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Experimental Assessment of the Impact of Pore Fluid on the Geotechnical Performance of Expansive Soil

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Abstract. Rapid population growth and industrialization have led to large quantities of untreated waste being disposed of on land. During the rainy season, this waste mixes with rainwater to form a toxic liquid known as leachate. The leachate percolates downward under gravity, contaminating the soil and groundwater. This contamination adversely affects the geotechnical properties of the soil: interaction with the effluent degrades these properties and can cause cracking, settlement, and heaving of structures built on the soil, and in severe cases may lead to their collapse. There is therefore a need to examine how the nature of the pore fluid affects the geotechnical properties of soil. Leachate may be acidic or alkaline, and it sometimes contains a high salt content. This study therefore investigates the effect of the pore fluid's nature on the plasticity and compaction characteristics of soil.

1 Introduction

The rapid growth in population and industrialization has resulted in significant waste generation, impacting soil properties either positively or negatively. When industrial wastes enhance soil properties, they can serve as stabilizers while ensuring safe disposal. Conversely, if waste degrades soil quality, understanding soil-pollutant interactions becomes critical for mitigation and determining soil suitability for construction.

1.1 Beneficial Uses of Industrial Effluents

The aluminium sludge which is a by-product of the aluminium industry can be used to improve the performance of pavements. Study [1] revealed that adding lime along with aluminium sludge increased compressive strength, flexural strength and surface energy, thus enhancing the durability of the pavement. Alum sludge obtained from wastewater treatment plants has proved its efficacy for use in geotechnical projects. Study [2] revealed that addition of 1.5% aluminum sulphate decreased soil dispersivity and liquid limit, while increasing hydraulic conductivity due to ion exchange and pH reduction.

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Red mud which is a by-product of Bayer process has been used successfully to stabilize clay liners. Study [3] revealed that the inclusion of red mud-cement additives increases compressive strength while decreasing hydraulic conductivity and swelling. Likewise, the white wash mud obtained from cellhouse industries enhances subgrade soil properties at a dose of 25% [4]. The spent orange dye waste from the textile industries can improve soil strength due to cementation and flocculation [5].

1.2 Harmful Effects of Industrial Effluents

Industrially discharged substances can affect soil behavior. The contamination of soil with phosphoric acid results in the variation of the volume and heaving of soil. According to [6], the leakage of phosphoric acid into the soil sub-grade resulted in tiltage of storage tanks due to gas pressure produced during the formation of phosphate. In Kerala, India, the same kind of damage occurred where phosphate retained in the soil changed its soil texture, and the measures taken included providing escape routes for the gas and improved drainage system.

Clay behaves differently when contaminated with brine solution. [7] shows that clay-brine interactions reduce plasticity and shear strength and increase hydraulic conductivity. [8] states that salt brines result in particle aggregation and greater permeability.

High pH level substances like caustic soda (NaOH) have also negative effects on soils. [9] mentions that heaving of kaolinite soils due to caustic soda spillages occurs because of the dissolution of cementing iron oxide and is treated using ferric chloride and impermeable membranes. [10] reports a reduction in bearing capacity of about 33% due to NaOH pollution and recommends similar remediation strategies. It was observed that soil with more NaOH content swells and permeates while undergoing structural deformation due to alkali contamination.

1.3 Swelling and Shrinkage Behaviour of Marine Clays and Treatment Techniques

It is worth noting that the marine clays may behave in such a way that their expansion and contraction result in causing serious foundation problems, mainly resulting in excessive settlement. In addition, the process of lime stabilization has been utilized in many cases for treating the soft clays, such as marine clays [11]. The deep lime mixing approach has been recently used in the coastal areas for improving the performance of weak marine clays. However, lime treatment should be carried out cautiously where there is a significant presence of sodium sulfate in the soil.

The swelling associated with sulfate-induced heave can be attributed to both primary and secondary sources of sulfate. Primary sources include native sulfates in natural soils, while secondary sources include construction and industrial wastes, as well as spilled chemicals. These sulfates can alter soil-lime reactions, inhibiting strength development through cementation and reducing shear strength over time [12,13]. For instance, the amount of heave in lime stabilization was more than 30 cm due to ettringite formation in Las Vegas on Stewart Avenue [13]. The use of GGBS in partial substitution for lime will help reduce soil swelling caused by sulfate presence.

