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Transparent Aquabeads to Model Geotechnical Properties of Soils

by

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Abstract

This study proposes a new type of water-based transparent Aquabeads suitable for modeling the geotechnical properties of natural soils. A comprehensive study of the geotechnical properties of several types of Aquabeads, including permeability, compressibility, and yield stress, was performed in order to understand the feasibility of deformation modeling using transparent Aquabeads. The geotechnical properties of the Aquabeads are similar to those of sands and silts in permeability, with hydraulic conductivity of 10^{-2} to 10^{-5} cm/sec, and very soft clay in compressibility and yield stress. Soil-structure interactions beneath a reinforced soil foundation were studied to illustrate the beneficial use of Aquabeads in research studies. The results are similar to the behavior observed for natural soils. It is concluded that Aquabeads are suitable for simulating deformation in very weak soils. In the short term, transparent Aquabeads and the proposed optical set-up and image processing technique are expected to be easily adjusted and applied in geotechnical engineering research. In the long term, transparent synthetic soils should prove to be a powerful tool in solving many geotechnical and geoenvironmental engineering problems and be very helpful in designing many new structures.

Keywords: Transparent soil, Consolidation, Deformation, Digital image processing, Tank test

1. Introduction

Many geotechnical problems may be understood by the insight of the visualization of deformation and strain in soils. Non-intrusive optical visualization techniques help greatly in understanding of deformation problems inside a soil mass. For this purposes, transparent material with geotechnical properties similar to those of natural soils can be used to study them.

Transparent materials with geotechnical properties similar to those of natural soils, such as glass beads or quartz powder and matched refractive index pore fluids, have been used to help visualizing deformation and flow inside models [1- 4]. However, glass and quartz surrogates are limited by their inability to represent the geotechnical properties of a wide range of natural soils and also by their poor transparency. Transparent slurry, made of amorphous silica powder and pore fluids with a matching refractive index, was originally developed for modeling non-Newtonian slurry flow problems [5]. This material was consolidated and tested and found to exhibit macroscopic geotechnical properties of natural clays [6-7]. Geotechnical properties of transparent synthetic materials such as amorphous silica powder have been further developed by several researchers [8-10]. Amorphous silica powder has also been used in model tests with simple optical techniques to study flow of contaminants into perforated wick drains [11] and pile penetration in clays [12]. Silica Gel is a colloidal form of silica, which resembles coarse white sand [13]. However, transparency of amorphous silica powder and silica gel with pore fluids with a matching refractive index has been no longer than several weeks until the material turns translucent. And also, matched refractive index pore fluids cannot easily model the chemical and physical properties of groundwater such as the viscosity and so forth.

The transparent material used in this research is a water absorbent polymer named “Aquabeads”, which is a commercial product of Kuraray Chemical Co. Umeda, Kita-ku, Osaka 30-8611, Japan [25]. This resin looks granular & spherical and can rapidly absorb water. Once “Aquabeads” absorbed water, it releases minimal water. Deformation pattern within a soil mass can be easily modeled by using hydrated Aquabeads and water. Transparency of soil mass model was extremely improved and longer than the model using silica aggregates and pore fluids.

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The objectives of this research are to illustrate the possibility of using Aquabeads as transparent synthetic soils in studying geotechnical problems. The objective of this research is also to present feasible methods to obtain 2-D deformation inside transparent soil models non-intrusively. This investigation will use methods that the obtained deformation is non-intrusive and continuous without interruption from sensors.

2. Aquabeads Samples

This research studied three types of hydrated Aquabeads sample for the tests (Fig.1). *Aquabeads M* have a dry diameter of 0.6−2 mm. When water is added to Aquabeads M the particles reach a size of approximately 5−7mm. These particles were sometimes crushed after being fully cured in order to reduce their particle size. The crushed particles were oven dried at 100 ºC for 24 hours and the resulting blueish material was re-hydrated with water. This was done to produce a material with a lower permeability. The uncrushed Aquabeads are referred to as *NC100*. Two types of crushed Aquabeads are also discussed as *C50*. *Aquabeads #200* is delivered as a powder passing #200 sieve. It becomes a transparent gel when it is mixed with water. The percentage of Aquabeads (by weight) in the mixture is indicated as 200−1%. [26]

Fig. 1 Types of Aquabeads – (top) original specimens; (bottom) water hydrated specimens (from left to right: C50, 200-1%, and NC100)

3. Physical Properties of Aquabeads

Sieve analysis of dry and hydrated Aquabeads is shown in Fig.2. Tests were performed using the dry method for as delivered Aquabeads (ASTM D1921−06 Standard Test Methods for Particle Size (Sieve Analysis) of Plastic Materials), and the wet method (ASTM C92−95 (2005) Standard Test Method for Sieve Analysis and Water Content of Refractory Materials) for hydrated Aquabeads. The grain size distributions both dry and hydrated Aquabeads exhibit poorly graded or uniform behavior [26].

