Mem. Fac. Sci Eng. Shimane Univ.
Series A
40, pp.27-35 (2006)

Effects of initial high temperature curing on unconfined compressive strength and microstructure of foamed mixture lightweight soil

Takeshi KAMEI[1], Kazutoshi MATSUO[2] and Toshihide SHIBI[1]

[1] *Department of Geoscience, Interdisciplinary Faculty of Science and Engineering, Shimane University*
[2] *Ohmoto-Gumi Co., Ltd..*

Abstract

We found that the unconfined compressive strength of core samples of foamed mixture lightweight soils did not reach their design strength. At this time, we have focused on the effects of temperature increase in a fill induced by cement hydration, on the unconfined compressive strength of foamed mixture lightweight soils at a construction site. The maximum temperature inside field test bodies ranged from 80 to 100°C. In the present experiments, specimens were subjected to temperature of 20 to 90°C during a day and then cured at 20°C before unconfined compression testing, to investigate the effects of increased temperature on the unconfined compressive strength and microstructure of foamed mixture lightweight soils. Unconfined compressive strength decreases significantly from 20 to 90°C based on the field measurements. The unconfined compressive strength of specimens cured for 28 days at 80°C or more is about 20% of that of specimens cured at 20°C. This decrease in strength agrees well with the actual unconfined compressive strength sampled in the field. The primary reason for the differences in strength is more probably the difference in microstructure between the specimens cured at 80°C or more, and those cured at 20°C. Finally, we find the revaluation of the design strength is necessary and strict temperature management is important when foamed mixture lightweight soils are constructed.

1. Introduction

Lightweight soil technology is increasingly being accepted for use in construction projects to solve soft ground problems. The most important advantages offered by this technology are reduced foundation soil improvement costs and reduced construction period due to the reduced loading on the ground. Expanded Polystyrene (EPS) was also adopted for road embankments on soft ground overseas (Norway) in 1972 (Frydenlund and Aaboe, 1993), and the use of EPS as an insulating material for frost protection purposes in a road structure had then already been proved satisfactory. The advantage of using EPS as a fill material was of course to reduce the resulting load on the subsoil substantially since this material, when dry, is nearly 100 times lighter other materials ordinary used as light fill and has strength characteristics that will match the structural loads. After 14 years of experience with the use of EPS in road structures, this technique was introduced to Japan in 1986 (Yasuhara, 2002).

The use of weight reducing techniques for geomaterials started in 1974 in Japan, using styrofoam as a back-fill material to reduce the lateral earth pressure for quaywalls (Nakase, 1974). This method was successful in reducing the vertical loads on soft ground as well as the lateral earth pressures on wall structures. This technology is particularly useful in these cases: (i) reducing residual settlement of embankment constructed on soft ground, (ii) preventing differential settlement between approach embankment and structures, and preventing lateral flow of piled structures, (iii) preventing deformation during construction near housing, (iv) reducing the construction period, achieving nearly maintenance-free construction, and others (Miki, 2002). Possibly applicable field situations are schematically described in Fig. 1.

Lightweight embanking methods are broadly classified into i) methods using lightweight materials such as expanded polystyrol (EPS) blocks and coal ashes, ii) methods using such materials as air-mixed lightweight soil and air-mixed beads, which are mixed with soils generated at the site, and iii) methods which use corrugated pipes and box culverts as part of embankments to reduce the weight. In terms of the density, the materials for this method have a wide range, from EPS blocks to such materials as air-mixed lightweight soils and air-mixed beads whose density can be controlled freely. The method thus has various types and applications, so it is necessary to select the method according to the purpose.

In expressway construction by the Japan Highway Public Corporation, Foamed Cement Banking method (hereafter

