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Mechanical properties of lightweight treated soil under water pressure

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ABSTRACT: An artificial lightweight geomaterial (SGM) has been developed as a backfill to reduce the lateral earth pressure behind waterfront structures. The unit weight is reduced by mixing lightening ingredient, either air foam or EPS beads, with slurry of dredged soft clay, while certain cement is used as stabilizer to warrant compressive strength. This experimental investigation is conducted to characterize the strength and deformation properties of the lightweight treated soil. Considering expectable compressibility under pressured casting, curing or loading, samples were cured under various pressures, and subjected to undrained shear tests on triaxial apparatus modified able to detect volumetric change.

1 INTRODUCTION

1.1 *Application of SGM in port structures*

SGM is a lightweight technique developed to control unit weight and shear strength as desired, and to make beneficial reuse of surplus soil at the same time (Tsuchida, *et al*. 1996). Generally, unit weight of dredged soil is reduced by use of either air foam or expended polystrol (EPS) beads, while shear strength is obtained with cement.

Figure 1 presents two applications of the lightweight soil used in port structures. Probably, most of port structures are planned on soft grounds. So it is believed a ration option to decrease unit weight of backfill so as to increase the structure stability and to decrease the consolidation settlement.

1.2 *Underwater deployment*

As shown in Figure 1, the majority of lightweight soil needs to be placed underwater as deep as 10 m. Some peculiar techniques of underwater placement are required in order to prevent soil separate. There are working vessels available for producing lightweight soil and casting it underwater. Photo 1 shows one of them, when it was conducting backfill of lightweight soil (Yamamoto *at al*. 1997).

In addition to construction techniques, we need to comprehend mechanical properties of this developed material when deployed under large water pressure, because lightening ingredient (air foam or EPS beads) is significantly compressible. This paper presents a series of experimental study of the lightweight soil with triaxial apparatus.

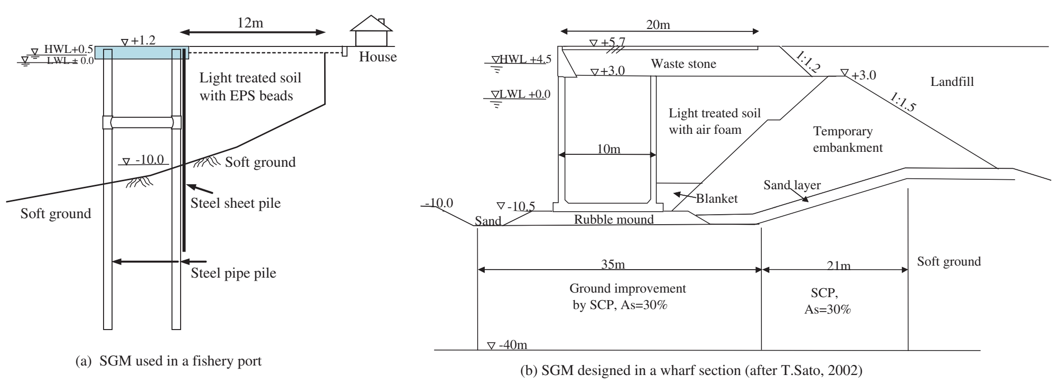

Figure 1. Applications of lightweight soil in port structures.

Photo 1. A working vessel placing lightweight soil underwater behind port structure.

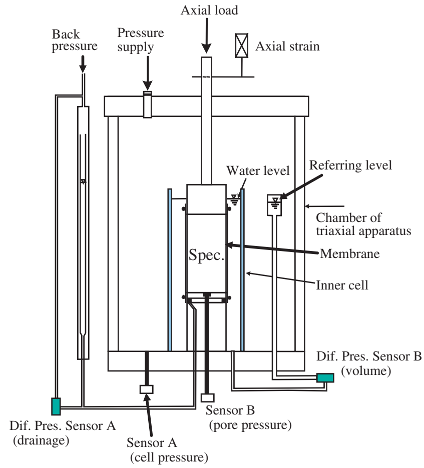

Figure 2. Triaxial apparatus modified to measure water drain-age and volumetric change.

