

Stabilization of Pavement Subgrade by Using Fly Ash Activated by Cement

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Abstract The performance of pavement is very responsive to the characteristics of the soil subgrade. For that reason, weak subgrade is enhanced by adopting the most efficient stabilization technique. Based on the literature review, stabilization with fly ash activated with cement was found to be an effective option for improvement of soil properties. In this regard an experimental program was undertaken to study the effect caused by the combined action of fly ash and cement stabilization on the geotechnical characteristics of expansive subgrade soils. Expansive soil treated with varying percentages of fly ash, 0, 5, 10, 15, and 20 percent combined with 5% cement content were studied. Consistency limits, compaction, California Bearing Ratio, swell potential and swell pressure tests were conducted on treated and untreated soils. The experimental results show that addition of cement-fly ash admixture to the soil has great influence on its properties. It was found that the optimum dosage of fly ash is 15% mixed with 5% cement revealed in significant improvement in strength and durability and reduction in swelling and plasticity properties of the soil. Based on the results, it is recommended that cement-fly ash admixture be considered a viable option for the stabilization of expansive subgrades.

Keywords: cement, fly ash, expansive soil, improvement, stabilization, subgrade

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1. Introduction

Subgrade soil provides base for the whole pavement structure. Weak subgrades of expansive soil has great tendency to swell and shrink when in contact with water. This behaviour is believed to have been derived from clay rich of montmorillonite mineral. These expansive soils can be improved through the addition of chemical or cementitious additives. These additives range from waste products to manufactured materials which include fly ash, cement, lime and proprietary chemical stabilizers. Weak subgrade soils are usually improved by cement or lime. In fact, cement stabilization provide an effective solution to the problem of fatigue failures caused by repeated high deflection of asphalt surfaces where a weak subgrade exists in the pavement structure, [1].

Experiences in areas of expansive subgrades, show significant improvement in strength and a marked decrease in deflection when subgrades are stabilized with cement, while treatment with lime or fly ash is a well known practice adopted to reduce swelling behaviour. The effect of fly ash stabilization on soil properties varies widely depending on the type of fly ash and its composition. Due to the lack of self-cementitious characteristics, class F fly ash activated by cement result in greatest improvement in strength and swelling of expansive soil. Some previous researchers pointed out that treatment of subgrade soils with cement-fly ash admixture

performs better than lime-treated soils particularly in soils with low strength and high swelling properties ([1,2,3]). Therefore, this study focuses on stabilization of expansive subgrades using fly ash combined with cement.

2. Literature Review

Soil stabilization is widely known as an effective alternative for improving soil properties. Stabilization can be derived from mechanical or chemical means. Mechanical stabilization, or compaction, is the densification of soil by application of mechanical energy. Chemical stabilization involves mixing or injecting soil with chemically active compounds such as cement, lime, fly ash, calcium or sodium chloride or with viscoelastic materials such as bitumen. Among these, the most widely used chemical additives are cement, lime and fly ash, [4]. These additives are most frequently associated with improving the strength and reducing the swelling properties of expansive soils and can be used with a variety of soils as described in Table 1, [5].

Extensive researches have been conducted pertaining to the use of chemical stabilizers, namely cement, lime and fly ash. The stabilization mechanisms for them are well documented, and their effectiveness has been demonstrated in many applications.

2.1. Cement Stabilization

Cement is the oldest binding agent since the invention of soil stabilization technology in 1960's. It may be

considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required. Cement is used to stabilize a wide range of soils. Numerous types of cement are available in the market such as ordinary Portland cement, blast furnace cement, sulfate resistant cement and high alumina cement. Usually the choice of cement depends on

type of soil to be treated and desired final strength. Normally the amount of cement used is small but sufficient to improve the engineering properties of the soil and further improved cation exchange of clay. Cement can be used to modify and improve the quality of the soil or to transform the soil into a cemented mass with increased strength and durability, [6].

Table 1. Common chemical stabilizers for soils (source [5])

Stabilizer	Application
Portland Cement	Generally used to stabilize well-graded granular materials and fine grained soils. Used mainly for strength and stiffness stabilization.
Lime	Used to stabilize high plastic clay soils in order to decrease plasticity, increase workability, reduce swell, and increase strength.
Fly ash	A pozzolanic material that reacts with lime and is usually used in combination with lime or cement in soils that have high plastic fines.
Lime-cement-fly ash	Used successfully for stabilization of various types of soils such as base granular materials and subgrade soils.