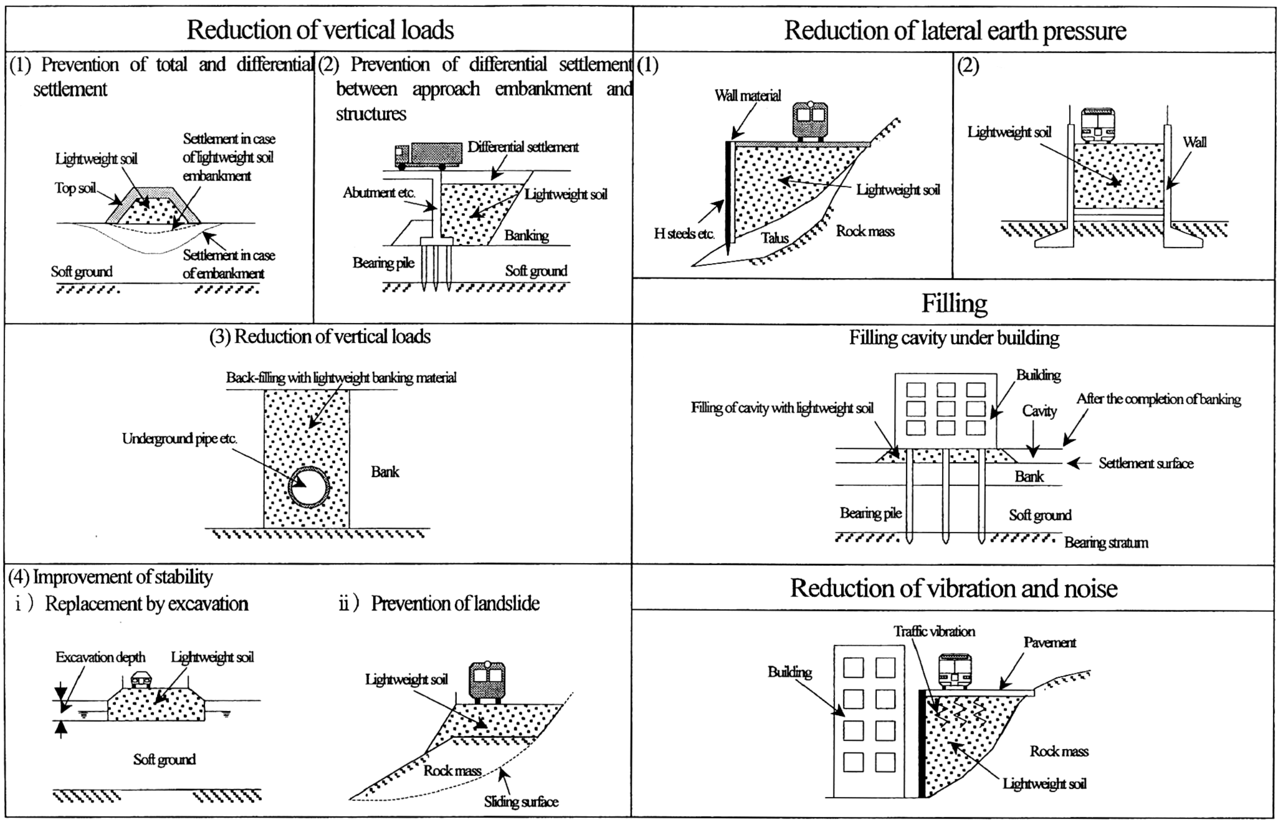

Fig. 1 Several usage of Foamed Cement Banking method (FCB method) (Kutara, 1994; Yasuhara *et al.*, 2001)

called "FCB method") is used at sites with special conditions, such as on soft ground, restricted terrain, reduction of construction cost, recycling of soils generated at the site, and to minimize the disturbance of the natural environment (Sano, *et al.*, 2002).

More than 15 years have passed since the introduction of the FCB method, and the volume of such construction is increasing rapidly. The in-situ strength of the FCB ground has not been tested although the fundamental mechanical properties of foamed mixture lightweight soil are already known. Previous work has shown the maximum temperature inside field test bodies changed with time in the range of 80-100°C, and that temperatures in the centers of the bodies were higher than those at the margins (Sano *et al.*, 2002; Goto *et al.*, 2002; Maekawa *et al.*, 2003).

Maekawa *et al.* (2003) also reported that the unconfined compressive strength of core samples of foamed mixture lightweight soils did not reach the design strength. They then focused on the effects of temperature increase of fill induced by cement hydration on the unconfined compressive strength of foamed mixture lightweight soils at a construction site. The specimen was cured at curing temperatures of 20 to 100°C before unconfined compression testing, to investigate the effects of temperature increase due to cement hydration on the unconfined compressive strength of foamed mixture lightweight soils. Unconfined compressive strength decreases significantly from 20 to 100°C. The unconfined compressive strength cured for 28 days at high curing temperature (80 to 100°C) is about 25% that of specimens cured at 20°C. Finally, they found that revaluation of the design strength is necessary, and temperature management is important when foamed mixture lightweight soils are constructed. However, volume expansion of specimens cured at 80 to 100°C were observed in their experiment. We need the check the strength deformation characteristics of the specimens cured at 80 to 100°C without volume change.