The falling head hydraulic conductivity test is conducted following the experimental procedure according to ASTM D5856−95 (2004): Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid−Wall Compaction Mould Permeameter. The hydraulic conductivity of Aquabeads NC100 sample ranges from approximately 2.81×10^{-2} cm/sec to 7.34×10^{-2} cm/sec. The hydraulic conductivity of Aquabeads NC100 sample is similar to coarse to fine sand. In addition, the hydraulic conductivity of Aquabeads C50 sample is between 8.53×10^{-6} cm/sec and 2.79×10^{-5} cm/sec, which matches the hydraulic conductivity of silt to silty clay. Furthermore, the hydraulic conductivity for #200 – 1% ranges from 1.41×10^{-4} cm/sec to 5.58×10^{-4} cm/sec. This result shows that the hydraulic conductivities of these types of Aquabeads are consistent with fine sand to silty clay [26].

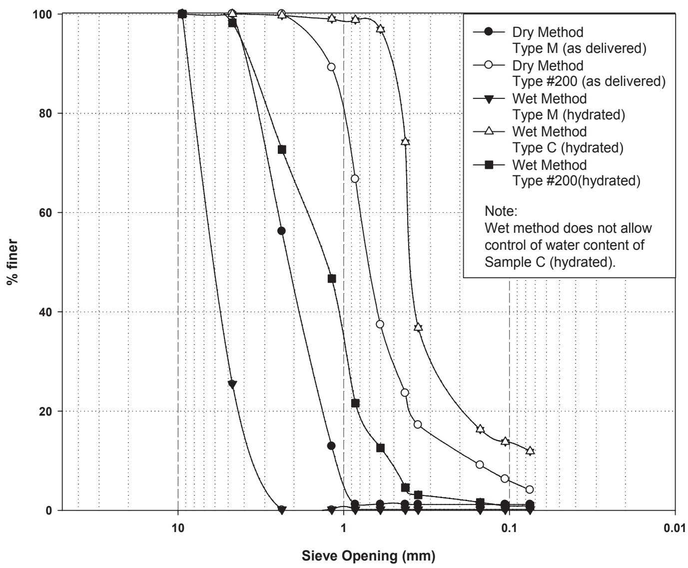

Fig. 2 Grain size distribution curve of Aquabeads samples

4. Compressibility of Aquabeads

Aquabeads changes its volume by approximately 200 times from its dried particle size when it absorbs water. Aquabeads particles are porous. The consolidated specimens exhibit a high apparent total void ratio, e, due to the internal porosity of the Aquabeads. Hydrated Aquabeads samples were used in one dimensional consolidation tests in accordance to ASTM D2435-90(1993): Standard Test Method for One-Dimensional Consolidation Properties of Soils. The results of these tests were summarized in Table 1 [26]. Samples were 38.1 mm (2.5 in) in diameter and 19 mm (0.75 in) high. Tests were conducted using conventional oedometer apparatus using fixed weights.

4.1 *Consolidation Behavior*

Typical consolidation volume change versus time is shown in Fig.3. The volume change was calculated based on the sample settlement. The volume change continued to increase with time and the end of primarily consolidation was not readily identifiable. These phenomena may be explained with the existence of two kinds of voids within and between the Aquabeads.

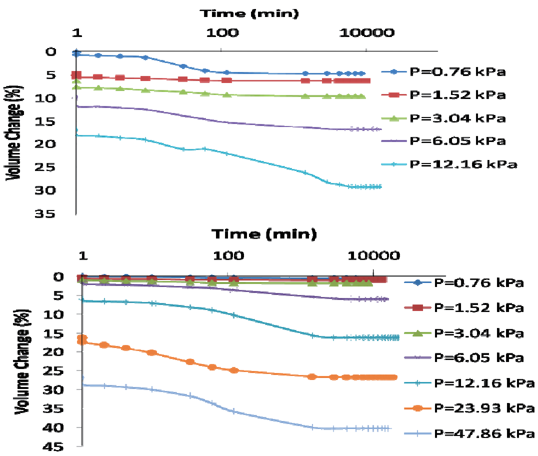

Fig. 3 Volume change vs. time for NC100 (top) and C50 (bottom)

The first consolidation process involves the pores between the Aquabeads, while the second involves the pores inside the Aquabeads [26]. Peat and organic clays have a macro-pore structure corresponding to the voids within the inorganic component in them, and a micro-pore structure corresponding to the pores within the organic matter component [14-16]. Similar behavior in terms of macroscopic behavior was reported in those soils.

