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The Effectiveness of Nominal Dosage of Ordinary Cement on Strength and Permeability of Clayey Soil

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Abstract

Pozzolanic materials, either naturally occurring or artificially made, have long been in practice for soil stabilization. Of the artificial pozzolans, the ordinary portland cement is the most commonly used globally. Literature review indicates that, to date, the percentage of the cement used to improve the properties of soil is 4 to 14% or more. For the sake of cost saving in soil-cement construction works, it is crucial to scrutinize the efficacy of an incredibly diminutive amount of cement on the engineering properties of soils. In this paper, efforts have been made to study the usefulness of nominal dosage rate of the ordinary portland cement on the bearing capacity and permeability of a clayey soil in Mie prefecture. Laboratory tests were conducted on California Bearing Ratio (CBR), unconfined compressive strength and the permeability coefficient of the clayey soil with the cement content of 0.0, 0.2, 0.4 and 0.6% in the ratio of mass. On the basis of the test results, it was concluded that both the CBR and compressive strength, a measure of bearing capacity of a soil, increased with the increase in the amount of cement. The stress-strain relationships of the soil under the unconfined compression tests indicated that the addition of the nominal dosage rate of ordinary portland cement reduced the strain at which the ultimate compressive strength occurred noticing the increase in the rigidity of soil. The modulus of deformation, a measure of deformation characteristics of a soil, was also found to increase with the increase in the quantity of cement content. Permeability tests revealed that the coefficient of permeability increased with the increase in the amount of cement.

Key words : Bearing capacity, Stress-strain relationships, Compressive strength, Modulus of deformation and Permeability coefficient

1. Introduction

It is recognized that soil, a bequest of nature, is both intricate and uneven material. Therefore, the soil existing at any particular site may not be appropriate for the intended purpose because of its complex properties and variable characteristics. Usually some techniques such as mechanical, chemical, thermal, electrical and physical etc. are used to improve the properties of *in-situ* natural soil for proper applications in the field (ACI, 1992 ; Sera, *et al.,* 1990). Among these, the use of supplementary cementing materials, such as ordinary Portland cement, is one of the most popular solutions anticipated to improve the properties of soils (Wilhelmsson, 1997 ; Awal and Mamun, 1998). Dating back some 50 years ago, Mitchell (1976) reported that the improvement of soil properties using cement began with the concept of the process of deductive reasoning (Ahuja and Swartzendruber, 1972 ; Kataoka, *et al.,* 1992). Cement treated soil is not a simple mixture of soil and cement but a unique conditioned material produced through the interaction between calcium oxide of cement and water contained among of soil particles (Boswell, 2000 ; Hossain, *et al.,* 2006).

A very little amount of ordinary Portland cement is, especially, suitable to improve the bearing capacity of clayey soil because of the chemical reaction that occurs between clay mineral and positive ion come from cement in water. Research has shown that more than 60% of the ordinary portland cement is calcium oxide ; a mixture of calcium, silicon and aluminium oxides ; quickly hydrate with water resulting a high concentration of calcium, and content of silica and alumina (Stocker, 1963 ; Ingles and Metcaf, 1972). These positive ions of calcium oxide provide cementing action among the clay particles bearing negative ions and, therefore, the ions unite the soil particles together as well as increase the stability of aggregates (Mindess and Young, 1981 ; Arora, 1989). Also, Marshal and Holes (1992), Prusinski and Bhattacharya (1999) and JSCE committee (2003) reported that the negative ions created by the clay minerals are, especially, attracted by the positive ions of calcium (Ca^{++}). As calcium ions stuck to the negative sites, it consequences the soil-cement mixture as a chemical compound that not only act to bring the clay particles together but also facilitate for binding the clay particles. According to Mindess and Young (1981), the main source of the observed strength in cement treated soils is due to the formation of $C_3S_2H_3$ compounds, a well-known binding agent. It is noted that the Ca^{++} ions released by cement connects to the Si^{3+} ions of clay mineral and therefore, it forms C_3S and C_2S compounds. These C_3S and C_2S compounds hydrate to form $C_3S_2\ H_3$ compounds which are particularly responsible to the strength development in cement treated soil even at a nominal dosage rate of cement content.

