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Research Article

Effects of Chemical Stabilisation of Eggshells-Lime and Fly-Ash-Cement on the Structural Strength of Subgrade Soil in Rural Roads

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Abstract

This study examines the chemical compositions of eggshell powder (ESP) and lime as the soil stabilisers and compared with the compositions of cement and fly-ash to understand the optimal distribution of chemical stabilisers maximising the bearing capacity and structural integrity of subgrade soil. The different proportions of eggshell powder (ESP) (2%, 4%, 6% and 8% of total soil mass) were mixed with a fixed proportion of lime (6% of total soil mass) to analyse the optimum proportion of eggshell maximising the soil structural integrity. Similar proportions of fly-ash (2%, 4%, 6% and 8% of total soil mass) were mixed with cement (4% of total soil mass) to analyse the comparative effects of ESP-lime and fly-ash-cement on the soil stability. The soil samples were collected from three different points of unpaved roads in Ganderbal district of Jammu & Kashmir State in India that experiences the seasonal variations resulting in uneven moisture distribution throughout the year. The CBR tests of both treated (chemical stabilisation) and untreated soils were performed followed the code of practices in

Indian standards that is IS: 2720 1985. The combination of 4% ESP and 6% lime resulted in highest CBR value at 19.06%; and the combination of 4% fly-ash and 4% cement had the CBR value of 18.73%. The increase in bearing capacity of subgrade soil mixed with ESP and lime supports the pavement structure with less thickness resulting in the reduction of budgetary allocation for road construction, maintenance and rehabilitation operations.

Keywords
Chemical stabilisation; eggshells; fly-ash; lime; cement; California bearing ratio

1. Introduction

Rural road has played an important role in land use change and economic development; and the increasing demands related to rural economic growth have also highlighted shortfalls in the quantity and quality of rural roads [1-5]. The structural strength of rural road has direct and indirect effects at various extents on human activities and land uses in rural areas particularly with limited access of transport facilities [6]. Rural roads in developing countries are mostly unpaved. For example, 70% (1.9 million km) of rural roads in India are unpaved. Unsuitable and lack of maintenance of rural roads result in poor load bearing capacity of subgrade soil that is subject to farm-bound traffic flows and moisture contents. The State of Jammu and Kashmir in India has a wide variety of soil types that experience seasonal variations with heavy rains, winter and summers resulting in uneven moisture distribution throughout the year. The uneven moisture distribution leads to poor quality of subgrade soil that is the main cause of poor condition of rural roads in the State of Jammu and Kashmir in India.

The drained and undrained shear strength, maximum dry density, optimum moisture content, proportion of fine aggregates, Atterberg limits are the physical parameters that define the strength of subgrade soil. The soil compaction, reinforcements, pore water pressure reduction (dewatering) and chemical stabilisation are typically used to improve the shear strength parameters and bearing capacity of subgrade soils [7, 8]. The methods of stabilisation, both mechanical and chemical, have significant impacts on settlement, shearing resistance, and bearing capacity of subgrade soil. The most common chemical stabilisers are lime, cement and fly-ash, although there are other methods of soil stabilisations such as geo-textiles and fabrics, recycled waste, thermal and electrical stabilisations.

Lime stabilisation is a historic technique for increasing flexible properties and strength of soil. Lime stabilisation that includes cation-exchange, flocculation, carbonation and pozzolanic response can change the plastic nature of soils, decrease the liquid limit and increase the soil strength [9, 10]. Cement is also commonly used as a binding agent to strengthen the bearing capacity of soil by the process of cement hydration. Cement stabilisation process depends on soil types, proportion of cement-water contents, degree of mixing and time of curing [11]. Portland cement is effective for rural roads, in terms of compressive strength, durability, uniform load distribution, deflection reduction and resiliency to leaching over long-term period in stabilising both granulated and fine-grained soils; however, cement stabilisation reduces the permeability of subgrades soil and comparatively expensive [12-14]. Azadegan et al. [7] investigated the soil stabilisation by cement kiln dust and fly ash (Class C) at five construction sites in Oklahoma and revealed that treated soils had 7 to 46 times resilient modulus than untreated soil. Similarly, Madhu et al. [15] experimented that mixing 10% cement and 5% lime with soil increased the California Bearing Ratio (CBR) value by 15% to 25% at 2.5 mm penetration.

