**IMPROVING TWO TYPES OF CLAY SOILS PROPERTIES BY HEATING**

**Mohammad Azzam Subhi Hosni Ghazal, Assistant Professor. Civil Engineering Department. An-Najah N. University. Nablus – Palestine. mashaghazal2022@gmail.com**

**ABSTRACT**

**Soils usually have many problems which limit their use as a construction material and as a suitable site for construction. Soils problems such as high water content, plasticity, activity, compressibility, and swelling potential and/or low permeability and strength often cause serious problems including bearing capacity failure, excessive settlement, and swelling, among other problems. As the availability of suitable construction sites decreases, it is becoming more important to utilize poor soils for foundation support and earthwork construction using different methods of soil stabilization.**

**The collective term for the methods which are employed to improve and modify certain unsatisfactory properties of natural soil is called soil stabilization. Methods of soil stabilization are numerous and divided mainly to mechanical, chemical, and physical methods.**

**Physical stabilization methods comprise several methods including electro-osmosis, consolidation, and thermal stabilization. Thermal stabilization refers to the artificial freezing and heating of soils for the purpose of improving the engineering characteristics of the ground soil. Both these processes involve the use of thermal energy, but they are quite different and opposite in their applications.**

**This paper concentrates on the study of the effect of thermal stbilization by heating on some clay soils. The selection of this specific method can be justified knowing that it was one of the most ancient methods used by man especially in old Egypt and Mesopotamia. Yet, it was ignored and not improved for many centuries until the last few years. Recently this method of stabilization took a momentum, Therefore, the concentration on the understanding and use of heating as an excellent soil stabilization method has increased drastically.**

**This paper is devoted to reveal the results of an experimental study that was carried out on two types of clays; Kaolin and Bentonite. These clays were heated gradually up to 6000c, and the effect of heating on swelling, compressibility, and strength of these clays were investigated.**

**The results showed that heating kaolin to a temperature of up to 300oC caused the elimination of its free and adsorbed water. Heating to a higher temperature of 400oC reduced its swelling and compressibi9lity, while heating to 500oC resulted in increasing its strength. On the other hand, heating bentonite to 300oC resulted in the elimination of its free and adsorbed water, while heating to 600oC changed it to a nonexpansive state, reduced its compressibilitym and increased its strength. These changes were irreversable.**

**Keywords: Soil improvement, clay soil stabilization, thermal soil stabilization, clay soil heating, kaolinite, bentonite**

1. **INTRODUCTION**

**Most of man’s constructions are done on, in, or with soil. The vast number and variety of natural soils have posed serious problems to the civil engineer including problems related to permeability, swelling, consolidation, and strength. Engineers use several methods to improve and modify the unsatisfactory soil properties. These methods of soil stabilization are numerous and some of them were developed thousands of years ago. Soil stabilization methods are divided to physical, mechanical, and chemical methods.**

**Physical stabilization methods include thermal stabilization which may be by heating or by freezing. The basic concepts of soil improvement by heating were developed in prehistoric ancient civilizations. The techniques of burning soils ( mainly clay soil ) to form a brick-like stone ware widely used in ancient Mesopotamia, Egypt, Japan, China and other parts of the Middle East as early as 10000 B.C. Brick-like stones formed by burning clay were used as a building construction material. Architectural discoveries reveled that throughout thousands of years, clay burned bricks dominated the area of building constructions. In Mesopotamia also, the first use of clay burned bricks as a road pavement material was recorded. Recently, new theories suggest that sculptures and monuments such as the Pyramids of Egypt and the Babylon Gardens were built of burned clay bricks. While some of the magnificent Roman roads and bridges were constructed using burned clay stones, most of the beautiful structures in the Islamic civilization were constructed using burned clay.**

**Recently, Irvine was the first to use heat treatment by burning wood for roadmaking in Australia in the years 1930 and 1934(1). He designed and built a wood-fired furnace and moved it a long a designed road to stabilize the soil where the road should be build. Heat treatment emplyed by burning liquid fuel or gas in boreholes has been reported in the previous USSR. This was done by Litvinov(2) 1959 and Morozov1979. Other contributers to this field of study include Beles and Stanculescu from Romania (1958), Fujii (3) from Japan (1971), Jurdanov and Koroteev from USSR (1978 and 1983, respectively), and Byers, FitzPatrrick, and Holtz (1991).**

**Koroteev (1983) treated a soil using an electrical heating method to construct a foundation to support 32 columns that kold abuilding in the USSR. Fujii (1971) used heat treatment to stabilize an embankment at Kanazwa Japan. The heat treated soil showed a strength equivalent to 10 to 20 times the original value even after total immersion in water.**

