Effect of fly ash on bearing capacity of clayey soil

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Abstract. The exceptional rise in the production of fly ash and its removal in an environment friendly way is progressively becoming a problem of universal interest. Clayey soils usually have the potential to exhibit unfavorable engineering behavior, such as low bearing capacity, high shrinkage and swell characteristics in addition to high moisture susceptibility. Stabilization of these soils is a usual practice for enhancing the strength. This study investigates the improvement in the strength of a locally available cohesive soil by addition of fly ash. The optimum fly ash content was found at 5\% considering the unconfined compressive strength of treated soil. Bearing capacity increases with the increase in curing period. The rate of achieving strength is very rapid during the early phase of curing i.e. upto 7 days curing with improvement ratios of 1.5, 2 and 2.8 after 1 day curing at depths 0.25B, 0.5B and B, respectively with an average ratio 2.1. Beyond 1 day curing (7 and 28 days), the improvement ratios become less showing average values of around 2.6 and 2.8 for curing 7 and 28 days for the three depth models. The bearing capacity ratios show definite slight increase further after curing the samples up to 28 days. Bearing values on treated samples with curing period beyond 7 days (such as 28 days) showed strength gains to similar levels as observed within the 7 initial days curing period. By comparing the results from depths 0.25B, 0.5B and B, it is clearly shown the difference in bearing ratios. As the depth and curing for more than one day increase, the acceptability of the soft soil will directly increase. Furthermore, the increase in depth causes an increase in bearing ratio. Consequently, it can be concluded that a substantial improvement in the bearing capacity was achieved with the addition of fly ash due to its pozzolanic and cementitious natures.

Keywords
Clayey soils, Fly ash, Bearing capacity, Stabilization

1. Introduction
Generally, clayey soils have the possibility to exhibit unfavourable engineering behaviour, e.g. high shrinkage and swell characteristics, low bearing capacity, in addition to high sensitivity to moisture. Improvement of clayey soil is generally experienced by stabilization of these soils [1]. Stabilization of a soil is a common expression for any chemical, biological, physical, mechanical, or united method of varying a normal soil to encounter the study of an engineering application [2].

Many studies, concerning stabilization of soils for enhancement to attain the desired achievement, have been reported to give solutions for foundation structures such as collapse in road construction projects, which are accompanied with the consolidation of the layers of the clayey soil [3,4].
The engineers must use the local soils for the foundation of pavement for establishing of country roads demands. This demand is frequently controlled by the scarcity in the materials, quality, as well as transportation and economic considerations.

Pavement constructions on poor soil subgrades display quick and trouble disturbances result in early failure of the pavement. If the substitution of the materials of the foundation with alternative good quality soils is inefficient, so these soils must be stabilized by applying various additives as a common implementation. Various additives like lime, cement, fly ash, and other chemicals can be applied for soils stabilization. Up to 10%, cement or lime may be used for weak soils stabilization. But with higher percentages (>10%) they become costly and may be replaced by fly ash. Karim and Al-Soudany (2015) [5] investigated experimentally the capability of using a polymer fiber material for improving and stabilizing the geotechnical properties of soft clay soil showing its effect on the engineering characteristics of the stabilized clay.

The use of unwanted products like fly ash in stabilizing of weak soils results in many benefits such as technical, economics and environmental [6]. It is worth to mention that the soil type and its mineralogy will determine the proper additive that can be used [2]. Since, fly ash is a waste material, which exhibits the characteristics of pozzolans, it is continually encouraged to use fly ash for stabilization of soil if it is available. It is a productive use of this unwanted output product in different ways [1].

Before a decade, the product of fly ash is regarded as a "polluting industrial waste” and the greatest amount of it was being thrown in the ponds of ash. Very few areas of fly ash exploitation were familiar and the people observation about it was destructive. Before the last 15 years, many studies have been conducted with concentrated push given by the Fly Ash Mission (FAM), Technology Information, Forecasting and Assessment Council (TIFAC) and Department of Science and Technology (DST) [7].