Literature review, clearly, indicated that, to date, the percentage of cement used to improve the properties of soil is 4 to 14% or more. A nominal dosage rate of cement to improve the bearing capacity and permeability of clayey soils is getting much attention lately in order to reduce the cost of the construction works. In spite of the volume of technical information existed on soil-cement and cement treated soil, there is no or little work available on the effect of very small amount of the ordinary portland cement to improve the bearing capacity and permeability of a clayey soil, although it has great advantages for the environmentally friendly construction of a farm road, option way & drain ditch etc. (Nagaishi *et al.,* 1985). The development of soil-cement with nominal dosage of cement is a significant contribution in this direction because of its environmental consideration, cost-effectiveness and drainage ability. In Japan, there is a lot of terrace land to which cement treated soil can be suitably and efficiently used for making new cultivatable paddy fields from unused land. In this paper, since the soil-cement is made from nominal dosage of cement, it has tremendous benefit to the environment and significant cost saving in material acquisition along with the development of strength and permeability.

The main objective of this research is to investigate the influence of nominal dosage of ordinary portland cement on the strength and permeability of locally available clayey soil to be used for soil structures applications. In view of this objective, the soil used in this research was collected from Kameyama mountain of Mie Prefecture, Japan. It is noted herein that this soil possesses some basic strength, however, further improvement in strength and permeability is necessary, because most of these soils are impervious which has many disadvantages especially in the rainy seasons causing disaster of sloping land. The present research is highly significant to overcome these basic needs. To date, a number of researches have been conducted on strengths characteristics of soil with cement content of more than 4.0%. The authors believe that the research reported in this paper is rudimentary and there is no research work on soil-cement with nominal dosage of cement content considered in this research article.

The bearing capacity of clayey soils has been investigated to study the effectiveness of the nominal dosage rate of the ordinary portland cement. A series of California Bearing Ratio (CBR) tests, Unconfined Compressive Strength (UCS) tests, permeability tests and Scanning Electron Microscopy (SEM) analyses of clayey soil with cement content of 0.0, 0.2, 0.4 and 0.6% in the ratio of mass were performed. Results on the CBR value, compressive strength, stress-strain relationships of the soil under unconfined compression tests, the modulus of deformation, the permeability coefficient and the SEM images are reported.

2. Materials and Methods

2.1 Properties of soil used

The soil samples were collected from the Kameyama Mountain in Mie prefecture, and tested at the laboratory. The particle size distribution curve is shown in Fig. 1. The soil has 66% percent of the clay and silt fractions. The other properties of the soil used in this research are shown in Table 1. According to the unified classification system, the soil used in this research is classified as CH. For obtaining the cohesion and frictional properties of soil given in Table 1, the specimens were tested by the direct shear test apparatus. The shear tests specimens of size 60 mm in diameter and 20 mm in height were prepared in cutter-ring placing into the mould of standard compaction test. The shear tests were carried out in accordance with Japan Industrial Standard (JIS). The dry bulk density given in Table 1 was determined by performing the standard compaction test. It is the maximum density at which the optimum water content was obtained. The densities of soil particles and the particles of soil-cement mixtures were determined by the particles density test method according to JIS A 1202.

2.2 Properties of cement

Any type of cement can be used for improving the engineering properties of soils. Ordinary portland cement (Type I), which is the

Table 1 Properties of the soil used

Parameters	Properties
Maximum dry bulk density (ρ_d)	1.59 Mg·m^{-3}
Optimum water content (W_{opt})	20.5%
Density of soil particles (ρ_s)	2.701 Mg·m^{-3}
Cohesion (c)	157.40 kPa
Angle of internal friction (ϕ)	32.8°
Sand, >75 μm	34%
Silt, 5–75 μm	33%
Clay, <5 μm	33%
Liquid limit	61.0%
Plastic limit	27.8%
Plasticity index	33.2