Several studies examined the process of soil stabilisation using fly-ash (a fine residue of coal combustion in thermal power plants) classified as class F or class C [16-21]. Senol et al. [18] investigated different proportions of fly-ash (0%, 10%, 18%, and 30%) and water contents in soil stabilisation process and concluded that fly-ash enhanced the CBR value of soil with a range of 15% to 31%. Similarly, Hatipoglu et al. [19] stated that stabilisation of road surface gravel in Minnesota with fly-ash increased the CBR value by 2 times. Prabakar et al. [20] determiend that fly-ash decreased the dry density by 15% to 20%, and increased the void ratio and porosity in soil. For example, the void ratio was increased by 25% with the addition of up to 46% fly-ash in soil [20]. Fly-ash (particularly Class C) alsoincreases the structural strengh and stifness of subgrade soil [16, 21].

Eggshell powder (ESP) is eco-friendly, economical and sustainable soil stabiliser that is available from kitchen waste without any cost and its production is very simple. Various studies analysed the effect of ESP on the strength and durability of soil. Paul et al. [22] investigated that ESP increased the optimum moisture content (OMC) and decreased the maximum dry density (MDD). Mn and Fo [23] argued that eggshell could be a potential replacment of cement stablised soil after observing the increase in soil strength with different proportion of eggshell powder mixed with cement stablised soil. Similarly, Ahmed et al. [24] found that the optimum soil stabilisation with ESP could increase the CBR value by 11%. Some studies tested ESP as the partial replacement of soil cement stabilisation, while studies used the combination of cement and lime stabilisation. Since rural roads in developing countries like India are deprived of infrastructure budget for periodic maintenance, a cost-effective solution for soil stabilistaiton can improve the condition of subgrade soil of unpaved roads. The 95% of eggshells is Calcium Oxide (CaO) while quick line is manufactured by transforming calcium carbonate ($CaCO_3$) into CaO. A combination of low cost and easily available eggshells and lime with similar chemical properites can enhance the soil stabilistion. This study examines the chemical compositions of ESP and lime as the soil stabilisers and compared with the compositions of cement and fly-ash to understand the optimal distribution of chemical stabilisers to maximise the bearing capacity of subgrade soil because ESP and lime are eco-friendly and least expensive stabilisers.

2. Methodology

The soil samples were collected from there points of unpaved roads in Ganderbal district of Jammu & Kashmir State in India. The sample soils were mixed with chemical stabilisers and oven dried at the laboratory of Roads and Building Department in Srinagar, capital of Jammu & Kashmir State. The chemical compositions of subgrade soil and the chemical stabilisers are given in Table 1. This study followed the code of practices in Indian standards that is IS: 2720 1985 for carrying out the soil experiments. The sample soils were compacted using proctor standard tests to get optimum moisture content corresponding to maximum dry density. The index properties of sample soils such as liquid limit, plastic limit, and plasticity index were examined. The sample soils with optimum moisture content were taken to perform CBR test.

Table 1 Chemical composition of subgrade soil and chemical stabilisers.