The main aim of this article is to investigate the possibility of using fly ash to improve the cohesive soil, as this material is available in Iraq and considered as a waste that affects environment. This is the essential idea of using such additive to reduce the compressibility and decreasing the dry unit weight of clay soil and other properties, and to find a solution to the problem of the failure of some soils after implementation.

2. Soft soil
Soft soils are typically problematic and distinguished by their highly compressibility and in turn with low permeability as well as with low shear strength. The shear strength of these soils are notified to be <40 kPa, which has the ability to be moulded by the pressure of light finger. Usually, there are several problems faced in the constructions such as formation of embankments, the extreme settlement after construction, the lack of stability on excavation as well as the deficient bearing capability. Theoretically, settlement phenomenon can be outlined as a soil deformation owing to the stresses applied. The geometry on load transferring system will change as a consequence of settlement, and if the groundwater level is high, a part of the fill materials due to buoyancy, will affect the total additional loading and the soil stability.

Clayey soils are mainly found in the middle and southern parts of Iraq, about 35% of these clays are weak. Consequently, the harms of these soils engaged the attention of Iraqi researchers since they are frequently used as normal foundation bases for engineering constructions. The great complications in engineering problems are found in the clayey soil, mainly when it is associated with moisture content alternations and suffering high settlements under long term loading. Failures of several engineering constructions established on such soils were reported in different sites in Iraq such as Basra, Nasiriya, and Ammara. The soil of these sites are characterized by compression index as high as 0.3, and are
recognized by their low undrained shear strength (c_u < 40 kPa) [4,8]. Consequently, it is essential to enhance these huge areas covered by such poor-quality soils that causing undesirable engineering difficulties to road, rail network and airports constructed on such weak soils.

3. Materials used

3.1 Soil
The soil used for this study was taken from Al-Nahrawan area in Baghdad. At first, the natural moisture content of the soil was calculated directly. Then, the soil samples were dried by spreading them in the laboratory for two weeks for air-drying at room temperature to eliminate the natural water which might affect the results. The soil is classified according to Unified Soil Classification System (USCS) as (CL) as the soil is found of low plasticity. Figure 1 and table 1, represent the grain size distribution and engineering properties of the soil used in this study, respectively.

![Figure 1. Sieve analysis of the soil used.](image)

Table 1. Engineering properties of the natural used soil.

| Test           | Value | Specification          |
|----------------|-------|------------------------|
| Liquid limit (LL) | 43    | ASTM D 4318-(2002) [9] |
| Plastic limit (PL) | 19    | ASTM D 4318-(2002) [9] |
| Plasticity index | 24    | ASTM D 4318-(2002) [9] |
| Specific gravity (Gs) | 2.67  | ASTM D 854-(2002) [10] |
| Gravel %, >4.75 mm | 0     | ASTM D 422-(2002) [11] |
| Sand %, 0.075-4.75 mm | 3     | ASTM D 422-(2002) [11] |
| Silt %, 0.005-0.075 mm | 35   | ASTM D 422-(2002) [11] |
| Clay %, < 0.005 mm | 62    | ASTM D 422-(2002) [11] |
| D85 mm          | 0.018 | ASTM D 422-(2002) [11] |
| D60 mm          | 0.0036| ASTM D 422-(2002) [11] |
| Activity        | 0.39  | Skempton formula       |

3.2 Fly ash used
Fly ashes are unwanted products formed mainly from coal burning in the stations of thermal power, which provides additional pollution to the environment. It is a result of naturally-cementitious coal burning [12]. The chemical composition and properties of fly ash vary substantially depending on the nature of the coal burned (i.e., anthracite, bituminous, and lignite) and the characteristics of the power
plant. Fly ash particles are commonly spherical in shape comprises of commonly hollow spheres of silicon, aluminum and iron; and oxides, and unoxidized carbon. It can be considered as non-plastic fine silt as stated by the Unified Soil Classification System (USCS). It produces spherical glassy particles finer than Portland cement. Fly ash particles consist mostly of silicon dioxide (SiO$_2$), aluminum oxide (Al$_2$O$_3$) and iron oxide (Fe$_2$O$_3$).