2.1.1. Chemical Composition

Portland cement is comprised of calcium-silicates and calcium-aluminates that hydrate to form cementitious products. According to ASTM [7], the chemical composition of typical Portland cement is presented in Table 2.

Table 2. Chemical composition of typical Portland cement

Chemical component	Percent
Alumina (Al ₂ O ₃)	5 – 9%
Silica (SiO ₂)	19 – 25%
Calcium oxide (CaO),	60 – 64%
Ferric Oxide (FeO).	2 – 4%
Tri-calcium silicate (C ₃ S), Di-calcium silicate (C ₂ S), Tetra-calcium aluminates	5 – 9%,

2.1.2. Stabilization Mechanism

Strength gain in soils using cement stabilization occurs through the hydration, cation exchange, carbonation and pozzolanic reactions, [8]. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil. This can be the reason why cement is used to stabilize a wide range of soils.

Hydration process: when water is added to cement, the hydration process begins. Cement hydration is relatively fast and causes immediate strength gain in stabilized soil, [8]. During the hydration process, free lime, Ca(OH)₂ is produced. This free lime in the high pH environment has the ability to react pozzolanically with soil. The major cementitious products like calcium silicate hydrates and calcium aluminium hydrates are produced. These cementitious materials provide the bond between the mineral particles.

Cation exchange: when cement is added to a soil, some reactions between the free lime and the clay minerals take place. Some of them occur immediately while others are slow to occur. One of the early reactions is base-exchange (ion-exchange). Clay particles are usually negatively charged, with exchangeable ions of sodium, magnesium, potassium or hydrogen adsorbed on the surface. The strong positively charged ions of calcium present in

replace the weaker ions (Na⁺, Mg⁺², K⁺ or H⁺), resulting in a preponderance of positively charged calcium ions on the surface of the clay particles. This in turns reduces the plasticity of the soil. The clay particles tend to agglomerate into large sized particles (flocculation), imparting friability to the mixture.

Pozzolanic reactions: After the above first stage reactions are complete, any additional quantity of cement will react chemically with the clay minerals. Cement contains the calcium and the silica required for the pozzolanic reactions to occur. Unlike lime stabilization, cement already contains the silica without needing to break down the clay mineral. Thus, cement stabilization is fairly independent of the soil properties. The aluminous and siliceous materials in the clayey soil will react with lime in the presence of water to form cementitious gels, which increase the strength and durability of the mixture. These pozzolanic reactions are slow and extend over a long period of time, several years in some instances.

Carbonation reaction: carbonation can occur when using cement stabilization. When cement is exposed to air, the cement will react with carbon dioxide from the atmosphere to produce a relatively insoluble calcium carbonate. Thus proper handling methods and expedited construction procedures should be employed to avoid premature carbonation of cement through exposure to air.

2.1.3. Influencing Factors

The factors that affect the performance of soil-cement mixture are cement content, soil type, compaction (i.e. moisture content and dry density), curing time and temperature ([9,10]).

The goal of soil-cement mixture design is to find the lowest cement content that will produce a desired strength. The strength of treated soil usually increases with increasing amount of cement. Consoli et al [11] emphasized that the addition of cement, even in small amounts, greatly improves the soil strength. The unconfined compression strength increased approximately linearly with an increase in the cement content. As observed by Davis et al [12], increasing the cement content increased the measured unconfined compressive strength and the maximum strength value obtained at 5% cement dosage for all four soils investigated. Ingles and Metcalf [13] indicated that strength gain of soil-cement mixtures increases linearly with cement content (Figure 1).