Materials	Subgrade soil (%)	Lime (%)	Fly-ash cement (%)	Eggshell (%)
Silicon dioxide (SiO_2)	67.1	10.3	64.6	0.07
Aluminum oxide (Al_2O_3)	19.83	1.52	28.2	0.04
Ferric oxide (Fe_2O_3)	8.17	0.9	2.1	0.02
Calcium oxide (CaO)	1.08	-	0.8	-
Magnesium oxide (MgO)	0.18	1.3	0.5	0.01
Potassium oxide (K_2O)	1.78	-	-	-
Titanium dioxide (TiO_2)	0.93	-	0.5	-
Calcium carbonate ($CaCO_3$)	-	83.9	-	95.2
Chloride ion (Cl)	-	-	-	0.65
Surfer trioxide (SO_3)	-	-	0.05	0.61
Disodium monoxide (Na_2O)	-	-	-	0.16

The CBR tests of both treated (chemical stabilisation) and untreated soils were conducted under soaked condition and the specimens were soaked in water for 4 days as the shear strength of soil decreases with the increase of moisture content. The prolonged soaking of soil increased the percolation of water to soil subgrade from the road surface or by seepage. The increase of moisture content in subgrade soil decreases the performance of the pavement. The different proportions of eggshell powder (ESP) (2%, 4%, 6% and 8% of total soil mass) were mixed with a fixed proportion of lime (6% of total soil mass) to analyse the optimum proportion of eggshell maximising the soil structural integrity. Similar proportions of fly-ash (2%, 4%, 6% and 8% of total soil mass) were mixed with cement (4% of total soil mass) to analyse the comparative effects of ESP-lime and fly-ash-cement on the soil stability. This study tested Class F fly-ash (consists of alumino-silicate glass mulita and magnetite) and quicklime as the chemical stabilisers.

Liquid limit, plastic limit and CBR tests were performed to understand the soil stabilisation process followed as per Indian Standards Code IS: 4332 (Part IV). The Casagrande apparatus was used to determine liquid limit of soil. The 120 grams of soil sample passing through 425-micron sieve was mixed with water to attain a uniform paste. The soil paste was placed in a cup and a sharp grove was made along the centreline. The cup was dropped from a height of about 1 cm by rotating the crank at the rate of 2 revolutions/sec till two splits of soil get separated along 12 mm. Number of blows were recorded, and a representative sample of soil cake was collected and oven dried to determine moisture content. The moisture content corresponding to 25 blows was taken as Liquid limit of soil.

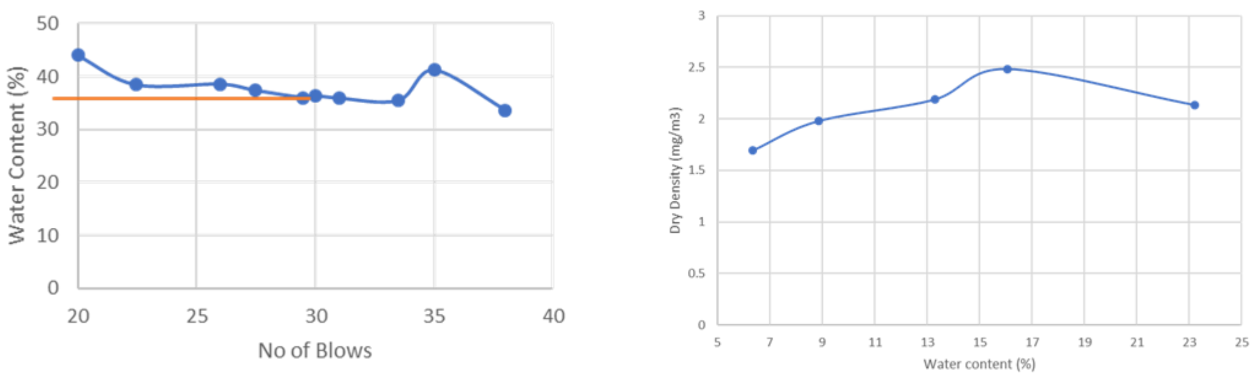
The soil samples of 20 grams passing through 425-micron sieve were mixed with distilled water in evaporating dishes to estimate the plastic limit of soils. An 8-gram ball of soil sample was rolled between fingers and a glass plate into a uniform thread. Rate of rolling was kept at 80 to 90 strokes per minute and continued till the thread reaches a diameter of 3 mm. Pieces of crumbled thread formed were put in a container to determine the moisture content. The average of trails was determined as the plastic limit of treated soils.