Two classes of fly ash are presented depending on the type of coal that was burnt: Class F fly ash and Class C fly ash. The main contrasts between these both classes are the quantity of silica, calcium, alumina, and iron oxide content in the ashes. Fly ash-Class C is resulted from burning of younger lignite or sub bituminous coal. It commonly comprises > 20% lime (CaO). This kind has both pozzolanic and cementitious properties. In contrast to Class F, self-cementing Class C fly ash does not need an activator. In general, alkali and sulfate (SO$_4$) contents are greater in Class C fly ashes compared to other. Class F fly ash has pozzolanic properties formed from burning of stiffer, older anthracite and bituminous coal. This fly ash comprises <10% lime (CaO). Possessing pozzolanic properties, the glassy silica and alumina of Class F fly ash needs a cementing agent, such as Portland cement, quicklime, or hydrated lime, as well as water in order to react and form cementitious components [13,14,15]. The Scanning electron micrograph (SEM) of fly ash particles is shown in figure 2. Note the characteristics spherical shape that helps in improving workability. The ash used in this study is of the type Class C fly ash (figure 3) which is a waste material derived from burning of coal in thermal power in Al-Doura power station.

![Figure 2. Scanning electron micrograph (SEM) of fly ash particles.](image)

(The average particle size is approximately 10μm. This image shows enlargement of one particle.)

![Figure 3. Fly ash used in this study.](image)

### 3.3 Water

Distilled and tap water was used in the tests.
4. Instruments used

4.1 Steel container
The tests were performed by using a container made of steel with internal dimensions of (400mm × 350mm × 300mm). The steel container is made of steel plates with 4mm thickness. The container was appropriately firm and displayed no lateral deformation throughout the soil bed preparation and during the tests. Figure 4 shows the steel container and loading assembly.

4.2 Steel foundation
Square steel foundations (60 mm×60 mm), and (4 mm) in thickness, were used in all tests.

4.3 Loading assembly
A special loading frame was used to subject the vertical static loads on the footing model. Other parts and details of the main features of the loading assembly are displayed in figure 4.

Figure 4. Steel container and loading assembly.

5. Samples preparation
For the preparation of the soil bed in the steel container, the subsequent steps have been followed. After crushing the natural soil to small sizes, it was left for 24 hr for air-drying; additional crushing was needed using a crushing machine. Then, the air-dried soil was divided into groups. Each group contains 5 kg of air-dried soil mass, which was mixed gradually and thoroughly with enough quantity of water about 29-30%. This range of water content was deduced from figure 5 which shows the variation of undrained shear strength with water content which provides shear strength in the range between 8-9 kN/m². After full mixing with water, the soft soil mass was spread as beds with thickness of 100mm into the container which was tamped using a tamping tool. The process was resumed until the desired thickness, 300mm, of the bed was achieved. Finally, to prevent any loss of moisture, the soil bed was covered with a nylon sheet and was left for days as a curing period for equalization of moisture content. A wooden board of similar area to that of the surface area of bed soil (500 × 300) mm was placed on the soil bed; a seating load 5 kN/m² was put for 24 hours. Variation of undrained shear strength water content.

6. Model testing procedures
After the completion of preparation stages regarding soil layers, the following steps are followed:

1. The loading frame (figure 4) was placed in position so that the center of the footing coincides with the center of box.
2. Loads were applied through a loading disk in the form of load increments.
3. Each load increase was left for six minutes before adding the next load increment.
4. Dial gauge reading were taken at the end of each time increment and before the adding of the next load increment.
5. The load increments continued until failure occurred.

