Durability of clayey soil stabilized with Potassium additive

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Abstract. Plastic clayey soils are characterised by large volume changes associated with moisture variation. These soils must be enhanced to ensure their suitability for the construction of engineering infrastructures. Chemical stabilisation with Potassium ions additives from Potash fertiliser (KNO₃) was explored in this research with main emphasis on durability of KNO₃ treated soil. Many complementary techniques were used in both micro and macro tests: X ray diffraction, mercury intrusion porosimetry test, full scale water retention curve, shear strength test, and California bearing ratio test were conducted. The results show that the optimum amount of KNO₃ required is 5% at 48 hours of curing. The addition of KNO₃ causes a reduction in the ability of soil to retain water and a variable variation in the grain and pore size distributions. Also, the addition of KNO₃ to the plastic clayey soil played an important role in the transformation of the soil mineralogical compositions from montmorillonite to illite behaviour. The test results obtained during and after water leaching process on the leachate and leached soils show the ability of soil-KNO₃ mixture to resist leaching is weak, and the necessity to protect the potassium stabilized soil against long term water penetration process.

1. Introduction
Chemical stabilisation of soft and problematic soils involves the addition of chemical admixtures and subsequent field compaction, resulting in enhancement of soil properties such as workability, strength, compressibility, stiffness, swelling characteristics, volume change, plasticity properties, and bearing capacity. thereby ensuring their suitability for various construction purposes [1-4]. Chemical treatment of soil encompasses gel formation and bonding of soil particles, along with a reduction in soil water affinity characteristics. Potash fertiliser is a readily available and cheap source of Potassium ions for chemical stabilisation of soils in Iraq. It readily dissolves in water and has adequate cations exchange potentials[5- 6]. Prior studies revealed that treatment of clayey soil with potassium fertilizers has diverse effects on their properties ranging from reduction in cation exchange capacity, soil plasticity, clay activity, and swelling behaviour. Also, it increases the California bearing ratio (CBR), changes the soil
strength components toward more frictional and less cohesive, and changes the structural composition of clay minerals [7-9]. Other researchers conclude that leaching of clayey soils increases their compressibility and reduces their plasticity and shear strength [10-12]. This research deals with the stabilization of plastic clayey soil by potassium nitrate fertilizer (KNO$_3$), a source of potassium ions and focuses on the durability of treated soil against water leaching process.

2. Methodology

2.1. Materials
Plastic clayey soil obtained from Mosul city in Iraq was used. Potassium Nitrate (KNO$_3$) salt was added in amounts of 3, 5, and 7% of dry weight of the soil. Distilled water was used for specimen preparations, while ordinary tap water with pH=8.16 and Electrical Conductivity (EC) = 494 µS/cm was used for the leaching process.

2.2. Index and engineering properties tests
The grain size distribution, specific gravity, Atterberg limits tests, direct shear, free swell, compaction and California bearing ratio (CBR) tests were conducted according to ASTM D 422-63; 854-02; 4318-00; 3080-11; 4546-08; 1883-07; respectively [13-18]. The components of direct shear strength were investigated for both natural and treated samples under consolidated drained conditions. The remolded samples were extracted at maximum dry density (MDD) and optimum moisture content (OMC). The test was conducted on sample of size of 60x60x20 mm at a shear velocity rate of 0.02 mm/min. The standard permeability mould was used to obtain the CBR values (CBR) in addition to its usage in the leaching process according to ASTM D1883-07[14]. The free swelling test was conducted using consolidation apparatus with ring samples of dimension 63.5 mm diameter and 19.05mm height.

2.3. Pore size distribution, X-Ray Diffraction (XRD) and chemical tests
The pore size distribution of the soil was done by mercury intrusion method by drying treated and untreated soil samples using nitrogen gas in liquid phase at temperature of -198°C. This was followed by drying the samples using vacuum pressure (up to 210 Mpa) in sublimation equipment (Avantec/Alpha 1-2 LD plus). X-ray diffraction patterns were obtained on powders of soil using Philips Apparatus with the Kα line of copper (λCu=1.5406Å) with 2θ from 1.5° to 60° for both untreated soil and soil treated with the optimum concentration of KNO$_3$. pH values and the cation exchange capacity, total soluble salts and organic matter were determined based on previously published methods [19-21]. Other soil chemical compounds were determined by X-ray fluorescence analysis on a Philips PW 2400 spectrometer XRF with a wavelength of 10-5Å to 100Å [22].