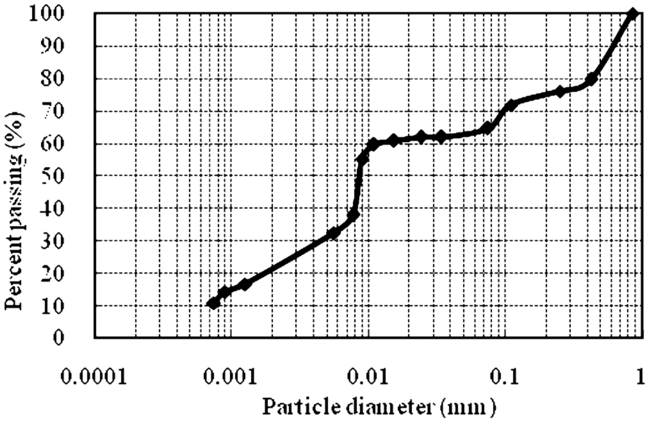


Fig. 1 Particle size distribution curve of the soil used

most common for construction works and also readily available in the local market, was used in this investigation. The detailed properties of this cement can be found elsewhere (Prusinski and Bhattacharya, 1999).

2.3 Preparation of specimens

The soil sample was air-dried in room temperature of nearly 25℃ and humidity of about 40% for 10 days, and it was grinded to ease the sieving process. For removing unnecessary elements from the soil and for reducing the variability of the particle sizes of the soil, it was sieved by JIS Sieve No. 4 (4 mm opening). The water content of the air dried soil was measured as 10%. The required amount of soil was taken, and the desired quantity of cement was mixed properly. In order to obtain the required percentage of cement in a mix, the amount of cement was calculated according to the following equation :

$$P=\frac{C}{S}\times 100\% \qquad (1)$$

where P is the required percentage of cement, C is the weight of cement mixed and S is the weight of air dry soil required for a test. It is noted that for each soil-cement ratio, three specimens were prepared and tested for all the cases. In case of unconfined compressive strength test, usually 2 kilograms soil was required. The amount of cement (C) was calculated as 4, 8 and 12 gms for 0.2, 0.4 and 0.6% soil-cement specimens, respectively. The soil and cement were mixed manually in a bowl with a scoop for 10 to 15 minutes to uniform the mixture. The calculated amount of water necessary to obtain the water-cement ratio of 0.5 was added gently to the dry mix, and, finally, the components were mixed thoroughly. Water up to the optimum water content was added gradually to the mixture while continuously stirred. The additional water calculated as water to cement ratio of 0.5.

It is noted here that the CBR values, compressive strengths and permeability of the specimens depend on the water content, dry density after compaction as well as the degree of compaction. In order to avoid these discrepancies, all the specimens were prepared with the optimum water content and compaction was done in accordance with the standard modified proctor test. All the samples for CBR, compression and permeability tests were moist cured for 7 days in room temperature of 25℃. All the tests samples were prepared with the optimum water contents of 20.5, 21.0, 21.5 and 22.2% for specimens containing 0.0, 0.2, 0.4 and 0.6% cement, respectively, obtained through the standard compaction tests. The compaction curves are shown in Fig. 2.

2.4 Method of CBR test

The California Bearing Ratio (CBR) test adopted here is widely used all over the world to evaluate the bearing capacity of soils and subgrades since its invention in 1930 by the California Division of Highways, United States of America. In this research, the CBR test specimens were prepared in steel mould of 15 cm in internal diameter and 17.5 cm in height. After placing a special disk of 5.0 cm in height in the mould, the soil was poured and compacted in three layers using a 5.0 cm diameter automatic rammer. The rammer mass was 4.5 kg with falling height of 45.0 cm. Each layer was compacted by 92 blows. The final height of the soil specimen was 12.5 cm. The compaction energy was calculated as 2500.0 kJ/m^3 for each specimen. All the CBR tests were carried out according to the JIS-A-1211 with the optimum water contents of soil.