4.2 *Consolidation Indices*

Typical *e*-log *p* curves from oedometertests are shown in Fig. 4 for two types of Aquabeads [26]. Void ratios were taken 24 hours after loading because of the difficulty in identifying the end of primary consolidation. The compression and recompression indices (Cc and Cr) are 0.1−0.15 and 0.02−0.03, respectively (Table 1). Both indices are within the range typically reported such as Ft. Gordon clay in Georgia (Cc=0.12), New Orleans clay (Cr=0.05), Montana clay (Cr=0.05) [17], and Montmorillonite minerals [18]. The ratio Cr/Cc is 0.2 which is within the normal range of 0.02 to 0.2 for natural soils [19].

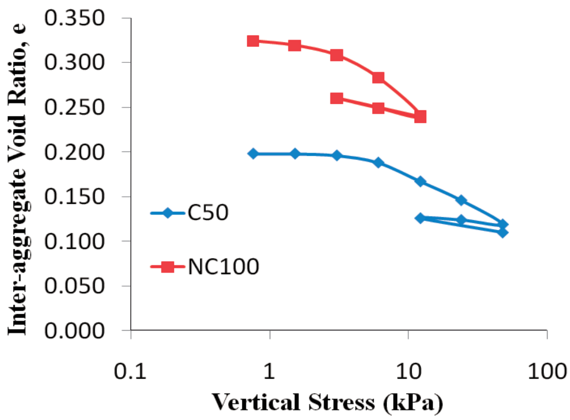

Fig. 4 e-log p curve for two types of Aquabeads from oedometer test

4.3 *Consolidation Coefficient*

The coefficient of consolidation, c_v, for Aquabeads NC100 and C50 is plotted versus vertical stress normalized by preconsolidation stress in Fig.5 [26]. This figure also shows the relationship in some inorganic and organic soils. According to the Fig. 4, the change in c_v is observed on both inorganic and organic soil data in the normally consolidated (NC) region (v/p=1).

This change in c_v around NC region can be seen on NC100 and C50 plotting with Logarithm of time method. For Middletown peat and Celery Bog organic soil, c_v markedly decreases with increasing vertical stress, however, Boston Blue Clay gradually increases with increasing vertical stress. The change in c_v after NC region for Aquabeads samples cannot be clearly identified but intermidiate characteristics between inorganic soils and organic soils [20-22].

Table 1 Consolidation properties of Aquabeads

Sample No.	C_c	C_r	C_r/C_c	Total Void Ratio e_t	Inter-aggregate Void Ratio, e	Preconsolidation Pressure, kPa
NC100	0.15	0.03	0.20	197.48	0.26	4.93
C50	0.10	0.02	0.20	127.8	0.19	6.32

5. Strength of Aquabeads

The yield stress measurement of Aquabeads was conducted using laboratory vane method [26]. The test program was designed to perform with the rotational speed of vane equipment was fixed to 0.0029 rad/sec (0.03%/sec). Two sizes of vane were used to measure the stress in the test. The first vane size was 12.7mm diameter * 12.7 mm height (D/H=1; Vane No. A), and the second size was 12.7mm diameter * 25.4 mm height (D/H=2; Vane No. B). Test samples were used C50, #200-1.0 weight % (200-1.0%). The shape of the stress−time curve for each Aquabeads sample was similar in linear to non−linear region, however, the data is not so repeatable that range of the yielding stress value varies about ±2 Pa on the same test sample. The repeatability of the vane test performances of 200-1% is shown in Fig.6. The yield stress was observed in the Aquabeads samples because stress-time profiles of these samples generally behave as an elastic solid up to 70 sec., then yielding of the samples generally occurs at 450 to 1000 sec, where torque reaches a maximum value. The torque is declined slowly or being kept constant level after yielding.

