost of lime per ton ranges from $90 to $150. This makes it the most expensive material in the green mix.  
  
Construction Costs:  
  
The construction costs of the green mix depend on various factors such as the thickness of the mix, the density of the mix, and the type of equipment used for construction. According to Raman et al. (2017), the thickness of the green mix should be at least 150mm. The density of the mix should be at least 95% of the maximum dry density (MDD) obtained from the standard Proctor test. The equipment used for the construction should be capable of achieving the required density.  
  
Comparing the material and construction costs of the green mix to the conventional subgrade materials reveals that the green mix is cost-effective. The cost of the green mix is lower than that of conventional subgrade materials. According to Varma et al. (2020), the cost of subgrade stabilization using conventional materials ranges from $15 to $20 per square meter. In comparison, the cost of stabilizing the subgrade using the green mix ranges from $5 to $10 per square meter.  
  
Conclusion:  
  
The use of the stone dust, fly ash, and lime mix is a cost-effective alternative to conventional subgrade materials. The material and construction costs of the green mix are lower than those of conventional subgrade materials. The cost-effectiveness of the green mix makes it a viable option for subgrade stabilization.

## **1.11 Conclusion**

Conclusion  
  
Based on the findings of this study, it can be concluded that using a mixture of stone dust, fly ash, and lime as a subgrade material is a viable green alternative to conventional subgrade materials such as gravel, sand, and crushed stone. The mix of stone dust, fly ash, and lime not only improves the strength and durability of the subgrade but also has significant environmental benefits as compared to the conventional materials. The use of this mixture helps in reducing the carbon footprint by reusing the fly ash generated from power plants and quarrying waste.  
  
The incorporation of stone dust into the mix helps in improving the geotechnical properties of cohesive soils, while lime acts as a stabilizer to reduce plasticity and enhance the strength. Fly ash provides pozzolanic properties, enhancing the strength and durability of the mix. The strength of the subgrade mix was found to exceed the requirements for subgrade materials specified by the American Association of State Highway and Transportation Officials (AASHTO) and the Indian Road Congress (IRC).  
  
Additionally, the mixture of stone dust, fly ash, and lime is relatively cheaper compared to the conventional subgrade materials. This is because the materials used in the mixture are industrial by-products which are readily available and would otherwise be considered as waste. The use of these by-products as subgrade materials results in a reduction in disposal costs while promoting sustainability.  
  
However, there are some limitations to the use of this green alternative that should not be disregarded. For example, the use of fly ash in the mix requires additional curing time to achieve optimal strength. Furthermore, the proportion of these ingredients in the mix needs to be adjusted according to the local soil conditions. This is essential in ensuring that the mix is effective in improving the strength and durability of the subgrade.  
  
Future research could be conducted to investigate the use of this mixture in other applications, such as pavement base and subbase layers. Additionally, research could be conducted on the long-term durability of the mixture, especially in areas with harsh climatic conditions.

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