2.5 Method of unconfined compressive strength (UCS) test

For the unconfined compressive strength (UCS) test, specimens were manually compacted in the mould of 12.5 cm in height and 5.0 cm in diameter. In this case also, the tests were carried out with the optimum water content of the soil with the different percentage of cement. The optimum water contents were 21.0, 21.5 and 22.2% as well as the particles densities of compacted soils were 2.705, 2.709 and 2.717 Mg・m^{-3} for cement content of 0.2, 0.4 and 0.6%, respectively. The specimens were

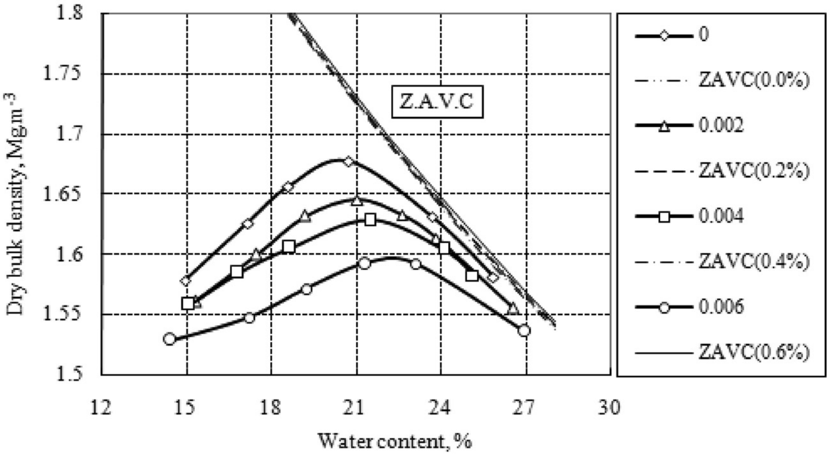


Fig. 2 Compaction curves of soil-cement with different cement content (Z.A.V.C. means zero air void curve)

compacted in three layers using a 4.9 cm diameter hand-rammer with rammer mass of 1.0 kg and falling height of 30 cm. Each layer was compacted by 20 blows. The samples were tested for the unconfined compressive strength at a loading rate of 0.1 mm per minute. Average strength values were calculated for each set of the three samples. These tests were also carried out in accordance of Japanese Industrial Standards (JIS-A-1211, 1980).

2.6 Method of permeability test

For the sake of clarification of the high pressure permeability testing apparatus used in this research, a simple diagram of it is shown in Fig. 3. The permeability tests were conducted by the constant head permeability test method according to JIS 1218. The specimens for the permeability tests were prepared in the steel mould of 10.0 cm in diameter and 6.2 cm in height. The compaction of the specimens was done manually using 2.5 kg rammer with the falling height of 30.0 cm. After compaction, the mould with specimen was placed on a stand to ease in collecting the outlet water by a graduated cylinder. The water pressures gauge was set at the upper plate of the specimens to confirm the constant water pressure on the specimen. Before applying the pressure from the gas cylinder, the water from the water tank was poured to the pressure chamber by adjusting the water control valve. The water of pressurized chamber was then poured on the specimen. During pouring the water into the mould, the air inside the mould on the top of the specimen was released by the air release

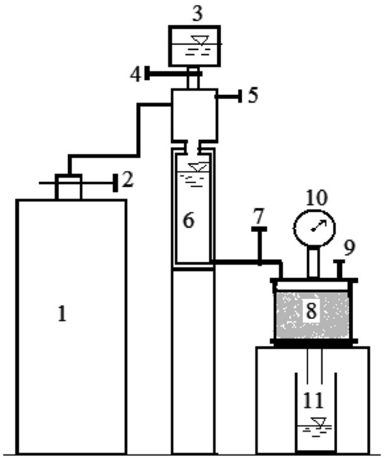


Fig. 3 High pressure constant head permeability test apparatus
(1. Gas cylinder, 2. Control valve for gas, 3. Water supply, 4. Control valve for water supply, 5. Air releaser, 6. Pressurized water, 7. Control valve for pressurized water, 8. Specimen, 9. Air releaser, 10. Dial gauge, 11. Graduated cylinder)

valve. The front face of the specimen was continuously connected to the pressurized water chamber during the test. Therefore, the top surface of the water in the mould was subjected to a constant pressure of 3.0 MPa (gauge pressure). The amount of water flowing through the specimen was measured by the collected water in the graduated cylinder. Before recording the readings, percolation was allowed for some time to ensure a high degree of saturation and uniformity of test results.