The standard proctor compaction test were performed to determine the optimum moisture content and dry density of soil. A soil sample of about 12-14 kg was mixed with 8% water and kept in an air tight container for about 18 hours. The soil sample was then divided into five equal parts and 2.5 kg of soil was taken in a tray. The diameter, height, volume and weight of moulds with base plate were recorded and the collar was attached. Soil was filed up to 1/3 height of moulds and compacted with 25 blows. The procedures were followed for the next two layers, collar was removed, and excess soil was trimmed using a straight edge. A sample soil was taken from the middle portion of compacted soil and mixed with 3% additional water. The process was repeated for 5 times to estimate the optimum water content maximising the dry density. The optimum water content of soil was used for CBR test.

According to Indian code IS 2720 (part 16), the standard penetration device is comprised of a mould with internal diameter 150 mm and a height of 175 mm; a detachable collar and a base plate having perforations at bottom; a spacer disk of 148 mm diameter and a height of 47.7 mm. The surcharge weights of mass 2 kg each and having a centre hole of 53 mm diameter and a slotted weight of 2.5 kg. A loading machine, capacity of 5000 kg, was equipped with a movable head and base travelling with a uniform rate of 1.25 mm/min. Test specimen for CBR test was prepared by dynamic compaction of 5 layers with 72 blows for each layer. The CBR values were investigated at 2.5 mm or 5 mm penetration for both untreated and treated soils (with different proportions of chemical stabilisers) to determine the subgrade soil's bearing capacity.

3. Results and Discussion

The liquid limit, plastic limit, standard proctor compaction and CBR tests were performed both for untreated and stabilised soil samples to understand the impact of chemical stabilisation on the physical properties of subgrade soil. The average value of liquid limit or water content of untreated soil, estimated from the Casagrande apparatus, was determined as 37 (Figure 1a). The plasticity index (%) of untreated soil is 10 that is within the range (7-16) of clay and low plasticity soil (Wagner 2013). The range of liquid limit (%) for the clay and low plasticity soil is 25-35 [25]. The sample untreated soil is categorised as clay with low plasticity and the liquid limit is considered as 27 for laboratory experiments. The clay, gravel and sand ratio of untreated soil is 85:3:12. The compaction test estimated the optimum moisture content of untreated soil as 16% with a maximum dry density of 2.5 mg/m^3 (Figure 1b). This optimum moisture content was used to estimate the soaked CBR values for treated soil mixed with chemical stabilisers.