7. Testing program
In the present research, systematic experiments were achieved to inspect the behavior of saturated clay-mixed with fly ash material and to investigate its behavior after adding the fly ash and curing period under the effect of vertical static loading. Three depths of clay-fly ash mixture (i.e., 0.25B, 0.5B, and B) are used; where B is the footing width. The percentage of fly ash used was 5% by dry weight of clay soil. This percentage represents the optimum quantity of the fly ash which was determined based on the results of the unconfined compressive strength of the treated soil. The percentage of fly ash added (5% of the weight of the mixture) is fixed with curing periods 1, 7 and 28 days. For saturated clay-fly ash, a total number of tested models were 13.

8. Results and discussion
8.1 Relation of settlement with bearing capacity for untreated soil (D=0.25B)
Since the failure is defined as the applied stress that corresponds to (S/B=10%), figure 6 demonstrates the relationship between bearing ratio (q_u/c_u) and settlement ratio (S/B) for the cases of untreated soil (clay soil only), and treated soil (clay-fly ash mixture) with 5% fly ash for D= 0.25B. From figure 6, the bearing ratio for untreated soil (clay only) is 4.7%. The variation of q/c, with S/B for treated soil with 5% fly ash for D=0.25B after curing 1, 7 and 28 days is shown in the same figure. The bearing ratio increases from 4.7% for untreated to 7.2% for treated soil with fly ash for D= 0.25B after 1 day. While the bearing ratio also increases to 8.5% for treated soil with fly ash for D= 0.25B after 7 days. At the end, the bearing ratio also increases to 9.7% for treated soil with fly ash for D= 0.25B after 28 days as shown in the same figure.

The difference in the variation of q/c_u with S/B for treated soil for D=0.25B after curing 1, 7 and 28 days is clear and has been shown by different ratios. Hence, it can be concluded that as the curing for more than one day increases, the tolerability of the soft soil will directly increase.

It is obvious that the fly ash chemical properties are basically affected by the chemical constituents of the burned coal, thus Class C fly ash formed from burning of the younger lignite or sub bituminous coal. In addition to possessing properties of pozollans, it also has some self-cementing properties. In the existence of water, Class C fly ash will react and form more cementitious components leading such ash to become tough and obtain strength along time.
Figure 5. Variation of undrained shear strength with water content.

Figure 6. Variation of $q/c_u$ with S/B for treated soil 5% fly ash for D=0.25B after 1, 7 and 28 days curing.

8.2 Relation of settlement with bearing capacity for 5% fly ash (D=0.5B)

Figure 7 reveals the relationship between bearing ratio ($q_u/c_u$) and settlement ratio (S/B) for the cases of treated soil (clay-fly ash mixture) with 5% fly ash for D=0.5B after curing 1, 7 and 28 days. For this model, the bearing ratio increases from 4.7% for untreated to 9.2% for treated soil with fly ash for D=0.5B after 1 day as shown in figure 7. While the bearing ratio also increases to 9.8% for treated soil with fly ash for D=0.5B after 7 days. Finally, the bearing ratio also increases to 10.45% for treated soil with fly ash for D=0.5B after 28 days as shown in the same figure.

The difference is also clear in the variation of $q/c_u$ with S/B for treated soil with 5% fly ash for D=0.5B after curing 1, 7 and 28 days as shown in figure 7 which has been shown by different ratios. Hence, it can be concluded that as the curing (more than one day) and depth increase, the tolerability of the soft soil will directly increase. This is clearly shown by comparing the results from the depths 0.25B, 0.5B and B. At the same time, the increasing in depth causes increase in bearing ratio.

Figure 7. Variation of $q/c_u$ versus S/B for treated soil with 5% fly ash for D=0.5B after 1, 7 and 28 days curing.