The purpose of this paper is to investigate the effects of high temperature curing on unconfined compressive strength and microstructure of foamed mixture lightweight soil at constant volume.

2. Outline and features of Foamed Cement Banking method (FCB method) (Sano, *et al.*, 2002)

The FCB method is one of the lightweight soil technologies in which foamed mixture lightweight soil is used as a geomaterial. Foamed mixture lightweight soil is produced from base soil, which is generated at the site or purchased, by mixing with cement, water, and foaming agent. The fine mousse-like bubbles are stable in cement paste and mortar,

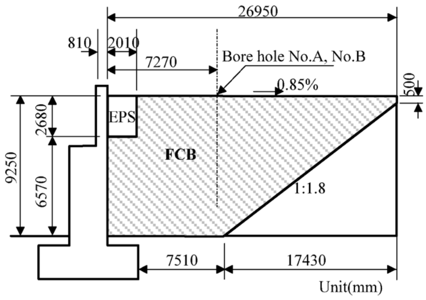

Fig. 2 Cross section of lightweight soil embankment and positions of boreholes (Maekawa *et al*., 2003)

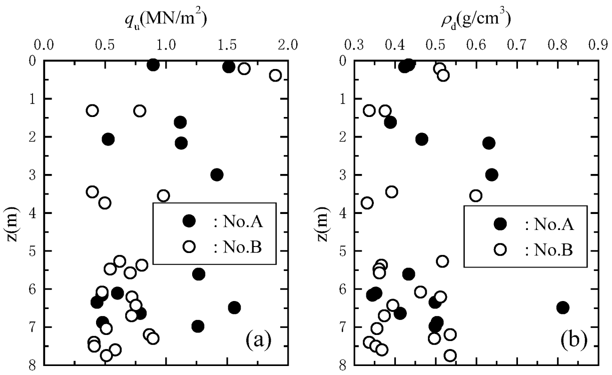

Fig. 3 Variation of (a) unconfined compressive strength and (b) dry density with depth from field measurements (Maekawa *et al*., 2003)

and do not break during transportation by pressure pump. It has been confirmed that the foamed mixture lightweight soil hardens, with the bubbles evenly distributed within the soil.

Unit weight (ρ_t = 0.5 to 1.3 g/cm^3) and unconfined compressive strength (q_u = 300-1000 kN/m^2) of the soil can be controlled freely by changing the content of bubbles and water cement ratio. The foamed mixture lightweight soil has various attributes such as lightweight, fluidity self-sustainability after hardening, workability, and durability. It can be pressure-transported through pipes by pump for up to 500 m without segregation, and the flow value can be controlled freely between 140 to 200 mm, according to transportation distance at the site. It can be transported long distances by pump and does not need spreading and compaction work, and it can also fill narrow spaces, and enables low-noise, low-vibration-execution of embankments within short periods. It is more resistant to ultraviolet rays, heat, and oil than organic high polymer materials.

Since the first application of the FCB method to the embankment of a construction road at a steep slope in the Sanyo Expressway project in 1988, use of this method has been increasing year by year. Applications of the FCB method include embankments for road widening, embankments on soft ground, landslide area and steep slopes, reduction of earth

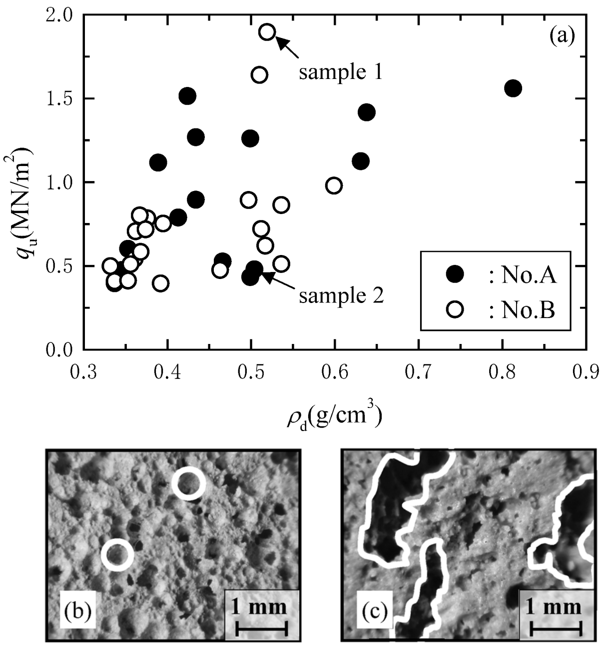

Fig. 4 (a) Relationship between unconfined compressive strength and dry density from field measurements, and (b) structure of sample 1 and (c) structure of sample 2