3. Results and Discussion

3.1 Results of California Bearing Ratio (CBR) tests

The results of the CBR test on cement treated soil containing 0.0, 0.2, 0.4 and 0.6% cement are shown in Fig. 4 in the form of the applied load vs. the depth of penetration relationships. As can be seen from this figure, all the curves are curvilinear initially and then linear. These curves also indicated that no initial correction for the calculating the CBR value is necessary except in the case of control specimen (0.0% cement content). For 0.0% cement content, the extension of the initial straight portion showed that it crossed x-axis slightly right side of the origin and this was taken account in calculating the final CBR value. It is noted herein that all the tests were carried out under optimum water contents (w_{opt}) of the soil. The w_{opt} were 20.5, 21.0, 21.5 and 22.2% for specimens containing 0.0, 0.2, 0.4 and 0.6% cement, respectively.

In Fig. 5, the calculated CBR values of the cement treated soils with cement content of 0.0, 0.2, 0.4 and 0.6% both at penetration level of 2.5 and 5.0 mm are shown. It is evident that the CBR values increased with the increase in cement content. The rate of the increase of the CBR values at 2.5 mm penetration is more than that at 5.0 mm penetration. Also, the CBR values at 2.5 mm penetration are higher than that at 5.0 mm penetration for all the level of cement content.

3.2 Results of Unconfined Compressive Strength (UCS) tests

In order to understand the bearing capacity of the cement treated soils, the compression behavior of specimens under unconfined compressive tests is demonstrated in Fig. 6 using the stress-strain curves. The stress-strain relationship of the controlled specimens (0.0% cement content) is also provided in the same figure for better comparison. For each curve, there is a peak or ultimate stress (here termed as compressive strength) and then, after the peak value, there is a softening behavior. It is observed that the compressive stress increases with the increase of displacement until appearing the peak value, naturally, but, owing to the different quantity of cement, the increment