**The most succerssful application of stabilization by heating has been to partly saturated fine-grained soil. Also, this method was used successfully to stabilize landslides, to improve strength of collapsing soils under existing structures, to construct a structural mat for foundation support, to form piles in place, to reduce lateral stresses on retaining walls and embedded structures, and to form a structural pad varying between 7 and 16m in thicknessand covering an area of 3000m2 as performed by Kurnakov (1972) and reported by Shaw(4).**

**İn the laboratry, electrical furnaces have been used in many projects to investigate the effect of heating on the properties of soils. Jurdanov used an electrical furnace in his study on thr effect of heating on a fine-grained cohesive clay soil. Lim, Arayssi, and Benway also used electrical furnaces as a source of heat in their studies.**

**Microwave ovens have also been used in the laboratory as it was found that the major advantage of these ovens was that they saved time during heating. Several investigators have used microwave ovens in their studies on the effect of heating on the properties of soil. Among those investigators are Denton 1987 and Gilbert 1991.**

**The proceding review indicates that considerable research concerning the effect of heating on gradation, specific gravity, and consistancy limits of kaolin and bentonite has been conducted. The effect of heating on swelling was investigated only for a limited range of conditions. On the other hand, no study on the compressibility behavior of soils heated above 42oC is available.**

1. **Irvine, R.H. (1934),“Road Making by Heat Treatment of Soils“, Trans. Institution of Engineers, Australia, Vol.XIV, pp.113-120.**
2. **Litvinov, I.M. (1960), “Stabilization of Settling and Weak Clayey Soils by Thermal Treatment“, Highway Research Board. Special Report 60. Pp. 94-112.**
3. **Fjii, T. (1971), “ The Practical Application of Thermal and Freezing Methods of Soil Stabilization.**

**" Proc. of First Australian-New zealand Conference on Geomechanics Engineering, Vol. 117, No. 1**

1. **Shaw, H.M. (1981), " Soil Improvement Methods and their Application in Civil Engineering**

**". Special Lectures, University of California at Berkeley. Pp.72-80.**

**The strngth properties of heated soil were studied primarily for dry specimens. Since in the field the heated soil is frequently exposed to water, the possible weakening effect of water on heated soil must be thoroughly investigated. Duo to this fact, this study was devoted to investigate the effect of heating on swelling, compressibility, and strength behavior of two types of clay; kaolin and bentonite.**

* 1. ***Structure of Kaolin and Bentonite***

**Geotechnical engineers classify soil based on nature, structure, origin, and particle size. Based on particle size of soil grains, soils are devided to gravel, sand, silt, and clay. Gravels are fragments of rocks with particle size more than 4.75mm. Sands have particle sizes that range from 0.075 to 4.75mm and composed mainly from quartz and feldspar minerals., Silt is similar to sand in its structure, yet the size of its grains is microscopic and ranges from 0.001 to 0.075mm. On the other hand, clay consist of clay minerals and its particles are less than 0.001mm in diameter.**

**Clay minerals are hydrous aluminium phyllosilicates, sometimes with variable amounts of iron,** [**magnesium**](https://en.wikipedia.org/wiki/Magnesium)**,**[**alkali metals**](https://en.wikipedia.org/wiki/Alkali_metal)**,**[**alkaline earths**](https://en.wikipedia.org/wiki/Alkaline_earth)**, and other**[**cations**](https://en.wikipedia.org/wiki/Cation)**found on or near some**[**planetary surfaces**](https://en.wikipedia.org/wiki/Planetary_surface)**.** [**Clays**](https://en.wikipedia.org/wiki/Clay)**form flat hexagonal sheets and thay are common**[**weathering**](https://en.wikipedia.org/wiki/Weathering)**products and at the same time low-temperature**[**hydrothermal alteration**](https://en.wikipedia.org/wiki/Hydrothermal_alteration)**products. Clay minerals can be classified as 1:1 or 2:1. This originates because they are fundamentally built of tetrahedral silicate sheets and octahedral hydroxide sheets. A 1:1 clay would consist of one tetrahedral sheet and one octahedral sheet, and examples would be kaolinite and serpentine. A 2:1 clay consists of an octahedral sheet sandwiched between two tetrahedral sheets, and examples are talc, vermiculite and montmorillonite.**

**Clay minerals include several groups among them the** [**Kaolin**](https://en.wikipedia.org/wiki/Kaolin)**group which includes the minerals**[**kaolinite**](https://en.wikipedia.org/wiki/Kaolinite)**,**[**dickite**](https://en.wikipedia.org/wiki/Dickite)**,**[**halloysite**](https://en.wikipedia.org/wiki/Halloysite)**, and**[**nacrite**](https://en.wikipedia.org/wiki/Nacrite)**, Smectite group which includes dioctahedral smectites such as**[**montmorillonite**](https://en.wikipedia.org/wiki/Montmorillonite)**,**[**nontronite**](https://en.wikipedia.org/wiki/Nontronite)**and beidellite and trioctahedral smectites for example**[**saponite**](https://en.wikipedia.org/wiki/Saponite)**,** [**Illite**](https://en.wikipedia.org/wiki/Illite)**group which includes the clay-micas and Illite, and** [**Chlorite group**](https://en.wikipedia.org/wiki/Chlorite_group)**which includes a wide variety of similar minerals with considerable chemical variation.**