The yield stress was calculated using proposed method by Dzuy and Boger [23]. The calculated yield stress value of Aquabeads ranged from 4 to 9 Pa. The yield stress values for Aquabeads sample were very similar or within the range of those for natural super soft clays[24]. The super soft clay is defined as an insensitive cohesive soil whose water content is higher than its liquid limit[24]. The relationship between the measured shear stress and strain rate for several kinds of super soft clays [24] plotted with measured shear stress of Aquabeads samples is shown in Fig. 7. According to the figure there is a scatter of super soft clay data when measuring shear stress at different strain rates. The scatter seemed to reduce as the water contents of natural soils reduced because the values of shear stress were higher (the plotting for Brown Till w=70%).

Estimated yield stresses of super soft clays using linear relationship were between 5 to 8Pa, and the value of Brown Till markedly higher as 20Pa [24].

All measured shear stresses of Aquabeads samples were plotted at 0.03%/sec of strain rate because the strain rate was fixed in the viscometer in this research, however, the range of measured shear stresses of Aquabeads is very similar to or within the range of measured shear stress values of natural super soft clays except for Brown Till (w=70%). Further studies of the vane test measurement of Aquabeads should consider the rate of stress development by focusing on the applied rotational speed, the measuring system stiffness and the vane size [26].

6. 2−D Deformation Measurement

Soil-structure interaction beneath reinforced soil foundation will be studied for feasibility to simulate 2−D deformation measurement using Aquabeads. The experiment was conducted on the case of geosynthetic reinforcement beneath a footing on the very soft clay soil [26]. The set-up of 2-D Geogrid-Reinforced Footing is shown in Fig.8. The geogrid tests were carried out on model footing supported on paper geogrid overlying Aquabeads (#200 -1% weight content of de-aired water) in the Plexiglas tank Test (Fig.9). Paper towel made of brown recycled paper (Georgia Pacific Envision® GPC263-1) was used to model geogrid.

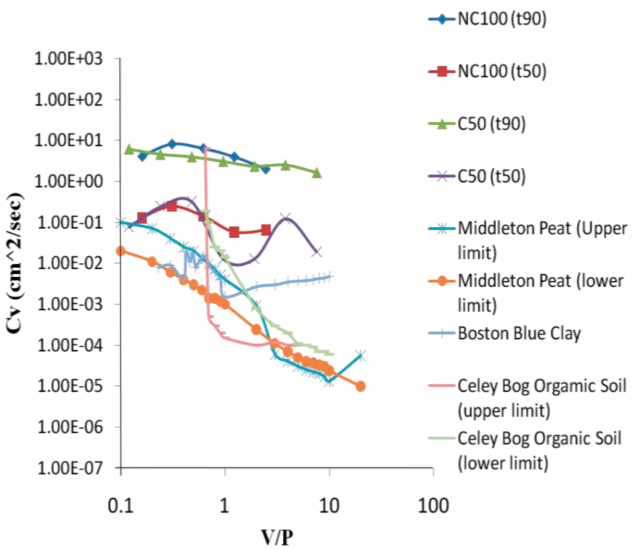

Fig. 5 Variation of the coefficient of consolidation with stress level with natural soil data [20-22]