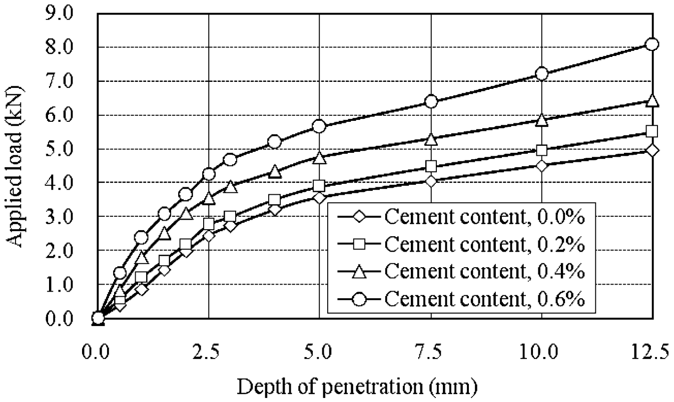


Fig. 4 Load vs. penetration curves of soil-cement under CBR tests

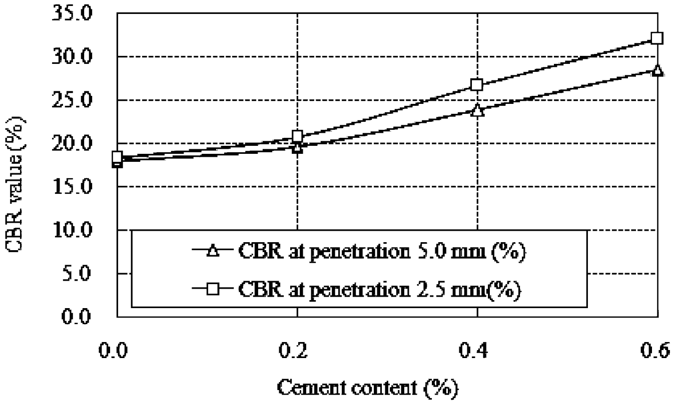


Fig. 5 CBR values of soil-cement with different cement content

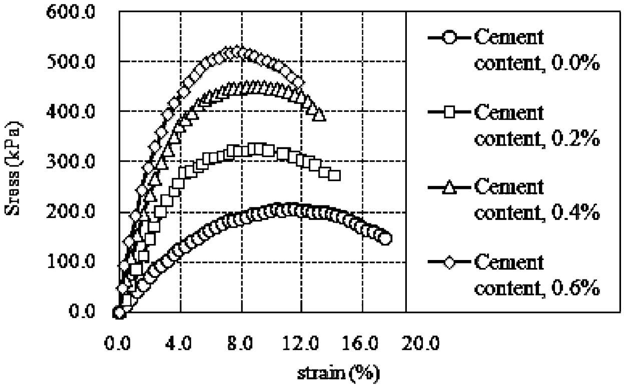


Fig. 6 Stress-strain relationships of soil-cement under compression

rate varies depending on the amount of cement content.

Figure 7 shows the variation of the compressive strength (q_u) and the strain obtained at the compressive strength with different levels of cement content. Notice a significant increase in the compressive strength with the increase in the percentage of cement content. The strain at the ultimate compressive stress (q_u), on the other hand, decreases noticeably with the increase in the quantity of cement content.

For the sake of calculating the modulus of deformation (E_{50}) of the cement treated soils with 0.0, 0.2, 0.4 and 0.6% cement, the stress-strain relationships of the straight portions, avoiding the initial and final nonlinearities, are considered. The values corresponding to the 50% compressive strength ($q_u/2$) are calculated as 101.7, 162.2, 225.0 and 260.1 kPa, and the corresponding strain (ε_{50}) are 2.9% 2.3%, 2.25% and 2.1% for cement content of 0.0, 0.2, 0.4 and 0.6%, respectively. The moduli of deformation (E_{50}) of cement treated soil are calculated by the following equation.

$$E_{50}=\frac{\frac{q_u}{2}}{\varepsilon_{50}}/10 \tag{2}$$

Here, E_{50} is the modulus of deformation of a soil in MPa, ε_{50} is the compressive strain when $\sigma=q_u/2$ in kPa. The moduli of deformation (E_{50}) calculated by equation (2) are shown in Fig. 8 with the different levels of cement content. It is evident that the moduli of deformation (E_{50}) of the cement treated soils are increased re-

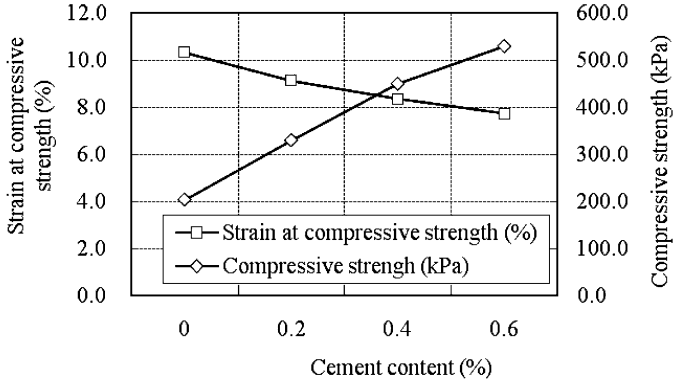


Fig. 7 Compressive strength and strain at compressive strength of soil with different cement content

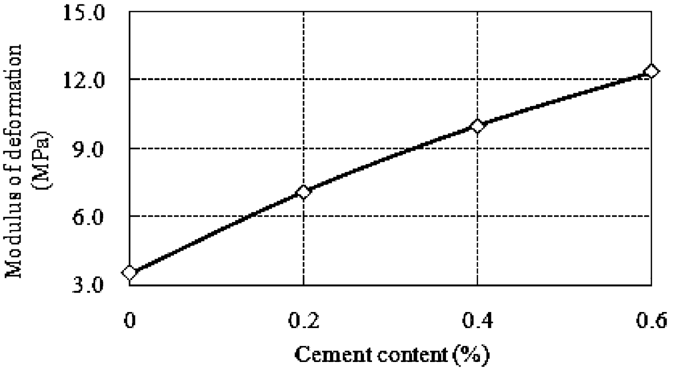


Fig. 8 Modulus of deformation of soil with different cement content

markably with the increase of the nominal dosage rate of cement content.