2 PROGRAM OF EXPERIMENT

2.1 *Modified triaxial apparatus*

Lightweight treated soil consists of compressible lightening material, either air foam or EPS beads. So it is expected to behave like unsaturated soil, even though the samples are prepared and sheared under saturated condition. To study deformation behavior, it is necessary to perform triaxial tests with volumetric change measured. For this purpose, a conventional triaxial apparatus was modified as shown in Figure 2, where an acryl cylinder peripheral to the specimen was erected inside the triaxial cell. Volumetric change of specimen was measured by monitoring water level of the inner cell by a differential pressure sensor (Tang, *et al.* 1996).

2.2 *Preparation and pressured curing of samples*

The original soft clay was dredged from Kawasaki Port. Table 1 shows the physical properties of Kawasaki clay.

Table 2 describes the designed proportions among clay slurry, lightener and cement. With target unit weight at 12 kN/m^3, the original clay was diluted to slurry states with water content about 2.5w_L for air foam mixing or 1.8w_L for EPS beads mixing. After examination of slurry density, certain quantity of cement based on target strength (e.g. $q_u = 200$ or 400 kN/m^2) was added in and agitated for 3 minutes. Then, pre-calculated quantity of lightener was mixed. The mixture was churned further for 3 minutes in EPS beads cases, or 30 seconds in air foam cases. It was identified that the unit weight of the created sample hereby met with 12 ± 0.3 kN/m^3 adequately. Otherwise, further adjustment was conducted by slight addition of lightener when it was greater than 12.3 kN/m^3 or by charging a little more cement mixed slurry when it was less than 11.7 kN/m^3.

The prepared lightweight slurry was poured into curing molds (ϕ50 mm × H100 mm) for specimen making. The molds were set into different containers, which were teemed with seawater, then sealed and applied by different curing pressure, $p_{cure} = 50$, 100, 200 and 300 kN/m^3, respectively. Underwater pressured curing was kept for 28 day in each case.

Table 1. Physical properties of Kawasaki clay

Physical index	Grain density	Liquid limit	Plastic limit	Plasticity index
	25.8 kN/m	76.1%	45.8%	31.3
Grain gradation	Coarse grain 0.3%	Sand 6.6%	Silt 77.1%	Clay 16.0%

Table 2. Target strengths, curing conditions, and designed proportions among slurry, lightener and cement.

Lightener type (kN/m^2)	Target strength (kN/m^2)	Curing pressure (kN/m^3)	Slurry (kN/m^3)	Lightener (kN/m^3)	Cement
Air foam	200	50,100,200,300	11.30	0.04	0.66
	400	50,100,200,300	11.20	0.04	0.76
EPS	200	50,100,200,300	11.33	0.03	0.64
beads	400	50,100,200,300	11.24	0.03	0.73

*Unit weight was targeted at 12 kN/m^3 for all cases.

2.3 *Procedures of triaxial experiment*

After pressured curing, the pressure in the sealed container was released. With the top-end of molded sample trimmed, the specimen was mounted onto triaxial apparatus. At first, cell pressure was resumed to the curing pressure (p_{cure}), while excess water or air

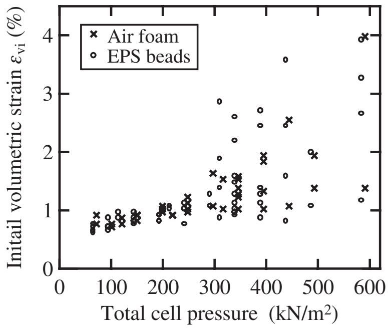

Figure 3. Initial volume change under cell pressure.