**In this paper, only 2 clay soils were investigated. Kaolinite, which is one of the most common minerals with the chemical composition**[**Al**](https://en.wikipedia.org/wiki/Aluminium)**2**[**Si**](https://en.wikipedia.org/wiki/Silicon)**2**[**O**](https://en.wikipedia.org/wiki/Oxygen)**5(**[**OH**](https://en.wikipedia.org/wiki/Hydroxide)**)4. It is a layered**[**silicate mineral**](https://en.wikipedia.org/wiki/Silicate_minerals)**, with one**[**tetrahedral**](https://en.wikipedia.org/wiki/Tetrahedron)**sheet of silica (SiO4) linked through**[**oxygen**](https://en.wikipedia.org/wiki/Oxygen)[**atoms**](https://en.wikipedia.org/wiki/Atom)**to one**[**octahedral**](https://en.wikipedia.org/wiki/Octahedron)**sheet of**[**alumina**](https://en.wikipedia.org/wiki/Alumina)**(AlO6) octahedra, see figure 1.  Kaolinite has a low**[**shrink–swell capacity**](https://en.wikipedia.org/wiki/Shrink%E2%80%93swell_capacity)**and a low** [**cation-exchange capacity**](https://en.wikipedia.org/wiki/Cation-exchange_capacity)**. It is a soft, earthy, usually white, mineral produced by the chemical weathering of**[**aluminium**](https://en.wikipedia.org/wiki/Aluminium)[**silicate**](https://en.wikipedia.org/wiki/Silicate) **minerals like**[**feldspar**](https://en.wikipedia.org/wiki/Feldspar)**.**

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**Figure 1. Structure of Kaolin**

**The other clay mineral which was investigated is Bentonite which belongs to the Montmorillonite group. This group of clay minerals is a very soft**[**phyllosilicate**](https://en.wikipedia.org/wiki/Silicate_minerals#Phyllosilicates)**group that form when they precipitate from water solution as microscopic**[**crystals**](https://en.wikipedia.org/wiki/Crystal)**. İt is a 2:1 phyllosilicate mineral that has two**[**tetrahedral**](https://en.wikipedia.org/wiki/Tetrahedral)**sheets of**[**silica**](https://en.wikipedia.org/wiki/Silica)**sandwiching a central**[**octahedral**](https://en.wikipedia.org/wiki/Octahedral)**sheet of**[**alumina**](https://en.wikipedia.org/wiki/Alumina)**. The particles are shaped with an average diameter around 1**[**μm**](https://en.wikipedia.org/wiki/Micrometre)**and a thickness of 0.96**[**nm**](https://en.wikipedia.org/wiki/Nanometer)**. Montmorillonite is characterized as having greater than 50% octahedral charge; its cation exchange capacity is due to isomorphous substitution of Mg for Al in the central alumina plane. The substitution of lower valence cations in such instances leaves the nearby oxygen atoms with a net negative charge that can attract cations.**

**Montmorillonite**[**swells**](https://en.wikipedia.org/wiki/Expansive_clay)**with the addition of water and expands considerably more than other clays due to water penetrating the interlayer molecular spaces. The amount of expansion is due largely to the type of exchangeable cation contained in the sample. The presence of sodium as the predominant exchangeable cation can result in the clay swelling to several times its original volume. The structure of Montmorillonite is shown in figure 2.**

**İn this study commercial types of kaolinite and bentonite were used. Edgar Plastic Kaolin and Western Bentonite available and well known in the USA are investigated. Properties studied are swelling, compressibility, and strength. For the compressibility tests, the heated specimens are completely saturated before testing. For the strength test, triaxial compression tests are performed on both dry and fully saturated specimens. Soil specimens were heated to 600oc in a special programmable electric furnace.**

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**Figure 2. Structure of Montmorillonite**

1. **EXPERIMENTAL WORK**

**In this study, as stated earlier, kaolin which is commercially available under the name Edgar Plastic Kaolin (EPK) and highly plastic clay which is commercially available under the name Western Bentonite (WB) were investigated. The Edgar Plastic Kaolin is available in powder form. It has a liquid limit of 45.8, a plastic limit of 31.5, and a plasticity index of 14.3. Its specific gravity is 2.6 and its classification is A-7-5(4) and CL according to AASHTO and UNIFIED classification systems, respectively.**