pressures behind structures, filling of narrow places where compaction work is difficult, and counterweight fills at tunnel portals.

3. Field measurements

Maekawa *et al.* (2003) investigated the mechanical properties of lightweight embankment. Two exploratory boreholes, named A and B, were made to depths ranging to 8.5 m, 28 days or more after embankment formation (see Fig. 2). Borehole A was 3 m inside the edge of the lightweight embankment, whereas borehole B was nearer the center, 9.45 m from the edge. Representative core samples were retrieved for examination and unconfined compression tests. Fig. 3(a) shows the variation of unconfined compressive strength with depth. Although the design is 1.0 MN/m^2, unconfined compressive strength values ranged between 0.4 and 1.9 MN/m^2, irrespective of depth. However, variation in dry density was comparatively small, with most values lying between 0.32 and 0.52 g/cm^3 (see Fig. 3(b)). The allowable error for wet density is 0.1 Mg/m^3 or less in the quality control criteria of the FCB method (Japan Highway Public Corporation, 1996).

A plot of unconfined compressive strength against dry density (Fig. 4(a)) shows no significant relation exists between the two parameters, although unconfined compressive strength generally increases with increasing dry density. We assumed the difference in unconfined

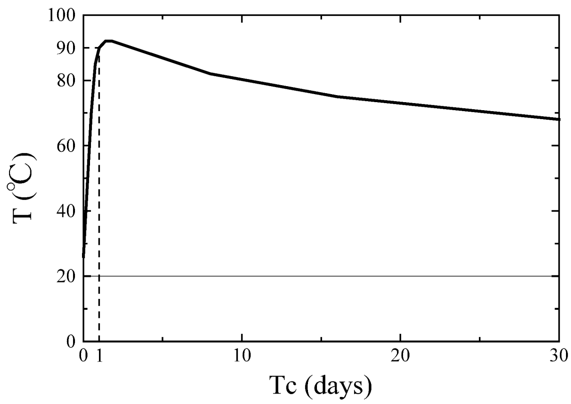

Fig. 5 Internal temperature history from field measurement

Table 1 Mix proportion

Water cement ratio W/C	0.71
Cement C (kg/m^3)	353.0
Water W (kg/m^3)	253.6
Air foam agent m_1 (kg/m^3)	1.6
Diluting water m_2 (kg/m^3)	25.0
Mixing water m_3 (kg/m^3)	227.0

*$W = m_1+m_2+m_3$

Table 2 Quality control criteria

Wet density at mixing stage (g/cm^3)	0.6±0.1
Flow value (mm)	180±20
Volume of air foam (%)	70±5

compressive strength could be attributed to differing microstructure of the lightweight soils, and so investigated the microstructures using a stereo microscope. Fig. 4(b) and Fig. 4(c) illustrate typical microstructures of foamed mixture lightweight ground, and samples with these structures were observed in all places in the cores. The microstructure of sample 1, which has higher unconfined compressive strength, contained uniformly distributed discontinuous small air bubbles. In contrast, the microstructure of sample 2 with lower unconfined compressive strength contained large, continuous, deformed air bubbles scattered throughout. These differing microstructures might result from a large amount of heat released by cement hydration under curing. Accordingly, the thermometry in FCB ground was measured in another project. The internal temperature history from field measurement is shown in Fig. 5. After pouring and spreading of the foamed mixture lightweight soil, the internal temperature rose rapidly from 20 to 90°C in the first day. The temperature subsequently fell slowly. It is notable that the internal temperature was very high (90°C) in the early curing period. Consequently, it is necessary to investigate the influence of initial high temperature curing on the unconfined