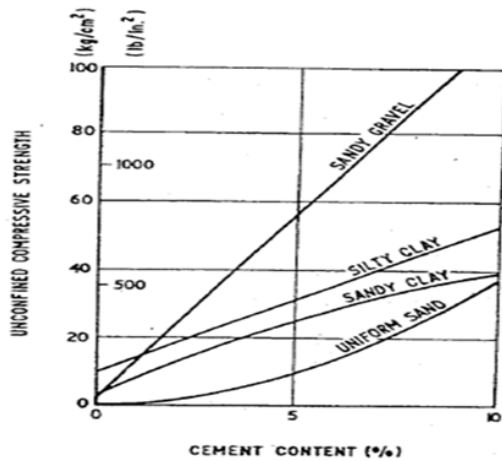


Figure 1. Strength and cement content relationship for different type of soils (source [13])

The type of soil has great influence on the soil strength as shown in Figure 1. From this figure, it is observed that sandy gravel has higher strength than clay and uniform sand soils. If a soil contains too much organic matter, cement would not produce proper strength. Though Lambe et al [14] suggested that addition of 0.5 to 1% of sodium silicate, calcium chloride or alkali-metal compounds may improve the strength of soil cement mixture.

Density is another important parameter that affects stabilized soil strength. In general, the higher the density, the higher the strength is expected. The rate of strength gain increased with an increase in the dry density of the compacted soil-cement mixture, indicating that the effectiveness of the cement is greater in more compacted mixtures. Moreover, for a given dry density, the variation in moisture content affected the strength of the soil-cement mixture. Generally, an increase in strength is observed with increasing moisture content until a maximum value is reached, after which the strength decreases. It appears that this effect of moisture content varies with the cement content, [11].

It was shown by Miura et al. [15] that the primary factor governing the behavior of cement-stabilized soil is the water-cement ratio. The water-cement ratio is defined as the ratio of moisture content of the soil to the cement content, with both the moisture content and cement content expressed in terms of dry weight of soil. Their study results indicated that increasing water-cement ratio produced decreasing strength of the cement-stabilized soil.

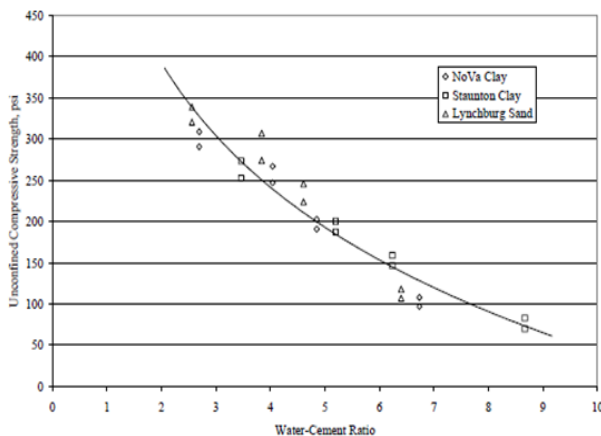


Figure 2. Relationship between 28-day Unconfined Compression Strength and Water-Cement Ratio (source [16])

Geiman [16] reported that the water-cement ratio of cement-stabilized soil had the dominant influence on unconfined compression strength and durability of stabilized samples tested (see Figure 2). In this figure, the relationship can be used to predict the amount of cement needed to achieve a desired strength.

Also curing temperature and curing time are importance factors that influence soil strength (see Figure 3). Accordingly, many mixture design procedures involve molding and curing specimens at varying cement contents until the lowest cement content which provides the required strength is achieved.

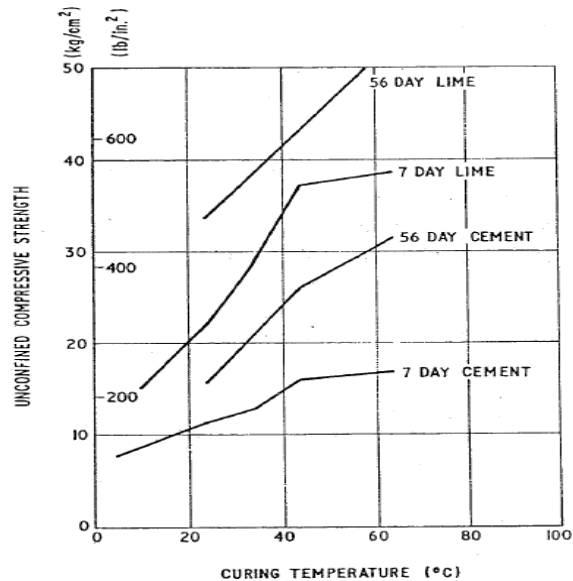


Figure 3. Influence of curing time and temperature on strength (source [13])

2.2. Fly Ash Stabilization

Fly ash has historically been used in concrete and soil stabilization. Fly ash is a by-product material from burning coal during power generation, while lime and Portland cement are manufactured materials. As with other by-products, the properties of fly ash can vary significantly depending on the source of the coal and the steps followed in the coal burning process.