8.3 Relation of settlement with bearing capacity for 5% fly ash (D=B)

The variation of $q/c_u$ with S/B for treated soil (clay-fly ash mixture) with 5% fly ash for D=B after curing 1, 7 and 28 days is shown in figure 8. As mentioned above, the bearing ratio for untreated soil (clay only) is 4.7%. The bearing ratio increases from 4.7% for untreated to 13.1% for treated soil with fly ash for D=B after 1 day. While the bearing ratio also increases to 18.3% for treated soil with fly ash for D=B after 7 days. Then, the bearing ratio also increases to 19.9% for treated soil with fly ash for D=B after 28 days as shown in Figure 8.

The difference is also clear in the variation of $q/c_u$ with S/B for treated soil with 5% fly ash for D=B after curing 1, 7 and 28 days as shown in Figure 8 which has been shown by different ratios. Therefore, it can be concluded that as the curing (more than one day) and depth increase, the tolerability of the soft soil will directly increase. This is clearly shown by comparing the results from the depths 0.25B, 0.5B and B for each curing period as shown in figures 9 to 11. At the same time, the increasing in depth causes increase in bearing ratio.
From the above results, it can be deduced that there is substantial improvement in the bearing capacity with the addition of fly ash due to the pozzolanic and cementitious natures of such ashes. Besides, as lime (CaO) represents about 20% in the Class C fly ash, so the noticeable improvements in the clayey soil is due to such ash in addition to the lime present which is regarded as good stabilizing agent of clayey soil. All strength results show higher values after curing which is indicated by several researchers. With the increase in curing period, the bearing capacity value increases. The amount of achieving strength is very fast during early curing stage i.e. up to 7 days curing. Where the improvement ratios were 1.5, 2, to 2.8 after 1 day curing for depths D=0.25 B, D=0.5B and D=B respectively, while the improvement percentages were 53%, 96% to 178% respectively. The average ratio and percentage after 1 day curing for the three depth models are 2.1 and 110%; 2.1 and 2.2; 3.9 and 4.2 after curing 7 and 28 days for D=0.25B, D=0.5B and D=B, respectively. For the depth models, the average improvement ratios are 2.6 and 2.8, while the average percentages are 159.8%
and 185.5% after 7 and 8 days curing respectively. Thus, the adequate curing period is between 1 to 7 days as maximum. The bearing capacity shows definite slightly increment after further curing the samples up to 28 days. Strength values on treated samples with curing period beyond 7 days (such as 28 days) showed strength gains to similar levels as observed within the 7 initial days curing period. Besides, at higher curing period beyond 7 days, the durability of the stabilized fly ash gets improved due to formation of pozzolanic reaction. The results from the experimental program seem to propose that fly ash may efficiently enhance soft clays and can be used successfully in the civil engineering constructions since fly ash exhibits the characteristics of pozzolans. So, it is permanently induced to utilize fly ash for stabilization if it is simply and economically presented to make use of this waste material to protect our environment.

9. Conclusion
This study was directed to examine the stabilization of a clayey soil with fly ash material and inspect the effect of its addition on bearing capacity. The following conclusion can be drawn from the extensive experimental test results of this study:

1. The optimum fly ash percentage was found at 5% employing the unconfined compressive strength of treated soil.
2. Substantial improvement in the bearing capacity was reported with the addition of fly ash due to the pozzolanic and cementitious nature of such ashes.
3. With the increase in curing period, the bearing capacity increases. The speed of achieving strength is very quick during early curing phase up to 7 days with improvement ratios of 1.5, 2 and 2.8 after 1 day curing at depths 0.25 B, 0.5 B and 1 B respectively with an average ratio 2.1.
4. Beyond 1 day curing (7 and 28 days), the improvement ratios become less showing average values of around 2.6 to 2.8 for curing 7 and 28 days for the three depth models.
5. The bearing capacity ratios show definite slightly increment after further curing the samples up to 28 days. Bearing values on treated samples with curing period beyond 7 days (such as 28 days) showed strength gains to similar levels as observed within the 7 initial days curing period.
6. By comparing the results of depths 0.25B, 0.5B and B, it can be concluded that the curing for more than one day and depth increase, the tolerability of the soft soil will directly increase besides the increasing in depth causes an increase in bearing ratio.

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