**Western Bentonite is also available in powder form. It has a liquid limit of 431 and a plastic limit of 48 and a plasticity index of 383. Its specific gravity is 2.78 and its classification is A-7-5(20) and CH according to AASHTO and UNIFIED classification systems, respectively.**

**2.1 *Specimen Preparation***

**Specimen preparation involved mixing, consolidating, heating, coaling. and soaking. Since soil specimens were prepared from air-dried powder, it was very important to obtain a uniform soaked mixture. Therefore, a mortar mixture was used to mix the clay powder with tab water. Water was poured into the mixer first, and then powder was scooped gradually while mixing continuously. During mixing lumps of clay soil were broken apart by hands. It took a mixing time of about 90 minutes for the kaolin and 150 minutes for the bentonite to reach a uniform clay mixture.**

**After mixing, the soil-water mixture was transferred into a steel box designed specially to consolidate the clay soil to the required void ratio. The average time needed for the kaolin to reach a void ratio of 1.2 was 20-25 days, whereas 42-48 days were needed for the bentonite to reach the same void ratio.**

**After consolidation, test specimens were obtained using thin wall tube samplers. Two different tube sizes were used, 3 inches in height and 1.4 inches in diameter were used to obtain samples for triaxial tests, while 2x2.5 inches in height and diameter respectively were used to obtain specimens for swelling and consolidation tests.**

**Heating kaolin and bentonite specimens is considered one of the most crucial parts of specimen preparation because of its effect on the final results of testing. To control the heating rate and time, programmable electric furnace was used. The Fisher Isotemp Programmable Ashing Furnace Model 497 was used.**

**At the beginning, heating resulted in specimen cracking and damaging. Therefore, special attention was given not only to finding the optimum heating rate, but also to understanding the process of heating itself and the way it affects the soil specimens. After several trials, the heating programs adequate to heat the clay samples without causing any cracks or damages were reached and used. When reaching the desired heating temperature, we aimed to find the minimum heating time needed to insure that the specimen is truly and completely heated to the desired temperature. For kaolinite and bentonite, specimens were kept under the desired temperatures for 24 hours.**

**After heating, the specimens were cooled in a desiccator. Upon removal from the desiccator, the top and bottom of the specimens were made smooth if necessary using sand paper to ensure that both ends are flat. Sides also were treated to ensure their perpendicularity with the flat ends.**

**In doing the triaxial compression tests for the determination of strength of the clay soils, air-dried and saturated specimens were used. Saturating the specimens was very difficult and took very long time. A large triaxial chamber was used were specimen was placed at the base of the chamber and valves under the base were open to allow water to penetrate the soil from down to top of the specimen. Once water begins to flow out of the top of the specimen, we were sure that the specimen is fully saturated.**

**2.2 *Testing***

**Swelling tests were conducted by using modified consolidation apparatus. After having every specimen weight, height, and diameter recorded, the specimen was placed in the consolidometer which has a diameter of 2.5 inches and a height of 1.0 inch. Dial readings were recorded at times from 1 up to 1440 minutes. For bentonite clay, additional time for testing is needed. Readings were recorded up to 8640 minutes ( 6 days)**

**The consolidometer was used also to perform the consolidation tests. After applying the load, dial readings (deformation) were recorded beginning with 0.25 minutes up to 1440 minutes (24 hours). After every test, load applied is doubled and readings were recorded again.**

**For the determination of the strength of kaolin and bentonite, triaxial compression tests were carried out on dry and fully saturated specimens. All specimens were prepared to dimensions of 2.8 inches in height and 1.4 inches in diameter. When the tests are done on saturated samples, the air-dried samples were placed on the base plate and water was pumped into the specimens until they become fully saturated. After that, axial loads were applied gradually on the specimens until it fails. Load, deformation, and pore water pressure for all specimens were measured and recorded**

**Heating effect on swelling consolidation, and strength of kaolinite and bentonite heated to 100, 200, 300, 400, 500, and 600oC were studied using ASTM testing procedures. In addition, wet and air-dried specimens were tested. Some other additional important tests were carried out when necessary. These tests will be mentioned and explained later on.**

1. **RESULTS OF THE STUDY**

**In this part of the paper heating effect on swelling, consolidation (compressibility), and strength of Edgar Plastic Kaolin and Western Bentonite is discussed. Results of the tests and discussion on these results are presented thoroughly.**

**3.1 *Heating Effect on Swelling***

**Because clay particle surfaces are usually negatively charged, water molecules are strongly attracted to the clay particles. This has important consequences in regard to the swelling behaviour of the clay soil. Clay soils swell differently, and their swelling is influenced, mainly, by the type of bonding between their unit layers. The relatively small size and weight of clay particles compared to their large surface area also play important role in the swelling behaviour of the clay soil.**