Table 3 Curing temperature history

	0～1(days)	2～28(days)
T_{ic}-90	90℃	20℃
T_{ic}-80	80℃	20℃
T_{ic}-60	60℃	20℃
T_{ic}-40	40℃	20℃
T_{ic}-20	20℃	

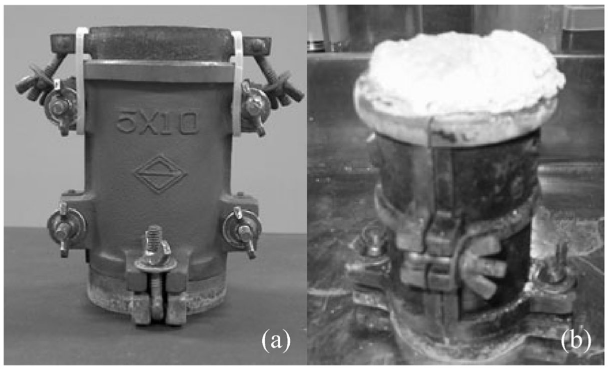

Fig. 6 Foamed mixture lightweight soil specimen cured at high initial temperature under (a) closed system conditions and (b) open system conditions

compressive strength and structure of foamed mixture lightweight soils.

4. Samples and testing program

The mix proportion of foamed mixture lightweight soil is shown in Table 1. The soil was prepared using blast furnace slag cement (B type), water, and synthetic surfactant foaming agent. Whipping the foaming agent after dilution generates fine mousse-like bubbles. The foamed mixture lightweight soils are made by mixing cement paste with the bubbles. The quality control criteria of the mixed material are shown in Table 2. The mixed material was put into a steel mold with diameter of 50 mm and height of 100 mm. By putting a lid on the mold, the sample was held at the constant volume during curing (Fig. 6(a)). The sample was subjected to prescribed initial curing temperatures (T_{ic} = 20°C, 40°C, 60°C, 80°C, and 90°C) for 1 day, and was then cured at 20°C for fixed periods (see Table 3). All samples became self-supporting after the first day. We therefore judged that their internal structure was then completed and that the curing temperature history after the first day unlikely to affect their unconfined compressive strength and internal structure. If samples were unconfined to permit volume change and were then subjected to initial high curing temperatures (80 to 90°C, for 1 day), the molded mixed materials expanded considerably and overflowed the molds

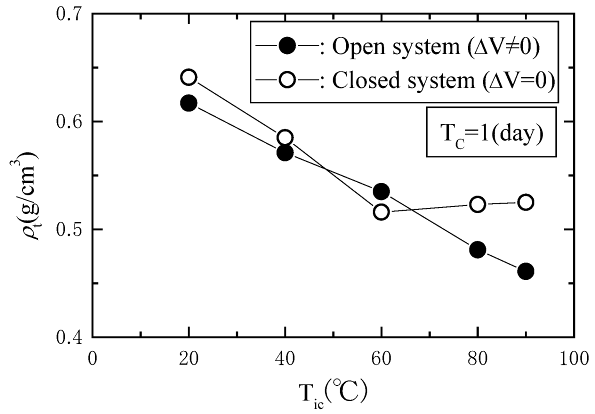

Fig. 7 Typical relationship between wet density and initial curing temperature in samples cured for one day

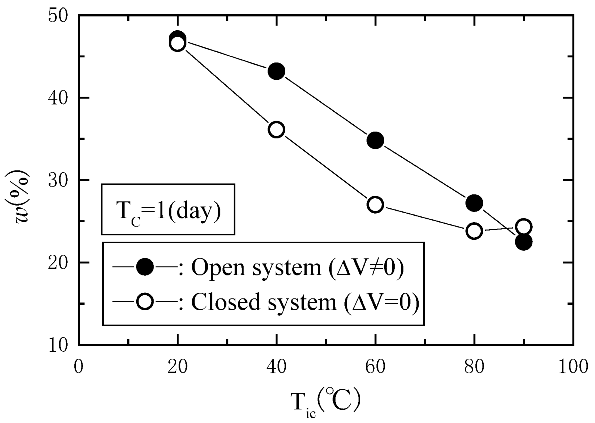

Fig. 8 Typical relationship between water content and initial curing temperature in samples cured for one day