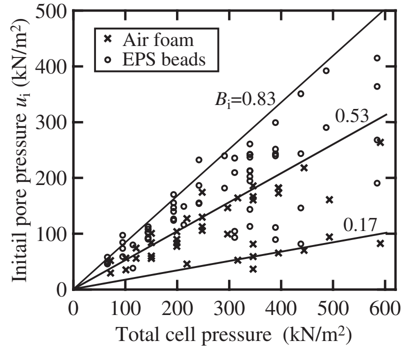

Figure 4. Pore water pressure response under cell pressure.

was squeezed out of the specimen. 10 minutes later, the specimen was switched to undrained state, and additional isotropic cell pressure was applied on respective specimen by $\Delta\sigma_c = 20$, 50, 100, 150 and 300 kN/m^2. The second procedure was also kept for 10 minutes. Soon, undrained shear was carried out on specimens at an axial strain rate of 0.2%/min with confining cell pressure constant.

3 MECHANICAL PROPERTIES

3.1 *Initial responses*

As the lightweight soil samples were resumed to the curing pressure and then applied by additional cell pressure (total cell pressure $= p_{cure} + \Delta\sigma_c$), they exhibited volume reduction and pore water pressure increase simultaneously. Figure 3 shows initial volumetric strain related to total cell pressure before the specimens were subjected to undrained shear. It can be seen that volume reduction of specimen increases with total cell pressure. The scatter looks more significant as total cell pressure exceeds 300 kN/m^2. Figure 4 shows the pore water pressure response. Even though efforts were made to produce saturated samples, the pore water pressure response were considerably retarded, with pore water coefficient B_i ranging from 0.17 to 0.83.

3.2 *Undrained shear behaviors*

During the undrained shear process, both pore water pressure and volume change of the specimen were measured. Figures 5 and 6 show some examples of experimental results for air foam mixed and EPS beads mixed samples.

From these figures, compressive strengths q_{max} are obtained by the maximum values of deviator stress, which are equivalent to unconfined compression strength q_u excepting that various cell pressures exerted on the specimens. It is found that air foam mixed samples shows significantly greater

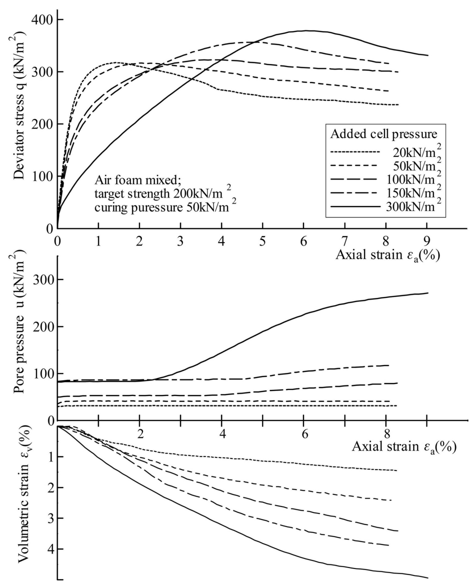

Figure 5a. Undrained shear curves (air foam, qu = 200 kN/m^2).

compressive strength q_{max} than the designed target strength q_u. For EPS bead mixed samples, on the other hand, q_{max} seems nearly equal to or slightly less than the target strength q_u.

During the undrained shear process, specimens' volume kept shrinking. Beside the volume reduction depended mainly on total cell pressure. Pore water pressure generally exhibited plus response, which also depended on the condition of cell pressure.

3.3 *Factors affecting strength*

It is usually recognized that increment of unit weight contributes to strength gain for soil samples. Figure 7 shows the change of unit weight with increasing curing

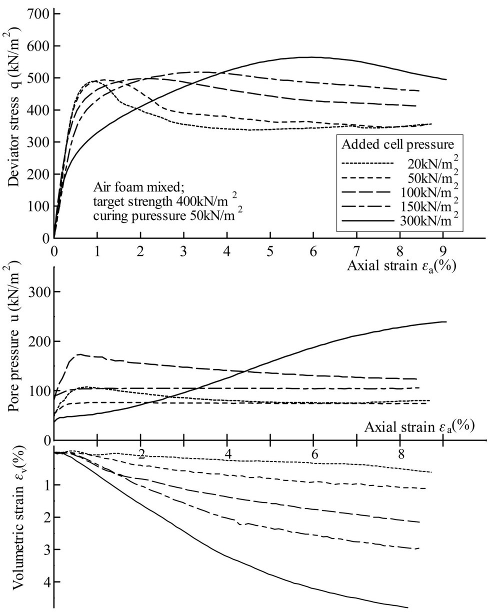

Figure 5b. Undrained shear curves (air foam, qu = 400 kN/m^2).