1.4 Impact of Oil Contamination on Soil Properties

Sources of crude oil in soil pollution include oil spills owing to ruptured pipelines, tanker accidents, offshore petroleum operations, and oil seepage. These sources may include oil spills during the Gulf War in Kuwait and the oil spill caused by the Exxon Valdez disaster in

Alaska. Soil pollution in Saudi Arabia is mostly associated with oil spills caused by leakage in the pipeline. Oil polluted soils experience deterioration in geotechnical characteristics, affecting their engineering performance [14].

There are significant changes in the maximum dry density (4%), cohesion (66%), angle of internal friction (23%), and unconfined compressive strength (35%) of oil polluted soils, with an increase in liquid limit by 11% [14]. The geotechnical characteristics of oil polluted soils can be improved through the addition of soil stabilization materials, namely lime, fly ash, and cement, both singly and as mixtures. The improvement can be attributed to the presence of cation exchange, agglomeration, and pozzolanic reaction in the process. The most effective additive material is made up of 10% lime, 5% fly ash, and 5% cement; this mixture helps in the formation of CSH which binds soil particles together to lower leachable oil [14].

1.5 Settlement Characteristics of Petroleum-Contaminated Clays

The study was conducted on the settlement properties of clay soils contaminated by petroleum hydrocarbons such as used engine oil, diesel, gasoline, and kerosene. The study found that the soils were affected by contamination and showed settlement properties higher than usual due to an increase in compression indices. Simultaneously, there is a decrease in the coefficient of consolidation in contaminated soils and significant bearing capacity loss in sandy soils.

1.6 Influence of Other Contaminants on Soil Behavior

Several authors investigated the influence of pollutants like waste engine oil and coconut oil on the characteristics of the soils. It was observed that the plasticity values were lowered, whereas permeability coefficient, consolidation, and the compression index were enhanced due to pollution. It was also observed that shear strength diminished as the pollution was intensified. On similar lines, urea pollution lowered the value of plasticity, whereas swelling pressure, consolidation coefficient, and the compression index became high [12].

Studies have reported that soils exposed to detergent solutions undergo deformation. Soils in contact with effluent from fertilizer plants showed increases in consistency limits, permeability, and the compression coefficient, accompanied by reductions in shear strength and bearing capacity. These changes were attributed to a lower cation content and a more aggressive leaching solution.

1.7 Influence of pH

Fine-grained soils, particularly clays, exhibit mechanical behavior that depends on the chemistry of their surroundings to a large extent. The term used for such interactions is chemical-mechanical coupling. This refers to the impact of chemistry of the pore fluids on the soil's behavior. Some of the factors that result in chemical-mechanical coupling are the dielectric constant, electrolyte content, and the pH of the pore fluids.

Kaolinite clays exhibit pH-dependent edge surface charges that play a crucial role in their mechanical properties. At low pH values (between 7.2 and 4.0), the edge charges become positive, interacting with the negatively charged particle faces, resulting in a flocculated structure. Influence of the process of flocculation on the engineering properties of kaolinite includes an increase in the following characteristics: permeability, compressibility, and shear strength. Moreover, flocculated fabrics have higher liquid limits and shrinkage limits.

On the contrary, when the value of pH is high, both edges and faces of the kaolinite particles become negative charged, leading to a deflocculated fabric. Thus, the process of deflocculation reduces the above-listed geomechanical properties of kaolinite. At the same time, extremely low pH values lead to positively charged edges and faces of the clay particles, resulting in a decrease in mechanical properties of kaolinite.

On the other hand, smectite clay demonstrates a permanent negative charge as the result of isomorphous substitution of elements in the clay structure. Moreover, the negative charge of smectite particles is not affected by pH but is balanced by the diffuse double layer (DDL) that surrounds the particles. Negative charges dominate on the faces of smectite particles while their edges contain pH-dependent ions (Al-OH and Si-OH).