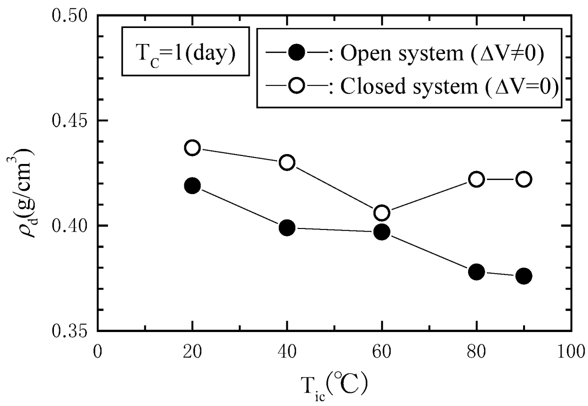

Fig. 9 Typical relationship between dry density and initial curing temperature in samples cured for one day

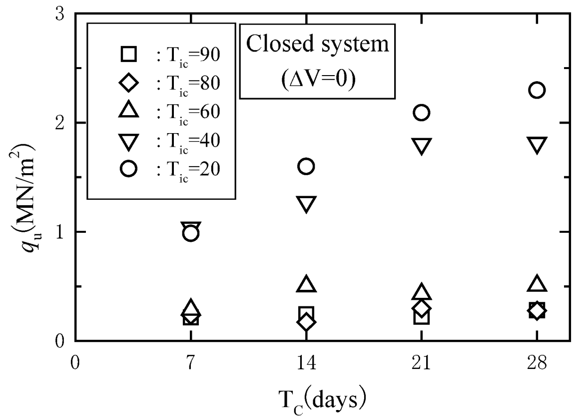

Fig. 10 Typical unconfined compressive strength cured under closed system condition with varying curing times

(Fig. 6(b)). In contrast, the volume scarcely expanded in lower temperature conditions (less than 60 °C).

Unconfined compression tests were conducted on several representative samples of foamed mixture lightweight soils with ages of 7, 14, 21, 28 days. The tests followed standard procedure of the Japanese Geotechnical Society and employed a strain-controlled apparatus. The axial strain rate was 0.1%/min for unconfined compression tests.

5. Experimental results

Figure 7 shows typical relationship between wet density after curing for 1 day and initial curing temperature for foamed mixture lightweight soil under both open and closed system conditions. Wet density decreased almost linearly with increasing initial curing temperature under open system conditions. In addition, heating at 80°C or more made the samples expand considerably, overflowing their molds (Fig. 6(b)). In contrast, under closed system conditions wet density decreased almost linearly with increasing initial curing temperature up to an initial curing temperature of 60°C. When initial curing temperature exceeded 60°C, under closed system condition wet density became constant because the samples could not expand at initial curing temperature of 80°C or more.

Determination of water content in samples cured for 1 day under open and closed system conditions shows contents decreased almost linearly with increasing initial curing temperature under both conditions (Fig. 8). Water in the samples evaporated due to the heating, leading to decreased water contents.

The relationships between dry density after curing for 1 day and initial curing temperature under open and closed system conditions are given in Fig. 9. Dry density decreased linearly with increasing initial curing temperature under open system conditions because of the sample expansion. Under closed system conditions dry values decreased with up to 60°C, but became more or less constant value at initial curing temperature of 80°C or more. This occurred because overflow from molds of mixed samples shown in Fig.3(b) was

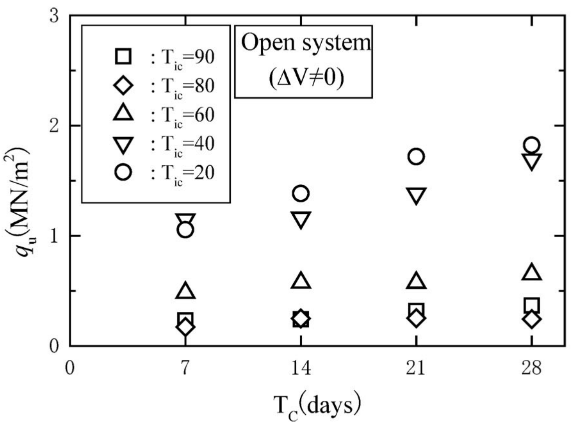

Fig. 11 Typical unconfined compressive strength cured under open system condition with varying curing times