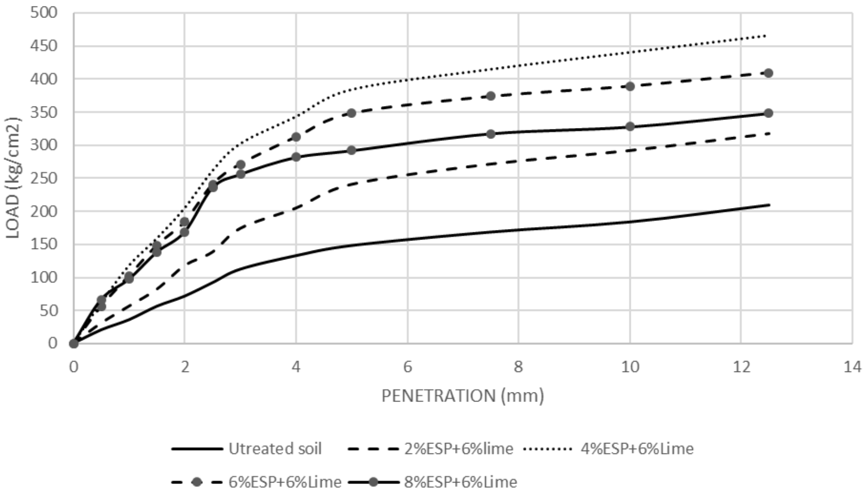


(a) Liquid limit

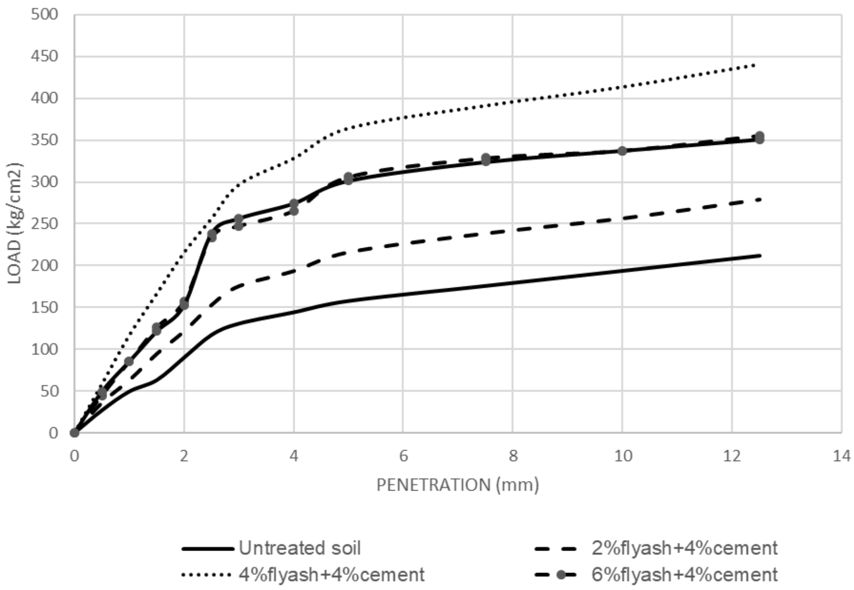
(b) Proctor compaction test

Figure 1 Physical properties of untreated soil.

The soaked CBR values for soils mixed with different proportions of chemical-stabiliser mixtures were investigated to achieve the optimum contents of chemical stabilisers that ensure the highest CBR values and bearing capacity of subgrade soils. The different proportions of eggshell powder (ESP) (2%, 4%, 6% and 8% of total soil mass) were mixed with a fixed proportion of lime (6% of total soil mass) to analyse the optimum proportion of eggshell maximising the soil structural integrity. Similar proportions of fly-ash (2%, 4%, 6% and 8% of total soil mass) were mixed with cement (4% of total soil mass) to analyse the comparative effects of ESP-lime and fly-ash-cement on the soil stability. During the penetration test, the penetration piston is forced into the soil samples at a constant loading rate. The load-penetration curves for different proportions of chemical stabilisers mixed with soil samples were obtained observing the displacement and contact force of soil's wall (Figure 2a and Figure 2b).



(a) Composition of eggshell powder and lime



(b) Composition of fly-ash and cement

Figure 2 CBR values of soil chemical stabilization.

The CBR values of sample soils for different proportions of chemical stabilisers were calculated from the correlated unit test load values corresponding to 2.5 mm and 5 mm penetration from the load-penetration curve. Since the CBR values at 2.5 mm penetration were higher than that of 5 mm penetration, CBR values at 2.5 mm penetration were compared for soil samples mixed with different proportions of chemical stabilisers. The CBR value for untreated soil at 2.5 mm penetration was found to be 6.73%. The CBR values were increased with addition of both compositions of chemical stabilisers but started to decrease after more than 4% of total mass of soil samples. The optimum proportion of ESP and fly-ash in both chemical stabilisation processes is 4%. The ESP and fly-ash have no significant influences on the CBR numerical results as additive materials when their proportions exceed 4% of total mass of soil. The CBR value for soil mixed ESP and lime was highest (19.06%) for a mixture of 4% ESP and 6% lime. Similarly, the highest value (18.73%) of CBR for treated soil was achieved with a composition of 4% fly-ash and 4% cement. The CBR value remains constant after reaching the highest value despite addition of ESP and fly-ash in the soil samples. The IRC 37-2012 code is used for designing flexible pavements in India. The standard range of CBR value for subgrade material is 15% to 19%. Moreover, the CBR values were almost similar for both chemical compositions of soil stabilisers. This investigation reveals that using the same proportion (4%) of ESP and lime as additive materials for soil, the subgrade soil of rural roads can achieve the equivalent bearing capacity with that mixed with fly-ash and cement. The chemical composition of ESP and lime is eco-friendlier, and the eggshells can be collected from the kitchen waste almost free of costs.