These by-products can broadly be classified into class C (self-cementing) and class F (non-self cementing) fly ash based on AASHTO [17] and ASTM [7]. Class C fly ash contains a substantial amount of lime, CaO, but almost all of it is combined with glassy silicates and aluminates. Therefore upon mixing with water, a hydration reaction similar to that which occurs in the hydration of Portland cement occurs. As with Portland cement, this hydration reaction produces free lime which can react with other unreacted pozzolans, silicates and aluminates, available within the fly ash to produce a pozzolanic reaction, or it may react pozzolanically with soil silica and/or alumina. Class F ash, on the other hand, contains very little lime and the glassy silica and/or alumina exists almost exclusively as pozzolans. Therefore, activation of these pozzolans requires additives such as Portland cement or lime, which provide a ready source of free lime. The hydration or “cementitious” reactions and the pozzolanic reactions that occur when fly ash is blended with water form the products that bond soil grains or agglomerates

together to develop strength within the soil matrix. As discussed previously, maintenance of a high system pH is required for long term strength gain in fly ash-soil mixtures.

Arora and Aydilek [18] who investigated the use of Class F fly ash amended soil–cement or soil–lime as base layers in highways. He stated that Class F fly ash cannot be used alone in soil stabilization applications as it is not self-cementing. An activator such as Portland cement or lime must be added to produce cementitious products often called pozzolan stabilized mixtures. The developed mixture must possess adequate strength and durability, should be easily compacted, and should be environmentally friendly. Roadways have a high potential for large volume use of the fly ash stabilized soils. According to ASTM [7], the chemical compositions of typical fly ash are given in Table 3.

Table 3. Chemical Compositions of Typical Fly Ash (source [17])

Chemical component	Typical Fly ash	
	Class C	Class F
Silica (Si O ₂)	40	55
Alumina (Al ₂ O ₃)	16	26
Ferric oxide (Fe ₂ O ₃)	6	7
Calcium oxide (CaO)	24	9
Magnesium oxide (MgO)	2	2
Sulfate oxide (SO ₃)	3	1
Loss of ignition (LOI)	6	6

2.3. Cement-Fly Ash Stabilization

The concept of chemical stabilization is most frequently associated with improving the strength and swelling properties of expansive soils. Due to the lack of self-cementitious characteristics, class F fly ash activated by cement. Therefore, altering the properties of expansive subgrade soils by means of cement and fly ash stabilizers is more effective form of durable stabilization.

Soil stabilization occurs when a significant reaction takes place. This reaction can be due to hydration of calcium-silicates and/or calcium aluminates in Portland cement or fly ash or due to pozzolanic reactivity between free lime and soil pozzolans or added pozzolans. The strength improvement can be much higher when compared to the strength of the untreated soil. Therefore, this study focuses on key factors associated with stabilizing expansive soils using cement-fly ash stabilizer.

The cementitious reactions and pozzolanic reactions that occur in fly ash stabilized soils vary widely depending on the type of fly ash and its composition. Normally, class C fly ashes react rapidly upon hydration. However, class F fly ashes activated with lime or Portland cement produce substantially slower reactions than Portland cement – soil blends.

The potential and efficiency of adding fly ash into cement-admixed clay were studied by means of a series of unconfined compression strength and physical tests, [19]. From their investigation, it is confirmed that, with suitable cement content, this fly ash could be successfully added into soil cement to enhance both strength and physical characteristics. The strength of cement-fly ash admixed clay at high water content increased with increasing

amount of cementitious material content and duration of the curing time and decreased with increasing water content. The efficiency of fly ash depended on the portion of cement, fly ash, and water content in mixtures.

Lo and Wardani [20] who experimentally studied the mechanical behavior of a weakly cemented silt. The cementing agent was cement and fly ash slurry, and the samples so formed were slightly cemented. They pointed out that the cemented soils were initially less dilatant than their respective parent soils but eventually became more dilatant than the parent soils.