It is noted here that although the percentage of cement is very nominal, it is observed that both the bearing capacity and the modulus of deformation are conspicuously enhanced as compared to the controlled specimens (Figs. 5 to 8). It is also noticed that the addition of the very small quantity of cement gives a continuous increase of both the properties. This is due to the chemical reaction among cement, soil and water.

It was observed that the failure modes of test samples under unconfined compressive tests were varied depending on the quantity of cement added. These failure modes are clarified in Fig. 9. It is apparent from Fig. 9a that the cracks formed in the vertical plane for the control specimen without any cement content. No diagonal cracks were formed even the load was continued until compressive stain of 17.41 %. The addition of 0.2% cement in soil, although nominal, changes the failure pattern from vertical to diagonal direction as can be seen from the formation of major cracks diagonally in Fig. 9b. This change of failure plane or formation of diagonal cracks occurred at 14.70% strain indicates the development of the shear strength in soil by the addition of cement. Further addition of cement (0.4 and 0.6%), altered the failure modes of the soil in crashing type failure at strains of 13.11% for 0.4% cement content and 11.70% for 0.6% cement content as shown in Fig. 9c and Fig. 9d.

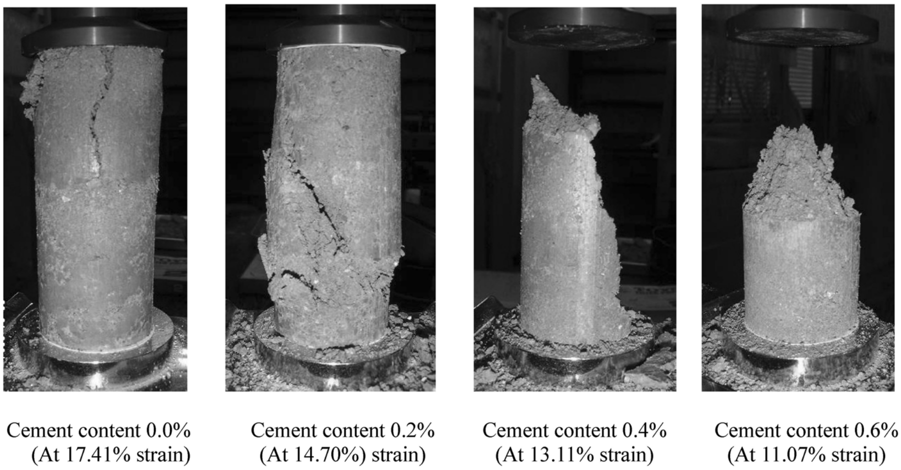


Fig. 9 Failure pattern of specimens under unconfined compressive strength test

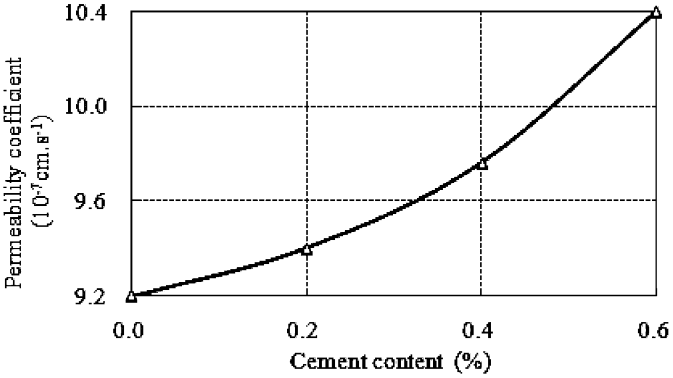


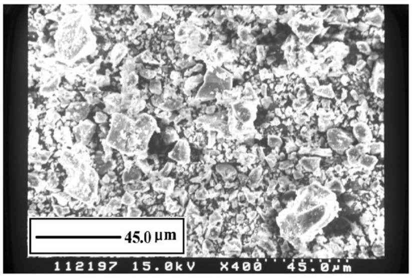
Fig. 10 Effect of cement content on permeability coefficient