**Kaolin and bentonite clays behave differently when interacting with water. In kaolinite, the short basal distance ( 7.2Ao ) and the opposing layers with different charges ( O - OH ) give rise to hydrogen and Van Der Waals bonds between layers. Such a strong bond does not allow a big amount of interlayer swelling comparing with bentonite.**

**Bentonite, on the other hand, is a highly plastic and swelling clay. The octahedral sheet that is sandwiched between two silica sheets all together form the montmorillonite unit layer. The layers are stacked one above the other and attached to each other by bonding forces. Bonding between these layers is by Van Der Waal and by cations balancing charge deficiencies. As stated above, swelling of montmorillonite is much more than swelling of kaolin. This is due to several factors including that the cation exchange capacity (CEC) of montmorillonite is higher than that of kaolin, ( *80-150 meq/100g compared to 1-10 meq/100g*).**

**Untreated and air-dried specimens, and specimens heated to 100, 200, 300, 400, 500, 600 Co were exposed to free swelling under no sustained pressure. When kaolin and bentonite were air dried, they lost part of their moisture and they exhibited some shrinkage. This shrinkage was taken in consideration when evaluating the amount of swelling.**

**Untreated kaolin exhibited a small amount of swelling (0.07%), while air-dry kaolin showed an increase of about 8% in total swelling which took place mainly during the first 180 *min* (3 *hours*). Heating kaolin caused it to lose more free and adsorbed water. At 100 Co no significant effect on the structure of the kaolin clay mineral can be observed. When the kaolin clay was given access to water, the exchangeable cations on particle surfaces hydrate. The hydration energy is usually strong enough to overcome the attractive forces between particles, thus resulting in a greater swelling.**

**Most of the swelling of kaolin specimens heated to 100 Co took place during the first three hours and then the swelling slowed down until it was a negligible amount. The total swelling of the kaolin reached around 15%. At 200 Co, all free water in the clay specimens was expected to be evaporated. Therefore, the effect of the double layer and the osmotic pressure was greater and so was the swelling. On the other hand, the trend of swelling exhibited by specimens heated to 200 Co was still the same in specimens heated to 100 Co. the only difference was the amount of swelling which reached about 27%. With further increase in the heating temperature up to 300 Co, the total amount of swelling increased up to 33% with a similar trend to that of specimens heated to 100 Co and 200 Co.**

**Kaolin specimens heated to 400 Co, 500 Co, and 600 Co showed very little amount of swelling (can be considered as negligible). Heating kaolin to these high temperatures causes the formation of small amounts of amorphous oxides from the alumina and silica in form of cation interlayers. This, in turn, enhances a strong attractive force that binds adjacent layers together. This explains the loss of swelling in kaolin clay heated to temperatures 400 Co and above.**

**Untreated bentonite showed a large amount of swelling (57.2%) that took place mostly during the first three days (4320*min*). On the other hand, air-dried bentonite showed an increase in swelling of about 138% which took place during the first 5760 *min* (4 *days*). The strong hydration energy which easily overcomes the weak attractive forces of Van Der Waal, the more concentrated electrolyte, the thicker double layer, and the higher capillary menisci are the main reasons for the high swelling of bentonite clay compared with kaolin clay. For specimens of bentonite heated to 100 Co, swelling occurred rapidly during the first 8 hours, slowed a little during the following 3 days, and finally slowed to an almost negligible amount during the remaining time (2 days). A total swelling of about 225% was achieved and the swelling behaviour was very similar in trend to the trend of untreated and air-dried bentonite specimens.**

**In bentonite, some of the cations which were initially exchangeable were fixed when the clay was heated up to 300 - 350`Co. this explains the small amount of swelling that was achieved. Heating bentonite up to 300 Co caused a total swelling of 250%. Bentonite specimens heated to 400 Co showed a swelling of 265%. At 500 Co bentonite specimens continued to swell but exhibited some changes in their swelling behaviour. These changes include the rate and the amount of swelling. The total amount of swelling was about 240% and the rate of swelling was smaller than specimens heated to 100, 200, 300, and 400 Co. Finally, bentonite specimens heated to 600 Co showed no sign of swelling.**

**As a conclusion, kaolin heated to temperatures up to 300 Co became fully saturated and very soft when submerged in water while specimens heated to temperatures 400 Co and above up to 600 Co showed no sign of swelling when submerged in water. On the other hand, bentonite specimens heated to temperatures up to 500 Co continued to swell while specimens heated to 600 Co stopped swelling. The overall increase in the swelling of the kaolin is much smaller than that of bentonie. Kaolin stopped swelling at 400 Co while bentonite stopped at 600 Co. this is due to the dehydroxylation process which begins at 400 Co for kaolin and at 600 Co for bentonite.**