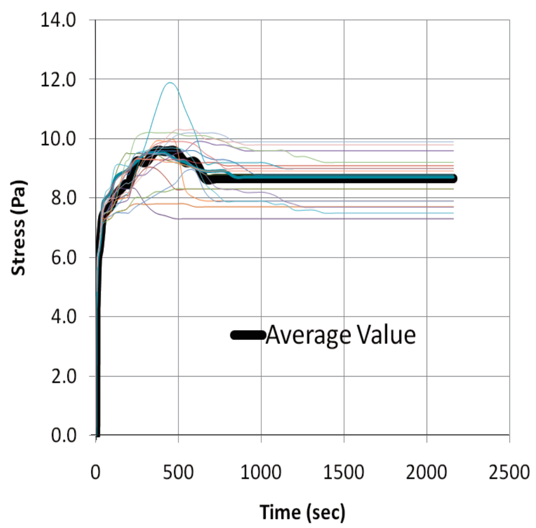

Fig. 6 Repeatability of the vane test performances

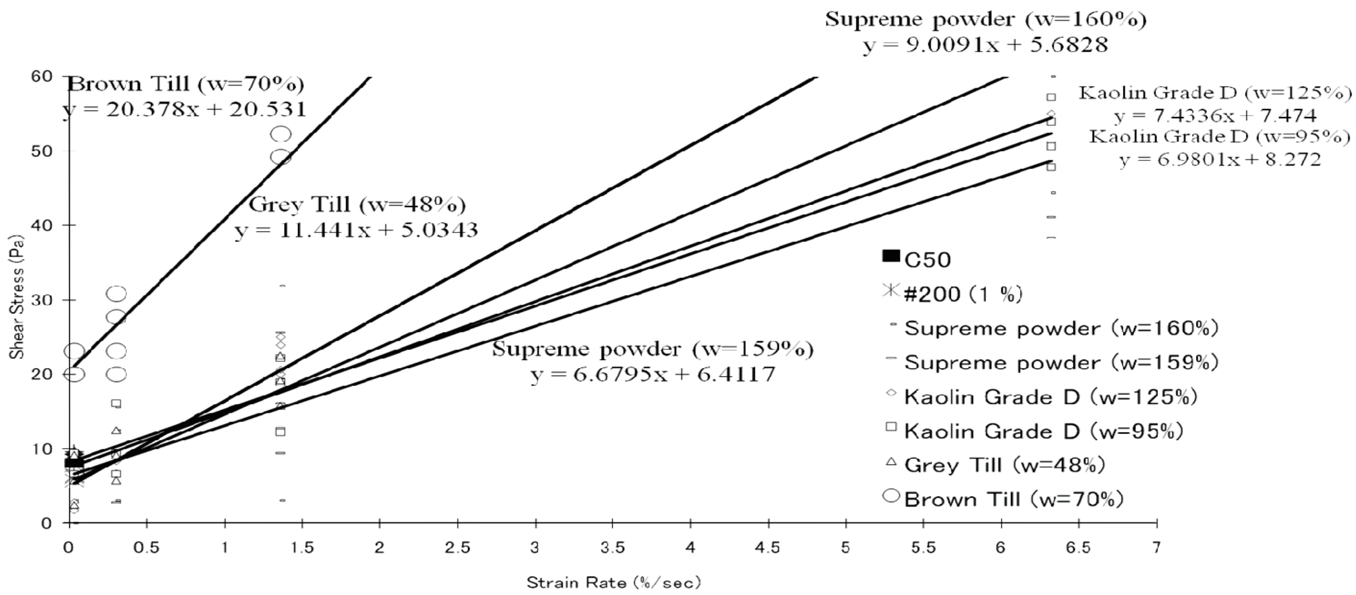

Fig. 7 Shear stress measurement of Aquabeads compared with data for natural soil [24)]

Fig. 8 Test set-up

A Plexiglas mode with dimensions of 50×150×300 mm was used in the tests. A model footing with a plan dimension of 50 mm by 25 mm was used. The footing simulated a continuous footing with a width of 25mm. Load was applied vertically through a screw mechanism. A load cell and a displacement gauge were connected to the loadframe to measure load and deformation during the test. The Aquabeads #200-1% was used in this study.

The bearing capacity behavior of a strip footing on geogrid-reinforced Aquabeads model was investigated. Typical captured picture on the experiment is shown in Fig.10. The boundary conditions of geogrid parameters were considered. Based on the results from this study, the following conclusions can be obtained. The improvement of Aquabeads increases with the presence of geogrid. The geogrid-reinforcement of Aquabeads improves significantly at initial stage up to the value of settlement ratio (settlement/width of model footing) of 0.05.

There is an optimum number of the geogrid layers (N) which is 3 for the bearing capacity improvement of Aquabeads (Fig.11). The bearing capacity improvement (BCI) in the figure is defined as the ratio of the footing ultimate pressure with geogrid reinforcement ($q_{ult\ reinforced}$) to the footing ultimate pressure in tests without geogrid reinforcement (q_{ult}). The BCI increases with the increase of N. However, the BCI decreases with increasing number of geogrid layersfrom N=3 after which the load improvement become much less. The

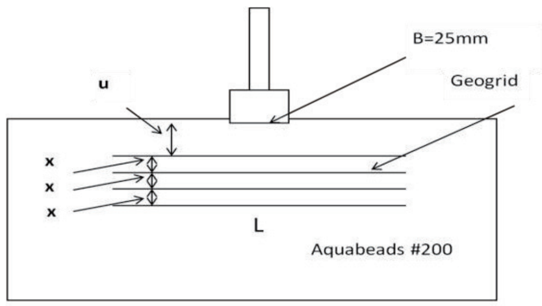

Fig. 9 Geogrid-reinforcement

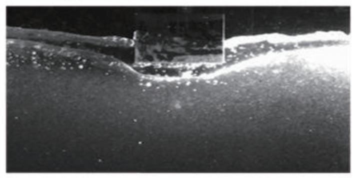

Fig. 10 Model tests in progress (N=1, L/B=6)