According to Kaniraj and Havanagi [21], the unconfined compression strength (UCS) of a fly ash-soil mixture increases due to addition of cement. Depending on the type of the mixture and curing period, the increase in UCS caused by the combined action of cement and fly ash is either more than or nearly equal to the sum of the increase caused by them individually.

3. Laboratory Investigation

The laboratory testing program was undertaken to achieve the objectives of the study. Laboratory tests were conducted on natural soil and treated soil with cement-fly ash admixture. Expansive soil stabilized with varying percentages of fly ash, 5, 10, 15, and 20 percent combined with a constant cement content of 5% were investigated to determine their influence on engineering properties of the soil. The laboratory tests to get these properties were carried out in accordance with BS [22].

3.1. Materials Used

The materials used in the study include expansive soil, fly ash and cement. Expansive soil sample was collected from Almenshia in Khartoum, Sudan. The soil taken was air dried and pulverized to pass through 425 microns sieve and then oven dried before testing. The physical properties of the soil used are presented in Table 4.

Table 4. Properties of expansive soil used

Property	Value
Sand	18
Silt	19
Clay	63
Specific gravity	2.72
LL	55
PI	30
USCS	CH

The Fly ash used for this research was obtained from thermal power generation station in Khartoum North. This fly ash is classified as class "F" type. It was added to expansive soil in varying percentages of 5%, 10%, 15%, and 20% by weight. The cement used for the study is Ordinary Portland Cement (OPC) which was purchased from the market. Based on literature review, the cement is used to activate the fly ash and is added at a constant content of 5%.

3.2. Testing Procedures

Initially the properties of natural soil were determined. The soil was then stabilized with cement-fly ash. The

amount of fly ash for stabilization is taken in the proportions of 5%, 10%, 15%, and 20% by dry weight of soil and the amount of cement was taken fixed at 5% by dry weight of soil. Using these proportions, mix samples were prepared as given below and a set of laboratory tests were performed to determine the index properties, swelling and CBR values of both natural soil and mixed proportion samples. The laboratory tests conducted on the treated expansive soil include; grain size analysis, Atterberg's limits, compaction, soaked CBR and swell potential and swell pressure tests. Mix Proportion Samples of soil, Fly ash and cement used for Stabilization are:

1. Natural soil.
2. Soil +5% Fly ash +5% Cement.
3. Soil +10% Fly ash +5% Cement.
4. Soil +15% Fly ash +5% Cement.
5. Soil +20% Fly ash +5% Cement.

4. Results and Discussion

The experiments results are presented and discussed here in this section. It is observed that the addition of cement-fly ash stabilizing agent has improved the soil properties.

4.1. Soil Consistency

The variation in soil consistency properties such as liquid limit, plastic limit and plasticity index of the expansive soil treated with cement-Fly ash is presented in Figure 4. From this figure, it is clearly observed that as the percentage of fly ash (with constant cement 5%) increases there is gradual decrease in liquid limit and plasticity index. Also there is increase for plastic limit values with addition of cement-fly ash as shown in Figure 4.

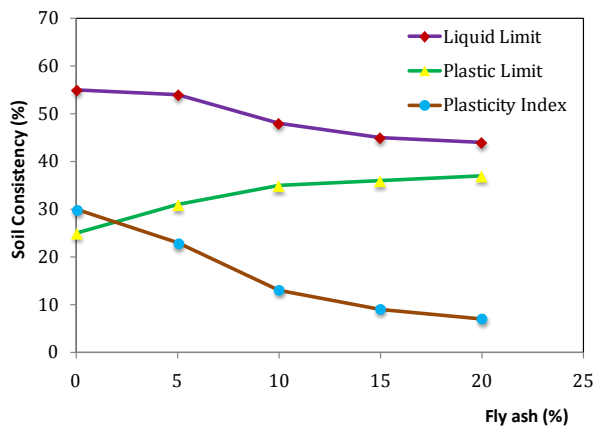


Figure 4. Effect of cement-fly ash on soil consistency

4.2. Swelling Characteristics

The swelling characteristics namely swell potential and swell pressure for the soil samples mixed with cement-fly ash are shown in Figure 5 and Figure 6. The tests results show that the swell potential and swell pressure values were decreasing significantly from 18.7 to 4.5% and from 175 to 75 KPa respectively with increased proportion of fly ash combined with 5% cement. As observed from Figure 5 and Figure 6 that addition of 5% fly ash with 5% cement is causing around 60% reduction in swell potential and swell pressure. This reduction in the swelling

characteristics can be attributed to the flocculation and cementation effects developed on addition of cement-fly ash.