4. Conclusions

The methods of soil stabilisation, both mechanical and chemical, have significant impacts on the settlement, shearing resistance, and bearing capacity of subgrade soil. The most common chemical stabilisers are lime, cement and fly-ash, although there are other methods of soil stabilisation such as geo-textiles and fabrics, recycled waste, and thermal and electrical stabilisations. This study examines the chemical compositions of ESP and lime as the soil stabilisers and compared with the compositions of cement and fly-ash to understand the optimal distribution of chemical stabilisers to maximise the bearing capacity of subgrade soil because ESP and lime are eco-friendly and least expensive stabilisers. Different proportions of ESP and fly-ash were mixed with a fixed proportion of lime and cement to analyse the optimum proportion of eggshell maximising the soil structural integrity and the comparative effects of ESP-lime and fly-ash-cement on the soil stability.

The soil samples were collected from three different points of unpaved roads in Ganderbal district of Jammu & Kashmir State in India that experiences the seasonal variations with heavy rains, winter and summers resulting in uneven moisture distribution throughout the year. The CBR tests of both treated (chemical stabilisation) and untreated soils were performed followed the code of practices in Indian standards that is IS: 2720 1985.

The laboratory investigation reveals that ESP and fly-ash can be used as the activators for lime and cement in improving strength properties of subgrade soil, respectively. The combination of 4% ESP and 6% lime resulted in highest CBR value at 19.06%. on the other hand, the chemical stabilisation with 4% fly-ash and 4% cement provides the CBR value of 18.73%. The increase in bearing capacity of subgrade soil supports the thickness reduction of pavement structure resulting in less budgetary allocation for road construction, maintenance and rehabilitation operations. In addition, chemical stabilization of soil with ESP and lime is more economical and eco-friendlier comparing to the production of other chemical stabilisers. Eggshells are produced in large quantities mostly from restaurants and hotels, and there is a disposal problem in developing countries. The use of ESP as the additive material of subgrade soil not only improve the bearing capacity of subgrade soil but also reduces the construction and maintenance costs of pavement structure as well as handling and recycling costs of food waste.

This study only investigated the ESP and fly-ash combined with lime and cement, respectively. There is a scope for comparative investigation on other stabilisers such as plastic bags, geo-synthetics, geo-fibres and geo-polymers that can be used for stabilisation process. The experiments were performed in a controlled environment with no variation in temperature. Future studies should investigate the chemical stabilisation of soil with seasonal variations and different temperatures. The CBR tests were performed on soil samples with optimum moisture content that is not feasible during the road construction projects. Further experiments such as unconfined compressive strength test, swelling, permeability and porosity of subgrade soil require to be investigated to understand the impacts of seasonal and temperature variations. The sample subgrade soils examined in this study were clay with low compressibility. The impacts of chemical compositions of ESP-lime and fly-ash-cement require to be investigated for other types of subgrade soil such as sandy, silty, and loamy.

Author Contributions

Dr. Amin: conceptualisation, supervision, writing-reviewing, editing; Mr. Khan: methodology, resources, experiments, writing-original draft, project administration.

Competing Interests

The authors have declared that no competing interests exist.

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