Thus, pH affects mechanical properties of smectite clays through the regulation of the thickness of the DDL. Under acidic conditions with high H+ concentration, the DDL becomes narrower because of the high ion concentration. A similar effect takes place when the pH level is high; however, hydroxyl ion (OH−) is more concentrated in this case. In acidic environments (when pH is less than 5), smectite forms a "card-house" structure due to the presence of positive charges on edges that interact with negatively charged faces. On the other hand, in highly basic environments (with pH>5), card-house structure disintegrates since the positive charges vanish.

As a consequence of pH changes, the engineering properties of smectite clays significantly differ. Namely, in acidic conditions, the flocculated state of the particles is observed, which leads to increased shear strength, compressibility, and permeability. On the contrary, when pH rises, all the mentioned properties drop down. Understanding how pH affects geotechnical properties of clays is important for engineers who work with soils that face significant pH changes. For instance, it may happen when treating acid mine drainage, oil spills, and contaminated groundwater.

The current research focuses on how different water types affect the properties of expansive soil. The research considers the following parameters of expansive soil: liquid limit, plastic limit, plasticity index, differential free swell index, optimum moisture content (OMC), maximum dry density (MDD), California bearing ratio (CBR), unconfined compressive strength (UCC), and undrained cohesion (Cu). Specifically, several samples of expansive soil were treated using different water types (tap water, acid water, base water, and seawater).

2 Experimental Investigation

2.1 Materials Used

Soil: This type of soil is very dense in nature with low porosity. It shows very high water retention ability, making it difficult for water and air to pass through. Once saturated, the soil sticks like glue but when dried, it becomes smooth. Due to its heavy and dense nature, this soil has low drainage ability.

Seawater: There are salts present in the seawater which affect the characteristics of the soil. According to the results obtained, the optimal dry unit weight increases and the optimum moisture content decreases due to the addition of seawater, even if there is only 10% of clay content.

Acidic Water: Acidic water has a pH less than 7. Natural sources like peat or humus-derived organic acids generally cause pH values around 5.5. When an acid dissolves in water, it increases the hydrogen ion concentration, making the reaction exothermic.

Alkaline Water: This water typically has a pH of 8 or 9, higher than neutral drinking water (pH 7). Alkaline water also contains alkaline minerals and negative oxidation-reduction potential (ORP), which imparts antioxidant properties.

Tap Water: Water obtained directly from a faucet or tap, typically untreated and unpurified.

2.2 Procedure for Mixing

Air drying followed by manual separation of pebbles and organic material is the first step in this process. The soil sample is then crushed and sieved through a mesh size of 4.75 mm. The sieve separated soil sample is kept in sealed containers. In the next step, soil and water are mixed together such that a certain moisture level is attained, after which the soil is allowed to equilibrate for 24 hours. Various pore fluids, which may be acidic, basic, or saline, are added to the soil.

2.3 Tests Conducted

Liquid Limit: The moisture content that causes the soil to change from plasticity to liquidity should be determined.

Plastic Limit: This refers to the determination of the moisture content where soil changes from plastic to semi-solid.

pH: pH, which indicates soil acidity/alkalinity, should be determined for soil samples.

Differential Free Swell Index (DFSI): The DFSI test measures the expansive capability of expansive soil mixed with different percent effluents (0%, 20%, 40%, 60%, 80%, and 100%). In this test, two samples of expansive soil of 10 grams that pass through the 425-µm I.S. sieve are used. One of the soil samples is poured into 100 mL of kerosene inside a cylindrical vessel, while the other soil sample is poured into another 100 mL of distilled water.

Compaction Test: Standard Proctor compaction test involves compaction of soil mixed with effluents with different percent compositions (0%, 20%, 40%, 60%, 80%, and 100%). A soil sample that is prepared to the desired moisture content is mixed with effluents and then compacted using a Proctor mold having dimensions of 100 mm diameter by 117 mm in height in three layers using 25 blows per layer. From this, the bulk unit weight, pore fluid content, and dry unit weight are calculated.