3.3 Results of Permeability tests

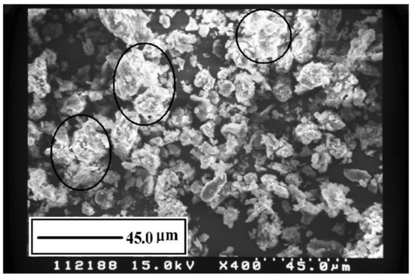
The test results on the permeability coefficient of the cement treated soils are depicted in Fig. 10. It is evident that the permeability coefficient increased with the increase in the amount of cement content. The higher rate of water permeability was occurred due to the flocculation of the soil particles. This flocculation brought the clay particles together by cementing them to form a compound or secondary particle. This phenomenon has already been discussed in the introduction section illustrating the effectiveness of nominal cement in forming the finer particles into secondary ones. The formation of secondary particles through cementing action is confirmed by Scanning Electron Micrographs (SEM) as shown in Fig. 11. It is also evident from the compaction curve given in Fig. 2 that the dry bulk density of the soil decreased with the increase of cement content indicating the influence of formation of bigger particles.

4. Conclusions

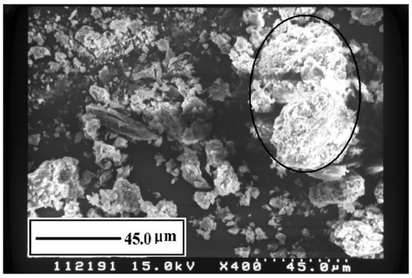
In this paper, the effectiveness of the very nominal dosage rate of the ordinary portland cement, such as, 0.2%, 0.4% and 0.6% was used to investigate the compressive strength, California Bearing Ratio, modulus of deformation and permeability of clayey soils in Mie prefec-



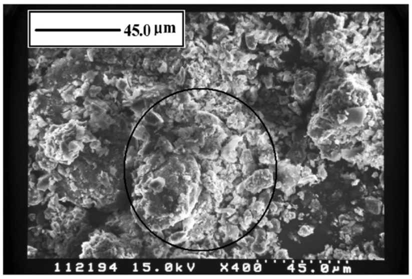
a. Soil with 0.0% cement content



b. Soil with 0.2% cement content



c. Soil with 0.4% cement content



d. Soil with 0.6% cement content

Fig. 11 Scanning Electron Micrographs (SEM) of cement treated soil

ture. From the analyses of the test results depicted above, the following conclusions can be drawn.

1. The bearing capacity in terms of the CBR value and the compressive strength was increased remarkably with the addition of the small amount of the ordinary portland cement.
2. The compressive strength increased with the percentage of cement content.
3. The modulus of deformation (E_{50}) increased with the increase in the percentage of cement content.
4. The addition of cement increased the permeability coefficient.

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少量のセメント添加による粘性土の強度および透水性の変化について

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要　　旨

現在まで，土の特性を改善する目的で，ソイルセメント工法が広く使用されてきている。しかし，これまでのセメント混合による土層改良に関する研究では，セメントの混合比が 4% から 14% 以上と比較的混合比が大きい場合がほとんどで，経済性および環境問題を考えると，少量のセメント混合による土の特性変化について研究することが必要である。そこで，本研究では，混合比が 0.6% までの少量のセメントを粘性土に添加することにより，支持力比（CBR 値），一軸圧縮特性，および透水性がどのように変化するかについて検討を行った。その結果，少量のセメント添加であっても，セメント混合比の増加に伴い，支持力比，一軸圧縮強度，変形係数および透水係数は増加することが明らかとなった。

キーワード：支持力，応力～ひずみ関係，圧縮強度，変形係数，透水係数

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