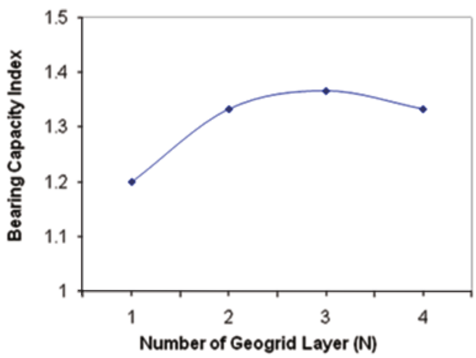

Fig. 11 Effect of number of geogrid layer (u/B=0.25, x/B=0.4, L/B=6)

figure demonstrates that there are an optimum number of reinforcement layers after which the gain in bearing capacity is not significant.

The effect of geogrid layer length for the bearing capacity improvement of Aquabeads is experimentally obtained to L/B=4 (L=length of geogrid). The maximum benefit of geogrid-reinforcement of Aquabeads achieves when the geogrid depth to top layer is 0.75B. The maximum benefit of geogrid-reinforcement of Aquabeads also achieved when the geogrid vertical spacing is set to 0.7B.

The results are similar to behavior observed for natural soils. Therefore it is conducted that Aquabeads is suitable for simulating deformation problem in very weak soils.

7. Conclusion

The transparent material used in this research is a water absorbent polymer named “Aquabeads”. This resin looks granular & spherical and can rapidly absorb water. Once “Aquabeads” absorbed water, it releases minimal water as long as the ambient pressure is not changed.

The falling head hydraulic conductivity test, the constant head hydraulic conductivity test were conducted to determine the hydraulic conductivity of Aquabeads. This result shows that the hydraulic conductivities of these types of Aquabeads are consistent with fine sand to silty clay.

Hydrated Aquabeads samples were used in one dimensional Ko consolidation tests. The compression and recompression indices (Cc and Cr) are 0.1-0.15 and 0.02-0.03, respectively. Both indices are within the range typically reported for natural clays. The ratio Cr/Cc is 0.2 which is within the normal range of 0.02 to 0.2 for natural soils [19]. The Volume change continued to increase with time and the end of primarily consolidation was not readily identifiable because of the existence of two kinds of voids within and between the Aquabeads aggregates.

Peat and organic clays have a macro-pore structure corresponding to the voids within the inorganic component in them, and a micro-pore structure corresponding to the pores within the organic matter component. Similar behaviors were reported in those soils. Therefore it is concluded that the consolidation behavior of Aquabeads is similar to that of natural organic soils.

The yield stress measurement of Aquabeads was conducted using laboratory vane method. The calculated yield stress value of Aquabeads ranged from 4 to 9 Pa. The shape of the stress-time curve for each Aquabeads sample was similar in linear to non-linear region, however, the data is not very repeatable and the yielding stress value varies about 2 Pa under similar test condition. The yield stress values for Aquabeads sample were very similar or within the range of those for natural super soft clays.

As the feasibility to simulate geotechnical problems using Aquabeads model research, the bearing capacity behavior of a strip footing on geogrid-reinforced Aquabeads was investigated. The effect of inclusion of geogrid reinforcement on the footing was demonstrated experimentally. The boundary conditions of geogrid parameters were considered. The increase of improvement of Aquabeads with the presence of geogrid was observed. The geogrid-reinforcement of Aquabeads improves significantly at initial stage up to the value of settlement ratio of 0.05. There is an optimum number of the geogrid layers which is 3 for the bearing capacity improvement of Aquabeads. The effect of geogrid layer length for the bearing capacity improvement of Aquabeads is experimentally obtained to L/B=4. The maximum benefit of geogrid-reinforcement of Aquabeads achieves when the geogrid depth to top layer is 0.75B. The maximum benefit of geogrid-reinforcement of Aquabeads also achieved when the geogrid vertical spacing is set to 0.7B. The results are similar to behavior observed for natural soils.

Therefore it is conducted that Aquabeads is suitable for simulating deformation problem in very weak soils. Numerical modeling of the deformation study is suggested to compare with image analysis.

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