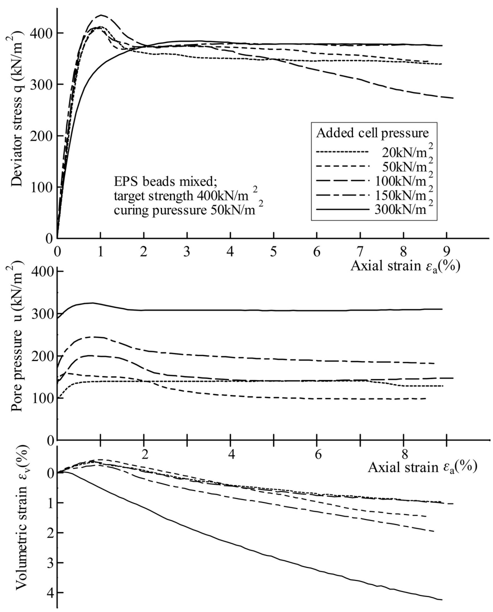

Figure 6b. Undrained shear curves (EPS beads, qu = 400 kN/m^2).

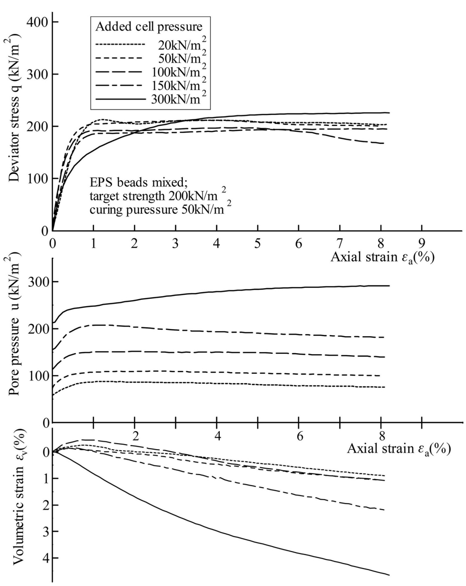

Figure 6a. Undrained shear curves (EPS beads, qu = 200 kN/m^2).

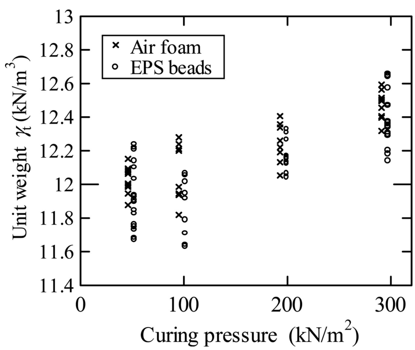

Figure 7. Unit weight changing with curing pressure.

pressure. Both air foam mixed and EPS beads mixed samples exhibit the similar tendency of unit weight increase induced by pressured curing. Yet, the unit weight increase is small and acceptable.

Figure 8 shows the relation between compressive strength q_{max} and unit weight γ_t. Certainly, the compressive strength increases with unit weight, but the tendency is more prominent for air foam mixed samples than that for EPS beads mixed ones. Although cement contents to ensure strength were designed nearly equal for each mixed cases as shown in Table 2, there arose a noticeable split in strength gain. It is suggested that such a discrepancy attributes to the pressured curing process.