2.4. Water leaching process and Water Retention Curve (WRC)
The leaching process was conducted on samples treated with the optimum concentration of KNO$_3$ which produced CBR value using permeability apparatus. The seepage gradient of the percolating water was limited to 8 to avoid any distortion or cavitation of the soil sample within the leaching process [23]. Leachate was collected periodically for the calculation of constant head permeability value, the pH value, and the concentrations of the dissolved ions in soil leachate. Before starting the leaching process, water was permitted to percolate upward the sample to remove air bubbles from sample structure. Then, the sample was left for 2 days to achieve saturation condition [11]. The leaching process proceeded till equilibrium in permeability values was reached. Then the CBR mould was kept in water tank for four days under 4.5 kg surcharge load before CBR test was conducted. The water retention curve (WRC) describes the relationship between the moisture content, degree of saturation, relative humidity of the soil, and the matric suction under equilibrium conditions[24-25]. Remoulded samples, 30 mm diameter and 12 mm height of untreated and treated soil were prepared at MDD and OMC of CBR test. The samples were oven dried at 105±5°C for 24 hours before conducting the test. The presented results are the average values from four tests.
3. Results and Discussions

Table 1 shows the properties of untreated soil from both laboratory and mercury intrusion tests. The soil could be described as a clayey soil with moderate to high plasticity value. Figure 1(a) shows the pore size distribution of the used soil, the pore size > 1 µm is the predominantly pore size diameter in the soil structure. The distribution could be described as a meso to micro pores (0.01 µm-1 µm) with a small amount of macro pores. Figure 1(b) shows the mineralogical composition of the used soil by X-ray diffraction, the clay minerals are: Montmorillonite, as a mixed layer with swelling chlorite mineral at random, Illite and Kaolinite minerals were also noticed, while the non-clay minerals such as Calcite and Quartz were also present.

| Property                        | Value          |
|---------------------------------|----------------|
| Natural Moisture Content        | 16.4%          |
| Specific Gravity (Gs)           | 2.73           |
| Liquid Limit (LL)               | 52%            |
| Plastic Limit (PL)              | 24%            |
| Plasticity Index (PI)           | 28%            |
| % composition of Sand           | 12             |
| % composition of Silt           | 45             |
| % composition of Clay           | 43             |
| USCS soil classification        | CH             |
| Maximum Dry Density (MDD)       | 1.83 gm/cm³    |
| Optimum Moisture Content (OMC)  | 16.6%          |
| California Bearing Ratio (CBR)  | 4.9%           |
| Total Soluble Salt              | 0.4%           |
| Gypsum content                  | 1.16           |
| Organic matter content          | 0.32%          |
| Cation Exchange Capacity        | 36 meq./100 gm |
| Bulk density                    | 1.79 gm/cm³    |
| Skeletal density                | 2.68 gm/cm³    |
| Porosity                        | 32.5%          |

Figure 1. (a) Pore size distribution and (b) mineralogical composition of the used soil
Figure 2 (a) shows that a decrement in both the liquid limit and plasticity index of KNO$_3$ treated soil was observed until the curing time reached 48 hours when an equilibrium condition was achieved. This reduction could be attributed to the dissolution of KNO$_3$ which increased the electrolyte concentration and subsequent reaction with soil mineral materials, which in turn reduce the thickness of diffuse double layer [26-28]. The curing period of 48 hours was thereafter selected as the optimum curing period for subsequent tests. The cation exchange capacity of the treated soil at 48-hour curing period also reduces with increase in percentage of KNO$_3$ added to the soil. This was due to the cation exchange between the additional ions from KNO$_3$ and the pre-existing ions in the soil, leading to a reduction in the cations needed to equilibrate the anions. Figure 2 (b) shows the grain size distribution of the treated soil at 48-hour curing period. There is a reduction in the amount of clay size particles ($\leq$0.002 mm) with an increase in the amount of silt size particles (0.002 mm - 0.074 mm), this could be related to the flocculation of clay size particles to form bigger sizes silt particles and the reduction in thickness of the diffuse double layer [6, 29].

![Figure 2. (a) Liquid limit and (b) particle size distribution of soil treated with KNO$_3$](image)

Variation of direct shear strength parameters ($c$ and $\phi$) at 48-hour curing period for soil treated with different percentages of KNO$_3$ was also observed. The parameters ranged from ($\phi=30$, $c=0.5$ kPa) for natural soil to ($\phi=36$, $c=0.35$ kPa) for the soil treated with 7% KNO$_3$. The KNO$_3$ addition increases the frictional property and decrease the cohesion property of the soil, this was due to the decrease in the size of the diffused double layer associated with KNO$_3$ additions.