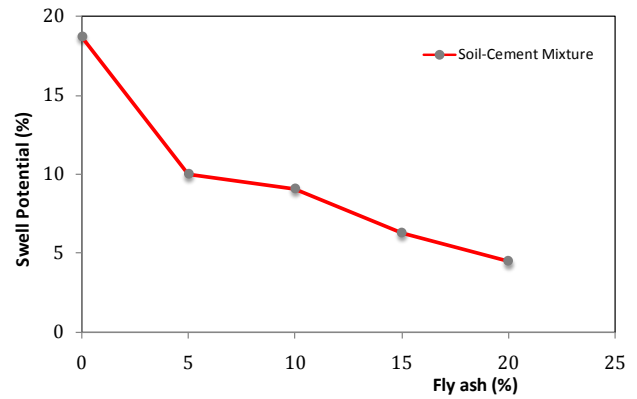


Figure 5. Effect of Cement-Fly ash on Swell Potential

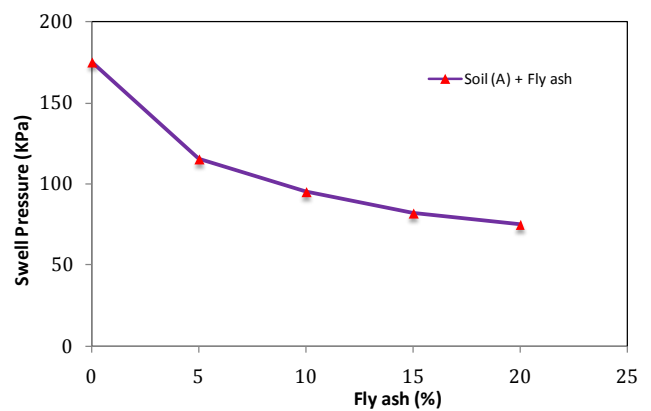


Figure 6. Effect of cement-Fly ash on Swell Pressure

4.3. Compaction Characteristics

The compaction characteristics as described by Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for soil samples stabilized with cement-fly ash are shown in Figure 7 and Figure 8. From these figures, the MDD show peak values at 5% and 15% fly ash (mixed at 5% cement). It is observed, MDD increased and OMC decreased with increasing fly ash content. At 15% fly ash content, the MDD of untreated soil increased by about 7%, and OMC decreased by about 15%. This result indicates that addition of cement-fly ash has significant effect on compaction characteristics.

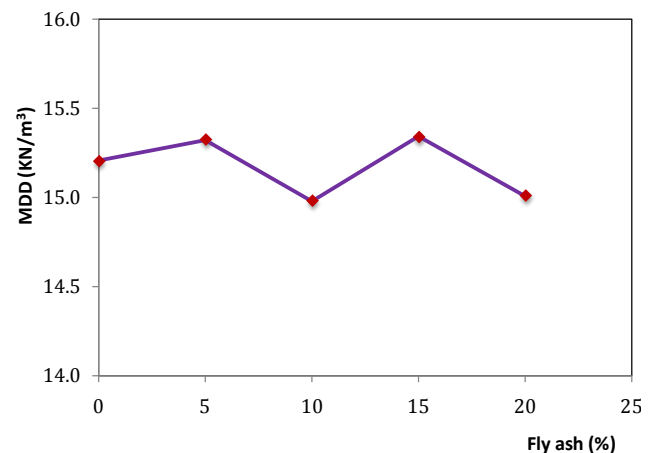


Figure 7. Effect of Cement-Fly ash on Maximum Dry Density (MDD)