In Figure 9, the difference of compressibility between air foam and EPS beads is illustrated. For air foam mixed slurry, the enclosed gas within individual trapped bubbles was compressed under curing pressure instantaneously. If assuming that volume

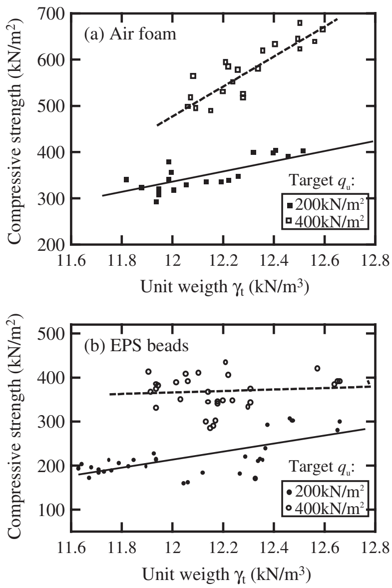

Figure 8. Correlation between compressive strength and unit weight.

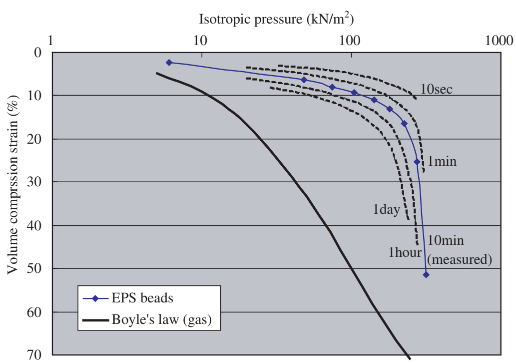

Figure 9. Comparison of compressibility between enclosed gas and EPS beads.

compression takes place in accordance with boyle's low as shown in Figure 9, the enclosed gas could be regarded as elastic material.

In contrast, EPS beads is a polymeric material compounded of abundant gas. It is highly compressible with distinct viscosity. The compression curves by the dotted line group in Figure 9 illustrate time-dependent property of EPS beads. During the pressured curing process, hereby, the bound structure by cement hardening was presumably destroyed to a certain degree, because of the continual compression of EPS beads under water pressure.

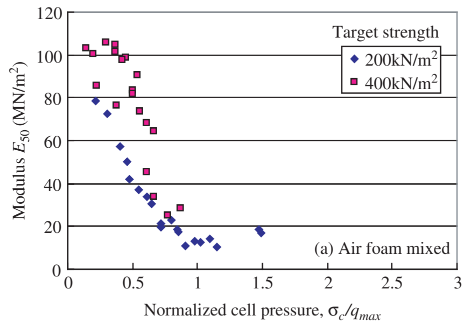

Figure 10a. Secant modulus E50 descending with normalized cell pressure (air foam mixed case).

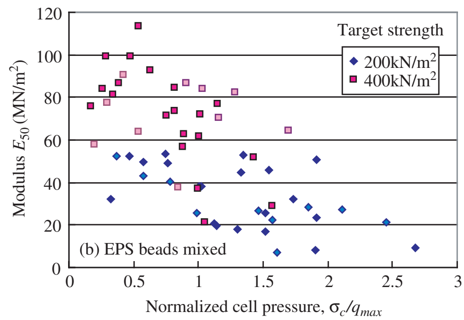

Figure 10b. Secant modulus E50 descending with normalized cell pressure (EPS beads mixed case).

3.4 *Deformation characteristics*

The secant modulus E_{50} is an important parameter to assess deformation characteristics. Here, E_{50} is defined as the gradient when a secant passing through the origin and the point at half maximum of deviator stress. That is, $E_{50} = q_{\max}/2/\varepsilon_{50}$. Here, ε_{50} is axial strain ε_a at $q_{\max}/2$.

Figure 10 shows the secant modulus with relation to total cell pressure, which is normalized with compressive strength $q_{\max}$. By normalizing with $q_{\max}$, we can evaluate the relative degree of confining pressure σ_c. It can be seen that E_{50} varies to such an extent that it decrease from over 100 MN/m^2 to less than 10 MN/m^2. For air foam mixed cases in Figure 10(a), there is an apparent correlation between E_{50} and $\sigma_c/q_{\max}$. As total cell pressure σ_c surpassed compressive strength $q_{\max}$, the bound structure due to cement hardening was destroyed radically, thus E_{50} descended to an ultimate low value.