Figure 3 shows the curves of dry density and CBR values against moisture content for untreated and treated soil using permeability mold at 48-hour curing period. A reduction in OMC was noticed with the increment in both dry density and CBR values for various percentages of KNO$_3$ additions up till 5%. Then a decrease in CBR and dry density values were observed for increasing OMC values. The increase of electrolyte concentration in soil media due to KNO$_3$ addition may be responsible for such trend, which in turn decreases the thickness of diffused double layer and flocculate soil particles. For further KNO$_3$ addition, a reverse trend was observed, this could be attributed to the effect of the repulsive forces initiated between soil particles which come from the extra concentration of cation [26].

The maximum CBR value of the untreated soil was at the wet side of the compaction curve. As the percentage addition of KNO$_3$ increases, this value moves gradually from the wet side to dry side of the compaction curve. This change could be related to the reduction in soil plasticity and conversion of the soil consistency from a cohesive material to a more frictional material[7, 26].
The swelling percentage also decreases with increase in KNO₃ concentration up till 5% KNO₃ addition before it slightly rose. This decrement was because of reduction in soil plasticity in addition to changes in minerals behavior from montmorillonite to illite. Thus, the 5% KNO₃ addition was chosen as the optimum KNO₃ salt concentration with the selected curing period of 48 hours for subsequent tests. The addition of optimum KNO₃ also changed the pore distribution of the soil by enclosing the macro pores (> 100 µm), turning the soil pore structure to meso-micro pore structure.

Figures 4 (a & b) shows the mineralogical compositions and variations in water retention ability of the soil treated with the optimum amount of KNO₃ respectively. The addition of KNO₃ reduced montmorillonite mineral peak and in return increased illite mineral peaks. The montmorillonite mineral in the randomly mixed layer now turned to illite i.e. potassium ion now settled down on the basal planes between the silica sheets of the montmorillonite mineral [26]. Furthermore, the reduction in the plasticity of the treated soil and the variation in the mineralogical compositions produced less ability to retain the water molecules within the treated soil structure.

The leaching process was conducted on soil samples treated with 5% KNO₃ and cured for 48 hours, MDD = 1.9 gm/cm³, OMC = 13.2% and yielded the maximum CBR value of 16.25%. A reduction in the coefficient of permeability was noticed during the leaching process by an amount of 84% till day 75, then an equilibrium occurred until the end of leaching process. This reduction came through the swelling of clay particles due to the removal of cations from the outer surface of treated soil and potassium ions between the silica sheets, this cation and potassium ions removal could be noticed by the reduction in EC values (Figure 5a). Figure 5(b) shows the leaching effect on the pH value of treated
soil media, this effect was observed through the alteration of its media from acidic condition to alkali one, accompanied with the removal of cation and potassium ions from leached soil media [27].

Figure 5. (a) EC and pH value and (b) ion concentration during leaching process

Figure 6 explicates the water retention ability of leached soil by mercury intrusion test. The washing of ions and additional potassium from soil media will increase the diffused double layer, and in turn increased soil plasticity and ability to retain water within soil structure [28]. The increment in the diffused double layer due to water leaching process produced defloculating of soil particles [23, 30]. The leached soil did not gain its original pore distribution, because of the dissolved soil material within the leaching process in the pore zone (7 – 80 µm) precipitated and enclosed the macro pores in the zone greater than 100 µm. Micro pores remained the same in natural, treated soil, and leached soil.

Figure 6. Pore size distribution by mercury intrusion

4. Conclusion
An investigation of the stabilization of plastic clayey soil with potassium nitrate fertilizer (KNO₃) was conducted. Laboratory techniques for index properties, classification, and some engineering properties were carried out with special focus on the durability of KNO₃ treated soil. From the results presented, it was observed that the addition of KNO₃ salt reduces soil plasticity, cation exchange capacity, and the ability to retain water within soil structure. The effective curing period of soil treated with KNO₃ salt was 48hours and the optimum concentration was 5% of KNO₃, the incorporation of KNO₃ close some of macro pores in the soil structure leading to change the pore size distribution. The ability of soil-KNO₃ mixture to resist water leaching process is weak, and the pore size distribution of leached soil did not return to its original natural state after leaching.
5. References

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