**3.2 *Heating Effect on Consolidation***

**In studying the effect of heating on the consolidation of clay soils, namely, the Edgar Plastic Kaolin and the Western Bentonite, concentration was given to study the heating effect on the void ratio versus the applied pressure, the effect of heating on the compression index ( Cc ), and the effect of heating on the coefficient of consolidation ( Cv ). All specimens of the two clay soils (kaolin and bentonite) were tested according to the ASTM D-2435-80 method.**

**The compressibility of a soil varies with both environmental and compositional factors. The environmental factors include water content, density, confining pressure, temperature, and particle arrangement, while the compositional factors are soil mineralogy, pore water chemistry, particle size and shape, and other factors.it is known, for example, that substantial changes in compressibility can be caused by changing the ion concentration and ( pH ), leaching, oxidation, salt precipitation and mineralogy. Yet, particle size, shape, and arrangement remain the most important factors in affecting consolidation. It is also worth mentioning the relationship existing between compressibility on one side and plasticity and activity of the soil on the other side.it is well known that the higher the plasticity and activity of a soil, the higher its swelling and compressibility.**

**Under the same conditions, different soils show different amounts of consolidation. Physical interactions, which include particle bonding, sliding, rolling, and crushing play a major role in affecting the amount of compressibility. The increase of in physical interactions leads to less displacement and smaller volume change. Physic-chemical interactions which depend on particle surface forces also play an important role in affecting the compressibility of the soil. These strong forces, as a result of the small size and weight of the clay particles compared to their large specific surface areas, are responsible for double layer interactions, surface and ion hydration, and interparticle attractive forces which, in turn, affect the soil compressibility.**

**Comparing kaolin and bentonite reveal that particles of the kaolinite are large, thick, and stiff in comparison to particles of bentonite which are small, very thin, and filmy. The structure of kaolin is different than that of bentonite as described earlier, and the basal distances are different. The basal distance in the case of kaolin is short and fixed at 7.2Ao, while it is in bentonite 9.6Ao expandable in the presence of water till the complete separation. Also, the attractive forces (hydrogen and Van Der Waal) are strong in kaolin while they are weak in bentonite. By considering all the above discussed factors and others it is expected that bentonite will undergo greater volume change under consolidation than kaolin clay.**

**Edgar Plastic Kaolin and Western Bentonite clay specimens were tested untreated, air dried, and heated to temperatures of 100, 200, 300, 400, 500, and 600 Co. During the one dimensional consolidation tests the applied pressures were 0.346, 0.692, 1.384, 2.682, 5.279, 8.913, and 14.710 *tsf*.**

**3.2.1 *Heating Effect on Void Ratio***

**Untreated (unheated and fully saturated) kaolin specimens did not exhibit a great volume change due to the fact that they were already consolidated during the preparation stage. The untreated kaolin had a smaller initial void ratio of about 1.2 compared with the air-dried and heated specimens. The void ratio changed from about 1.2 to about 1.0 at the end of the test. The height of the specimen decreased reaching about 10% of its original height. This happened under pressure of 2.5 *tsf*.**

**Kaolin specimens were air dried at room temperature, thus, they underwent some shrinkage. Air dry kaolin specimens were free to swell without a sustainable pressure during soaking prior to the consolidation tests. Therefore, the initial void ratio increase duo to swelling to about 1.32. The void ratio of air dry kaolin changed from 1.32 before testing to about 0.85 at the end, and the initial height reduction reached about 20%. It is worth mentioning that most of the volume change occurred under pressure exceeding 3 *tsf*.**

**Heating kaolin to 100 Co resulted in increasing shrinkage and the average change in void ratio reached about 0.7 ( 1.34-0.65 ). Most of this change took place under a pressure higher than 1 *tsf*. On the other hand, kaolin heated to 200 Co showed an average change in void ratio of about 0.8 ( 1.34-0.54 ), and this result was almost the same for kaolin heated to 300 Co. the height decrease was recorded as 34% for kaolin heated to 200 Co while it reached 35% for kaolin heated to 300 Co. kaolin specimens heated to temperatures 400 Co and above did not soften and, therefore, consolidation tests for those specimens were not performed.**

**While bonding forces between kaolin particles are strong, these forces are weak in bentonite. Therefore, bentonite showed different consolidation behaviour comparing with kaolin. In addition, kaolin reached dehydroxylation stage at 400 Co while bentonite reached this stage at 600 Co. at this stage kaolin and bentonite specimens did not soften and their consolidation tests were stopped.**

**Untreated bentonite specimens showed an average decrease in height of about 13%. The initial void ratio (about 1.2) changed to about 0.9 at the end of the test. This took place under a pressure of 2.5 *tsf*.**