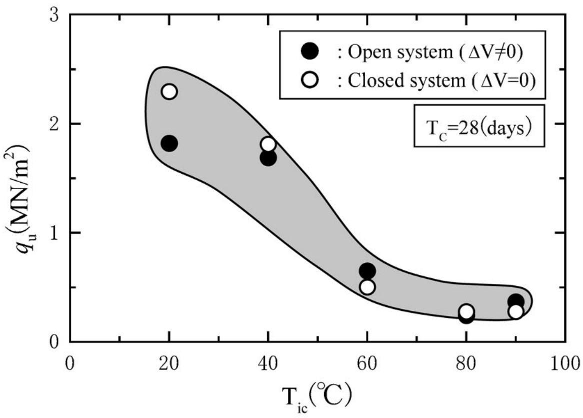

Fig. 12 Typical relationship between unconfined compressive strength and initial curing temperature in specimens cured for 28 days

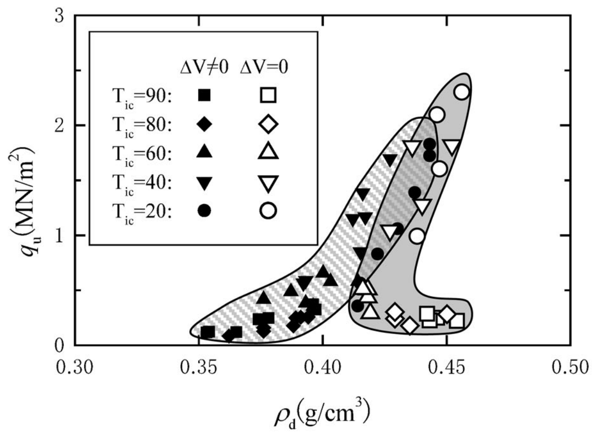

Fig. 13 Relationship between unconfined compressive strength and dry density

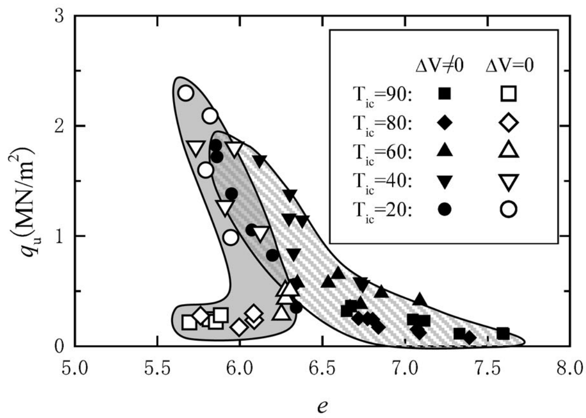

Fig. 14 Relationship between unconfined compressive strength and void ratio

restrained under closed system conditions.

Unconfined compressive strengths were determined under closed system conditions with curing varying from 7 to 28 days. Unconfined compressive strengths of each initial curing temperature increased with increasing curing (Fig. 10). Unconfined compressive strengths cured at high initial curing temperature (60 to 90^{o}C) were lower than those cured at 20^{o}C and 40^{o}C. This tendency was also recognized in equivalent experiments even under open system conditions (see Fig. 11).

The relationship between unconfined compressive strength and initial curing temperature (Fig. 12) shows results obtained under closed system conditions (except for unconfined compressive strength cured at 20^{o}C for 28 days) were very close to those obtained under open system conditions. Unconfined compressive strengths tended to be the same between T_{ic}=20^{o}C and 40^{o}C, and fell significantly from T_{ic}=40 to 60^{o}C. At initial curing temperature of 80^{o}C or more, unconfined compressive strengths were low and constant. Unconfined compressive strengths cured at 80^{o}C were about 20% of those cured at 20^{o}C.

Figure 13 illustrates the relationship between unconfined compressive strength and dry density under both open and closed system conditions. Under open system conditions, unconfined compressive strength decreased with decreasing dry density. This tendency is generally observed in soils. However, dry density fell from 0.44 to 0.35 g/cm^3, even though mix proportions were identical in all experiments. The primary reason for these differences in unconfined compressive strength was most probably the differences in volume change, because dry density decreases with increasing volume. Under closed system conditions, dry density ranged from 0.41 to 0.46 g/cm^3, and thus the variation in dry density was smaller than that under open system conditions. However, unconfined compressive strength varied from 0.2 to 2.2 MN/m^2, irrespective of dry density. This suggests that unconfined compressive strength cannot be estimated from dry density with any certainly. Such variation in unconfined compressive strength agrees well with the results of actual unconfined compressive strength sampled from FCB ground.