Unconfined Compressive Strength (UCS): UCS is performed on soil samples mixed with effluents (0%, 20%, 40%, 60%, 80%, and 100%).

California Bearing Ratio (CBR): CBR tests involve determining the bearing ratio for soil samples mixed with effluents (0%, 20%, 40%, 60%, 80%, and 100%).

3 Results and discussions

3.1 Soil Properties Overview

The soil under investigation was analyzed for its physical, plasticity, and strength characteristics, summarized in Table 1. The soil is predominantly fine-grained, with a high clay and silt content, making it expansive and prone to significant volume changes. The high value of the plasticity index of Atterberg limits shows high plastic nature of the soil under analysis. The properties related to compacting show moderate maximum dry unit weight and optimum moisture content. CBR and UCS values point to low to moderate soil strength. All of the parameters presented above highlight the importance of using soil stabilizers in construction works.

The soil used for research consists of 90% fine soil fractions, including silts and clays, as well as 7% of sands and 3% of gravels. This combination of fractions shows that the studied soil is highly cohesive and has high potential to change its volume depending on humidity changes. According to consistency limits, liquid limit of 53%, plastic limit of 28% and

plasticity index of 25% define medium to highly plastic and expansive soil. Moreover, DFSI of 61% additionally confirms high swellings with moisture content.
Maximum dry density is 1.90 g/cc and optimum moisture content is 19%. These parameters indicate what conditions must be present to have maximum compaction. CBR values of 4.5% at 2.5 mm penetration and 4.1% at 5.0 mm penetration demonstrate low subgrade strength. Moreover, the unconfined compressive strength is equal to 0.64 kg/cm², which shows that shear strength is also low. It means that the analyzed soil is characterized by expansive and weak properties.

3.2 Standard Proctor Test:

Figure 1 highlights the influence of water type on the properties of soil when subjected to compaction in the context of the SPT test. As shown in the figures, the highest maximum dry density achieved will vary according to the type of water used for compaction. In particular, water types include acidic water, basic water, seawater, and tap water, with each one showing varying results. Specifically, the dry density increases from acidic water, then basic water, tap water, to seawater. Such differences could be as a result of the chemical nature and ion concentration of the different water types.

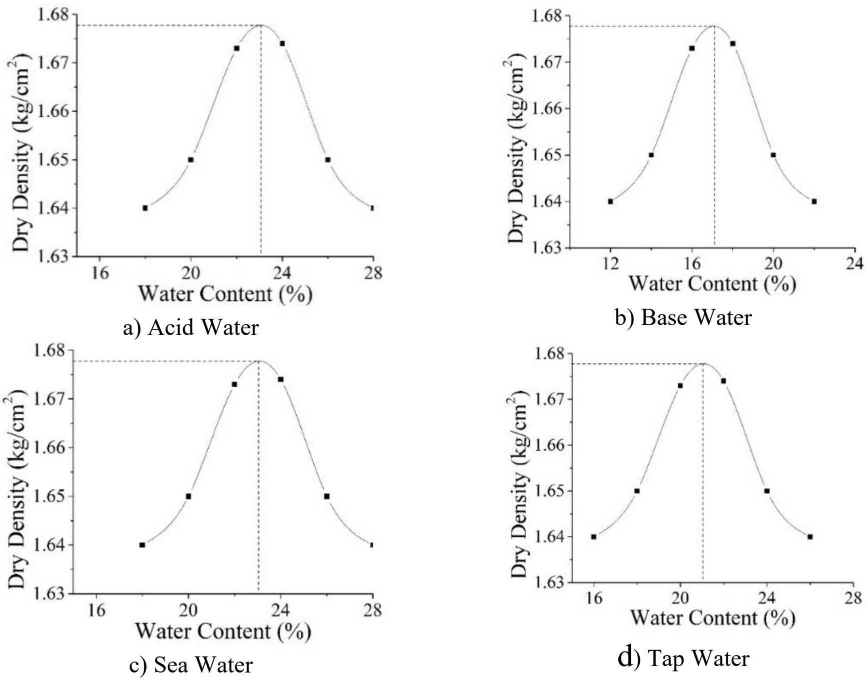

Fig. 1. Relationship between Dry Density and Water Content for Different Water Types