**Air dried bentonite specimens were free to swell without a sustainable pressure during soaking prior to the consolidation tests. Therefore, the initial void ratio increase duo to swelling to about 3.54 due to the ability of bentonite to swell more as explained earlier. The void ratio changed from 3.5 to 0.86 ( about 60% ).**

**Specimens heated to 100 Co showed a change in void ratio from 3.6 to 0.85 ( about 61% ). While specimens heated to 200 Co showed a change in void ratio from 3.69 to 0.83. T temperature of 300 Co, specimens did not show big difference. The change in void ratio was 3.71 to 0.78. this change continued to be small at temperatures 400 and 500 Co ( 3.71 to 0.86 ). The consolidation tests were eliminated at 600 Co because specimens were not soften as explained above.**

**3.2.2 *Heating Effect on Compression Index( Cc )***

**The compressio0n index ( Cc ) is defined as the slope of the field consolidation curve, which is the graphical relation between the void ratios and the consolidation pressures. Knowing the compression index is very important for engineers who deal with settlement problems.**

**The compression index, generally speaking, is smaller in kaolin than in bentonite. It varies with many factors such as particle size and shape, soil structure, cation type, and electrolyte type and amount. Usually, the compression index of kaolin ranges between 0.19 and 0.28 while in bentonite it ranges between 1.0 to 2.6.**

**In our study, the compression index of kaolin was 0.29 for untreated specimens, then 0.55 for air dry specimens. When kaolin was heated to 100, 200,, 300 Co, the compression index was 0.57, 0.7, and 0.73, respectively. At temperatures higher than 300 Co , no tests were done as stated earlier.**

**Bentonite,, on the other hand, showed a compression index of 1.38 for untreated specimens, 4.7 for air dry specimens, and 5.0, 5.86, 5.9, 3.3, 3.0 for specimens heated to 100, 200, 300, 400, and 500 Co, respectively. At 600 Co, bentonite specimens were not tested because they did not soften due to the process of dehydroxylation as explained earlier.**

**3.2.3 *Heating Effect on Coefficient of Consolidation ( Cv )***

**The coefficient of consolidation Cv is an essential soil property needed to determine the time needed for the foundation to settle. In general, the coefficient of consolidation of bentonite is smaller than that of kaolin. For all tested specimens of kaolin and bentonite, the coefficient of consolidation decreases with increasing consolidation pressure. The decrease can be attributed to the fact that consolidation pressure cause particle deformation, displacement, and rearrangement to a denser fabric which, in turn, causes a decrease in permeability and hence a lower coefficient of consolidation.**

**Results of testing kaolin clay showed an increase in coefficient of consolidation for untreated, air dry, and specimens heated to 100 and 200 Co. At 300 Co, a decrease in coefficient of consolidation took place. No further tests were undertaken as explained earlier.**

**Bentonite showed almost similar behavior. The coefficient of consolidation increased for untreated, air dry, and specimens heated to 100 and 200 Co. at 300, 400, and 500 Co the coefficient of consolidation decreased and at 600 Co tests were stopped.**

**foundation**

**3.3 *Heating Effect on Strength***

**All problems of foundation stability, slope stability, and others depend in one way or another on soil strength. Therefore, it is important to understand the strength property of clay and factors affecting it. This includes studying the effect of heating on the stress-strain relation, compressive strength, shear strength, and failure strain.**

**The surface texture, size, shape, arrangement of soil particles, the state of stress, the adsorbed cation type, the pH, the water content, and the physic-chemical interaction forces in the soil mass play a great role in the determination of the engineering properties of the given soil**

**Repulsive and attractive forces of interaction in clay soils exist between atoms, sheets, layers, and particles of the soil mass. Usually, the Van Der Waals forces are the most dominant between clay particles. A balance among all these forces is usually exist at equilibrium. As a result of heating, this balance is no longer exists, and thus, major or minor changes occur in the engineering soil properties.**

**Shear strength of the soil can be expressed in terms of the internal friction angle and the cohesion. The internal friction angle is a function of sliding, rolling, crushing, and confining pressure and it depends on particle size, shape, and surface texture. On the other hand, the soil cohesion depends on interparticle forces, cementation, electrostatic, and electromagnetic attraction forces. It is generally accepted that increasing the quantity of fine-grained clay in a soil would result in an increase of its true cohesion and, at the same time, a decrease in the true angle of internal friction.**

**Kaolin and bentonite specimens showed a general increase in their strength under increasing confining pressure and decreasing void ratio. Under the same confining pressure and void ratio, kaolin and bentonite heated to 100 Co showed a drastic decrease in their strength compared to air dry specimens. When these specimens were heated to 200 Co, a small increase in strength was obtained in kaolin while the strength of bentonite remained almost the same. At 300 Co, the compressive strength of kaolin continued to increase and bentonite also began to show little increase. This behaviour continued in kaolin until heating temperature reached 400 Co when the dehydroxylation process began and the strength began to increase drastically. Meanwhile, the compressive strength of bentonite continued to increase slowly and gradually until the 600 Co temperature. At 600 Co and above, the compressive strength of bentonite began to increase drastically.**