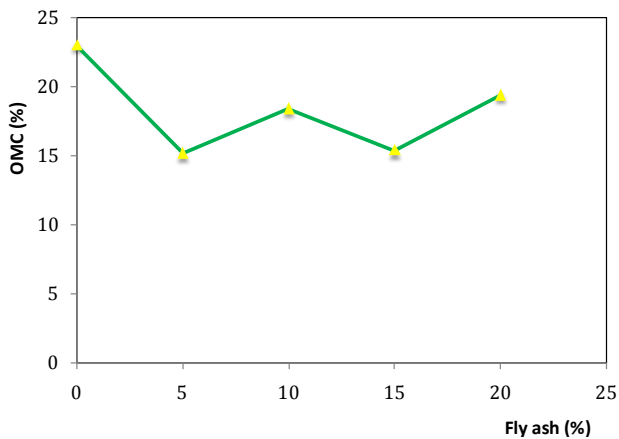


Figure 8. Effect of Cement-Fly ash on Optimum Moisture Content

4.4. Soaked CBR

The variation of soaked CBR of the soil stabilized with cement-fly ash is presented in Fig. 9. From this figure, it is clearly noticed that the soil shows great increase in the CBR with 5% Fly ash combined with 5% cement and thereafter, further addition of fly ash is causing gradual change in variation of CBR. The great improvement in CBR occurred initially at 5% fly ash with 5% cement about 90%. Also, it is noticed that at 5% Fly ash, the CBR value is about 17 times higher as compared to untreated soil. The peak CBR values are noticed at 5% and 15% Fly ash. The soils stabilized beyond 15% of Fly ash onwards, the CBR values are coming down. This improvement in CBR may be attributed to change of soil structure from dispersed to flocculate.

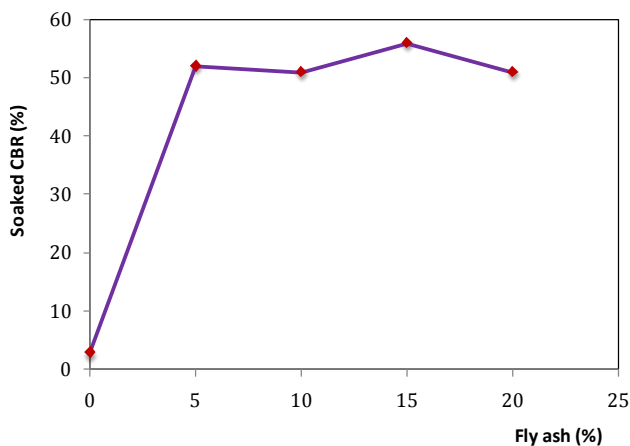


Figure 9. Effect of cement-fly ash on soaked CBR

5. Conclusion

An experimental study was carried out to investigate the effect of fly ash activated by cement on the geotechnical characteristics of expansive soils with reference to their use as pavement subgrade. The following are the main conclusions drawn from this study:

- Fly ash combined with cement is an effective agent of soil stabilization, based on the results observed and literature reviewed. In this study, expansive soil was treated with varying percentages of fly ash, 0, 5, 10, 15, and 20 percent combined with a fixed cement

content of 5% to investigate their effect on geotechnical characteristics.

- The native swelling values for the expansive soil were lowered dramatically with cement-fly ash stabilizer. The swell potential and swell pressure values decreased from 18.7 to 4.5% and from 175 to 75 KPa respectively with increased percentage of fly ash combined with 5% cement. It is observed that addition of 5% fly ash with 5% cement is causing great reduction in swell potential and swell pressure about 60% and then decreased at slow rate for further addition of fly ash.
- Significant strength improvements were observed for soil treated with cement-fly ash admixture. Most of the strength gains over the soaking period, suggesting that stabilization reactions and strength gains were ongoing. Cement-treated soil may be experiencing the formation of additional inter-particle bonds over time, while most of the fly ash stiffness gains were achieved very early in the curing process with little additional gains over time.
- For 5% cement content, the soaked CBR increased with increasing in fly ash till a 15% fly ash, then decreased gradually. The major improvement in CBR occurred at 5% fly ash mixed with 5% cement and thereafter, further addition of fly ash is causing gradual change in CBR values.
- From the results, it is clearly understood that there is a great improvement in strength and a marked reduction in swelling of expansive soils treated with 5% cement and 15% fly ash. Hence, 5% cement with 15% fly ash can be effectively adopted in stabilization of expansive soils as road pavement without much cost.

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