The Figure 2 displays the impact of different water types on the OMC of soil. The OMC, representing the water content at which maximum dry density is achieved, is observed to be significantly influenced by the water type. Acid water and sea water lead to a higher OMC compared to tap water and base water. These variations can be attributed to the chemical composition and ionic strength of the water, which affect the interaction between water and soil particles during compaction. From the Figure 2 it was observed that for tap water the Optimum moisture content is 20%. For base water and sea water the OMC moisture content increased with reference to tap water and is equal to 23% and 25% respectively. For Acid water the OMC decreased with reference to tap water and is equal to 18%.

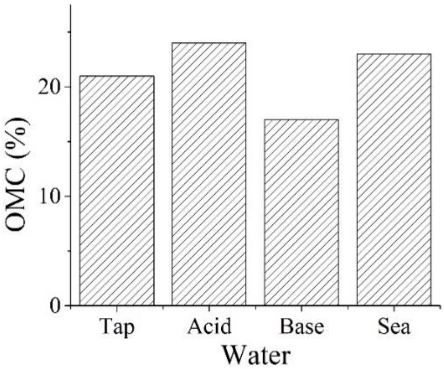

Fig. 2. Variation of Optimum Moisture Content (OMC) with Water Type

3.3 California Baring Ratio:

The Figure 3 presents the results of California Bearing Ratio (CBR) tests conducted on soil samples compacted with different types of water. The plots illustrate that the dry density of the soil increases with increasing penetration depth for all water types. However, the rate of increase varies depending on the water type. Acid water and sea water generally result in a higher dry density compared to base water and tap water at a given penetration depth. The differences in dry density occur due to the chemical nature of the water and its ionic concentration, because this will determine how the water and soil interact during compaction and, therefore, affect the properties of the soil in terms of strength and stiffness. Figure 4 shows CBR test results performed using soils compacted using different types of water. The CBR values are shown for two penetration depths, 2.5 mm and 5 mm. The graph reveals that the CBR values generally decrease with increasing penetration depth for all water types. However, the magnitude of this decrease varies depending on the water type. Acid water and sea water tend to yield higher CBR values compared to base water and tap water at both penetration depths. This suggests that the chemical composition and ionic strength of the water influence the soil's strength and stiffness, affecting its resistance to penetration and, consequently, its CBR values. From the Fig. 4 it was observed that for tap water the CBR value at 2.5mm penetration is 20%.For base water and sea water the CBR value increased with reference to tap water and is equal to 23% and 25% respectively. For the acidic pore fluid, the CBR value decreased relative to tap water, falling to 18%. A similar trend was observed at 5 mm penetration.