For the EPS beads mixed samples as shown in Figure 10(b), there exhibits the same descent tendency as that of air foam mixed ones. However, the correlation seems much more obscure. This result suggests that

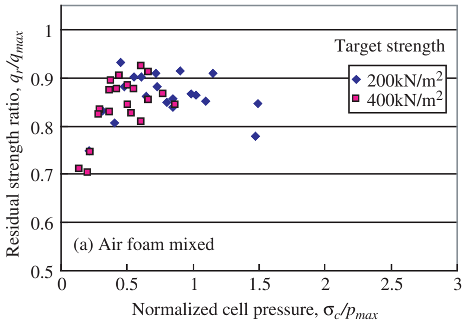

Figure 11a. Relation between residual strength and normal-ized cell pressure (air foam mixed case).

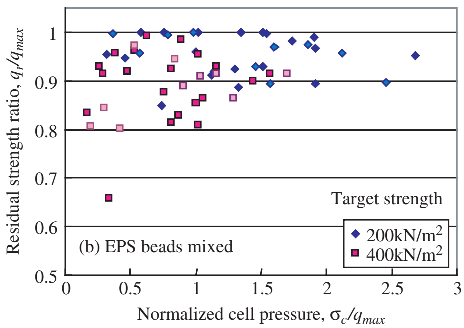

Figure 11b. Relation between residual strength and normal-ized cell pressure (EPS beads mixed case).

the role EPS beads plays in lightweight soil is more intricate than air foam does.

3.5 *Residual strength*

Figure 11 shows the residual behavior of compressive strength q_r. Here, axial strain ε_a when undrained shear experiment was terminated is regarded as ultimate state. Usually, the experiments were terminated around $\varepsilon_a = 8\%$. It was found that residual strength distributes within a range of $0.8 \sim 0.9 q_{max}$ for air mixed samples, comparing with $0.8 \sim 1.0 q_{max}$ for EPS beads mixed ones. As the lightweight samples underwent ultimate axial strain, bound structure due to cement hardening radically destroyed. So the deviator stress was born by soil particles under confined stress for air foam mixed samples, but EPS beads also shared a small part in the EPS beads cases.

Even though there is subtle discrepancy between different lightening ingredients, it is confirmed that residual strength is fairly larger than what is observed in unconfined compression tests. This result implies that lightweight soil treated with cement is not a vulnerable material as long as certain confining stresses exert on it.

4 CONCLUSIONS

Lightweight treated soil has found various applications in port structures. The new technology is aimed to reduce the earth pressure and the consolidation settlement, to enhance the stability of structure, and to make beneficial reuse of surplus dredged soft soil at the same time. Underwater deployment of lightweight soil requires us to make sure that the artificial geomaterial be adequately placed without soil separate. It is also important to confirm whether or not water pressure should inhibit the lightweight soil's mechanical properties as we designed. For this purpose, a series of undrained triaxial experiments were carried out on lightweight samples cured under various water pressures. The result may be concluded as followings.

1) Pressured curing resulted in an increase of unit weight, which remained in an acceptable range. It was observed that increase of unit weight induced strength gain, consequently.
2) Though prepared in saturated state, the lightweight samples exhibited unsaturated-like behaviors, such as volumetric compressible, retarded pore water response when subjected to undrained compression. During undrained shear, the specimens kept shrinking, showing plus pore water pressure.
3) Compressive strengths q_{max}, given by maximum of deviator stress, were significantly greater than the designed target strength for air foam mixed case, but nearly to or slight smaller than the target value for EPS beads mixed case. The reason for this result is unclear, but the strong viscosity of polymeric EPS beads is suspected as most important culprit.
4) Secant modulus E_{50} descends with increasing confining pressure. Residual strength q_r remains greater than $0.8 q_{max}$ as long as certain confining stresses exist under ground environment.

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