**As stated earlier, the shear strength property is determined in terms of strength parameters, cohesion and internal friction angle. Kaolin, for example, exhibit a decrease in cohesion when heated to 100 Co. heating to temperatures between 100 and 400 Co caused no big change in cohesion, while heating to higher temperatures (500 and 600 Co) caused a drastic increase in cohesion. Bentonite, on the other hand, showed a similar pattern for air dry specimens and specimens heated to 100 Co up to 400 Co. yet, the cohesion of bentonite continued almost at the same values when specimens were heated beyond 400 Co and up to 600 Co.**

**The internal friction angles for air dry kaolin and bentonite are smaller than those of heated specimens of the two clays. The internal friction angle of air dry kaolin is higher than that of bentonite. For both clays, the internal friction angle increases with increasing heating temperatures. The increase in friction angle for air dry specimens of bentonite and specimens heated to 100 Co is much greater than that of air dry kaolin specimens and specimens heated to 100 Co. Further heating of kaolin and bentonite to temperatures between 200 and 500 Co causes a gradual increase in the internal friction angle for both clays, although this increase is greater in the kaolin than in bentonite.**

**In summary, both clays exhibited a high strength when they were air dry, and lost much of their strength when heated to 100 Co. up to the end of the dehydration period, both clays did not exhibit major changes in their strength. After this stage ( about 300 Co ), both clays continued with the same pattern of strength increase up to the beginning of the dehydroxylation stage ( 400 Co for kaolin and 600 Co for bentonite ). Then the change in strength increased drastically. This was not clear for bentonite because the real drastic increase begins beyond 600 Co.**

1. **EXPLANATION of RESULTS**

**Although soil heating, especially clay heating, has been used thousands of years ago, the understanding of what really happens inside the clay structure, and why its strength, swelling, and consolidation change still need studying. To understand what happens exactly we need first to understand the water-soil relationships and the effect of heating on soil-water relation.**

**4.1 *Soil-Water Relationship***

**Clay minerals consist of particles and voids that may be filled with gas or water or both. Particles consist of layers bonded together by interlayer forces and layers consist of sheets that are bonded together by intersheet forces. Finally, sheets are composed of atoms that are bonded together by various types of bonds including ionic, covalent, hydrogen, Van Der Waal, and London forces.**

**In the clay soil there are three types of water, surface water that fills the voids between particles, inter layer water, and inter sheet water. Surface water usually evaporate at about 100 Co. This is the water that we get rid off when the moisture ( water ) content determination test is carried out. The interlayer water needs higher temperature and this is associate with the so called dehydration stage. The intersheet water can be removed at still higher temperature at stage called dehydroxylation stage. At this point the crystal structure of the soil is damaged and the soil itself will be at the state of fusion.**

**When soil is subjected to heat it passes through three different stages. Heating soil to about 100 Co will first evaporate the surface water ( interparticle water). Heating the soil to a temperature up to 300Co ensure that all surface and adsorbed water should have been vaporized. This is the dehydration stage. The second stage ranges from 400 to 1000Co and called dehydroxylation stage. The clay mineral undergo an endothermic reaction as a result of the loss of the hydroxyl (OH). At the third stage the clay mineral change from plastic to non plastic coarse material.**

**One of the methods that may help us understanding what happens inside the clay mineral when subjected to heating is the Differential Thermal Analysis (DTA). The DTA test is the most applicable thermal technique used to study clay minerals. In this test, reactions reflected by the difference in temperature between the sample and the inert substance are measured and presented through a differential thermal curve. The curve usually shows peaks down which represent endothermic reactions and peaks up which represent exothermic reactions. The endothermic reactions are caused by the sample taking up heat, while the exothermic reactions are caused by the liberation of heat from the sample.**

**DTA tests were done on kaolin and bentonite specimens heated to temperatures up to 1100 Co. kaolin showed endothermic reaction at temperatures between 400 and 600 Co where the removal of the crystal lattice water removed. The kaolin exhibited a sharp exothermic peak at about 980 Co. This is illustrated in figure 3.**

**Bentonite, on the other hand, showed an endothermic peak at the temperature of dehydration up to 200 Co. the other endothermic peak occurs at 600 to 700 Co. This is illustrated in figure 4.**

**The previous DTA tests give us an idea about the behaviour of water in the clay subjected to different temperatures in term of endothermic and exothermic reactions. This change in the condition of water may be the explanation of the change in soil engineering parameters.**

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