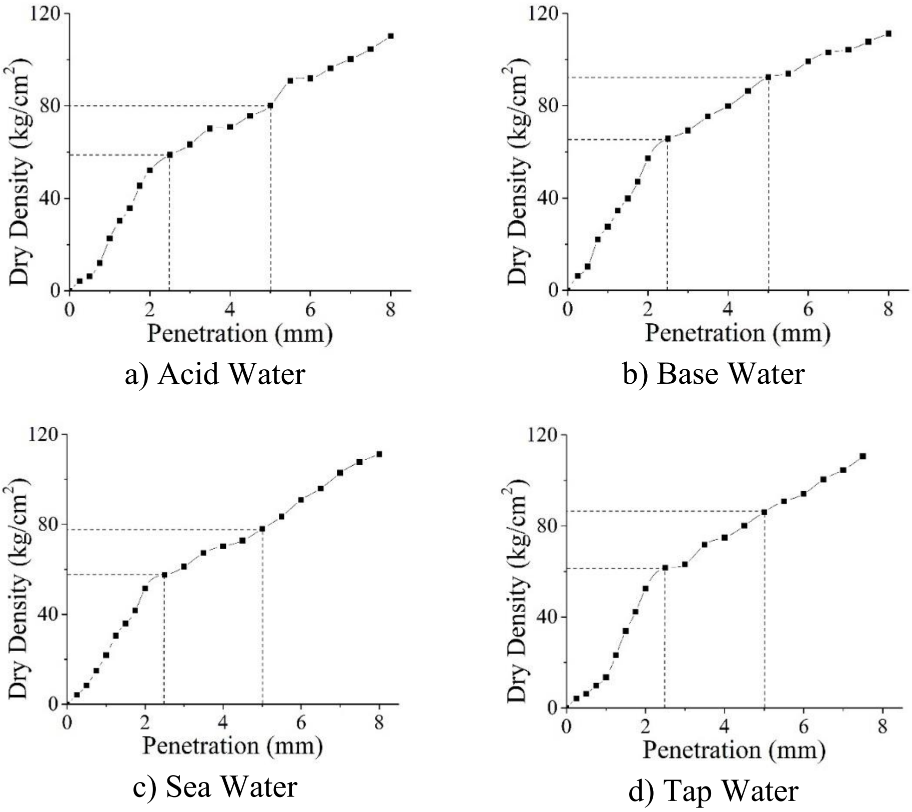

Fig. 3. Variation of Dry Density with Penetration Depth for Different Water Types

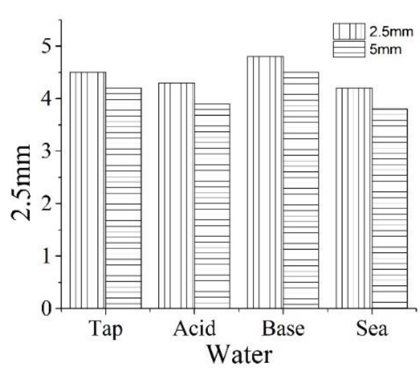

Fig. 4. CBR Values at Different Penetration Depths for Various Water Types

3.4 Unconfined Compressive Strength:

The Figure 5 presents the results of Unconfined Compression Tests conducted on soil samples compacted with different types of water. The plots illustrate the relationship between stress and strain for each water type. The curves exhibit a typical stress-strain behavior for soil, with an initial linear elastic region followed by a nonlinear plastic region. The peak stress and corresponding strain represent the failure point of the soil sample. The analysis reveals that the peak stress and strain vary depending on the water type. Peak values of stress and strain in acidic and seawater are normally higher than those of basic water and tap water. This shows that the chemical nature of the water and the presence of ions in the water affect the mechanical properties of the soil.

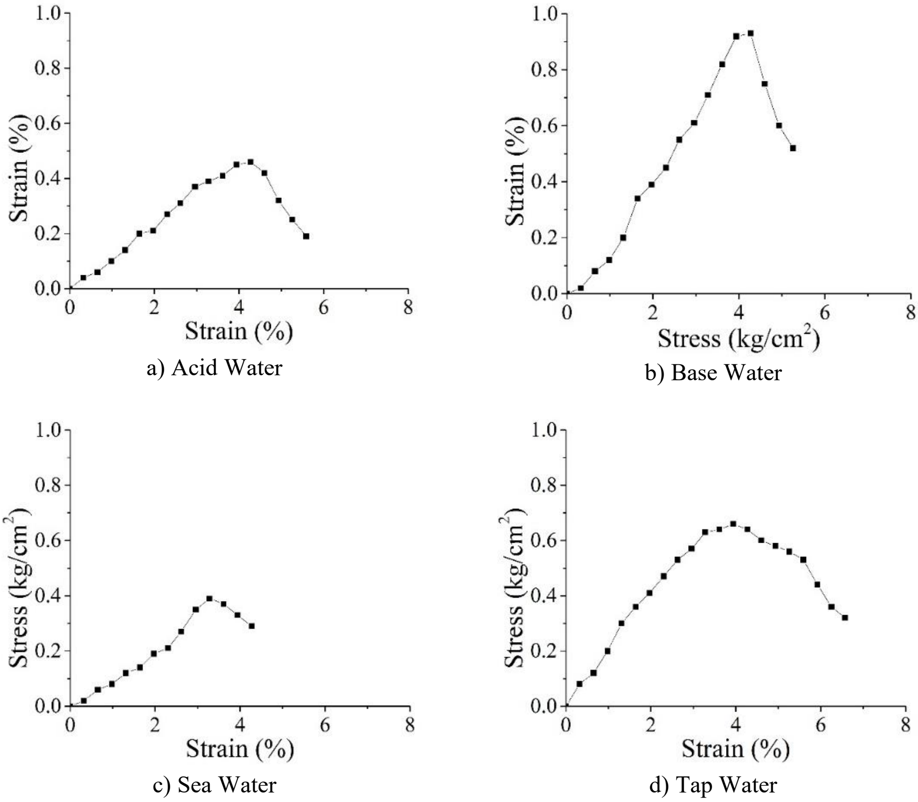

Fig. 5. Stress-Strain Curves for Different Water Types

The figure below illustrates the unconfined compression test results of soil samples compacted using different types of water. The graph shows the undrained cohesion, which indicates the shear strength of the soil sample for each type of water. It can be seen that the undrained cohesion differs considerably with respect to the type of water used. This indicates that the chemical composition and ionic strength of the water influence the soil's shear strength, affecting its resistance to failure under undrained conditions. From Figure 6, it was observed that the UCC value of soil treated with tap water is equal to 0.3 kg/cm^2. For sea water and base water, the UCC value increased with reference to tap water and is equal to 0.9 kg/cm^2. 0.4 kg/cm^2. For soil treated with acid water UCC value is decreased and is equal to 0.3 kg/cm^2. Similar trend is observed in undrained cohesion as it is equal to half of unconfined compressive strength.

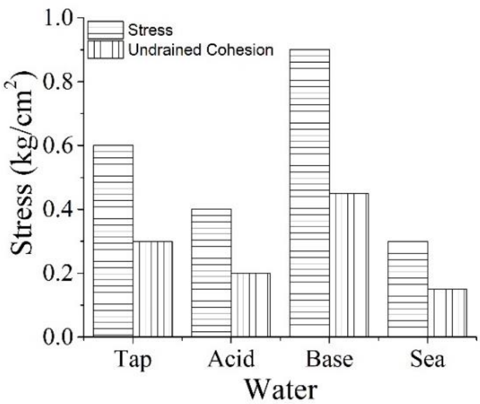

Fig. 6. Variation of Undrained Cohesion with Water Type

4 Conclusions

The purpose of this research is to explore the influence of different types of pore fluids such as tap water, acidic water, base water and seawater on geotechnical properties of expansive soil. The focus will be made on liquid limit, plastic limit, plasticity index, differential free swell index (DFSI), optimum moisture content (OMC), maximum dry density (MDD), California bearing ratio (CBR), unconfined compressive strength (UCS) and undrained cohesion (Cu).

It appears that the chemical nature of pore fluid has a great impact on the geotechnical behavior of expansive soils. First of all, it should be noted that soil subjected to alkaline water demonstrates the highest values of liquid limit, plastic limit and plasticity index. Thus, it means that such pore fluid increases water holding capacity of the soil and plasticity. On the contrary, acidic water is characterized by relatively low values of such indicators as liquid limit and plastic limit.

Moreover, the soil subjected to acidic water displays the highest DFSI value, meaning that it has high swelling tendency. However, the soil subjected to alkaline water demonstrates the lowest DFSI values, which proves that alkaline water may effectively stabilize such soils. Moreover, the values of OMC are the lowest for soil subjected to alkaline water, while such values are the highest for soil subjected to acidic water.

When speaking about bearing ratio, the CBR values for soil treated with alkaline water are higher than those for other types of pore fluids at both penetrations (2.5 and 5 mm). Thus, it can be concluded that such soil has higher load carrying capacity and higher resistance. Unconfined compressive strength and undrained cohesion are also the highest when soil is subjected to alkaline water. Thus, such type of pore fluid significantly improves soil's engineering properties and enhances its strength.

Therefore, this study proves that chemical nature of pore fluid significantly impacts the behavior of expansive soils. The soil treated with alkaline water demonstrates the best geotechnical properties; therefore, it is highly effective in terms of increasing load carrying capacity and reducing swelling tendency.

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