Figure 14 shows the relationship between unconfined

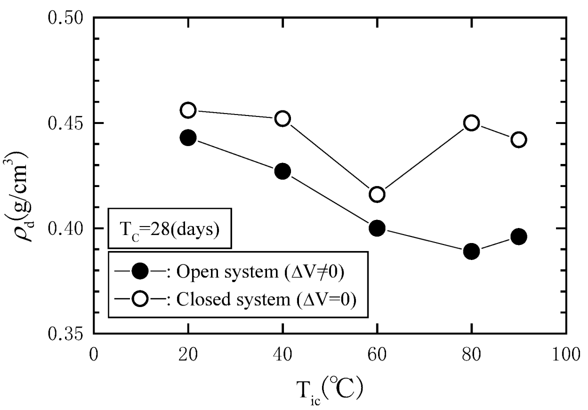

Fig. 15 Relationship between dry density and initial curing temperature in specimens cured for 28 days

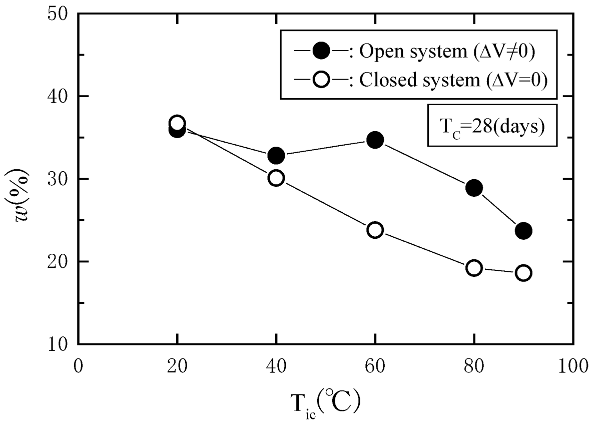

Fig. 16 Relationship between water content and initial curing temperature in specimens cured for 28 days

compressive strength and void ratio. Under open system conditions, unconfined compressive strength decreases with increasing void ratio. In contrast, under closed system conditions the void ratio ranges between 5.7 and 6.3, smaller than that under open system conditions, and no systematic relationship is evident. These results suggest that change in void ratio is a different manifestation of the same physical phenomenon which causes decreased dry density.

The relationship between dry density after curing for 28 days and initial curing temperature (Fig. 15) shows dry density decreased almost linearly with increasing initial curing temperature under open system conditions. In contrast, under closed system conditions dry density was not dependent on initial curing temperature. Values were almost constant at 0.45 g/cm^3, except at 60^{o}C initial curing temperature. This trend agrees with that reported by Kamei and Takeshima (2005). These results suggest that under open system conditions, decrease in dry density with increasing initial curing temperature originates from the increase in volume.

Water contents in samples cured for 28 days decreased with increasing initial curing temperature under both open and

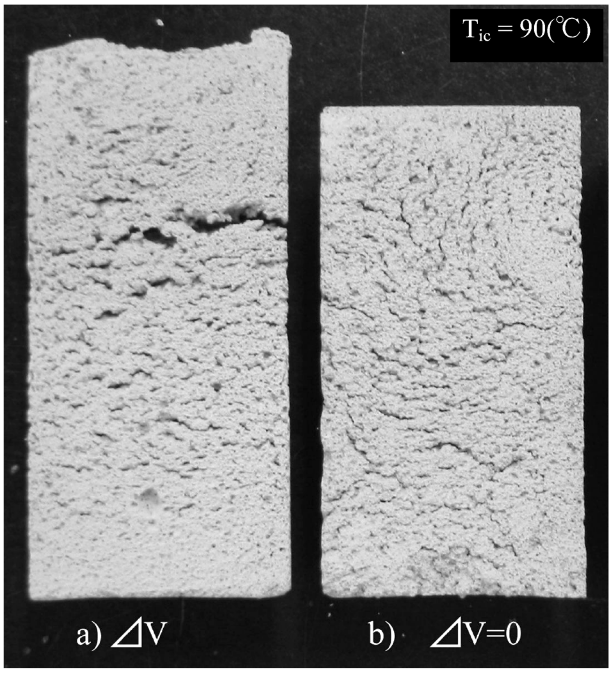

Fig. 17 Vertical sections of foamed mixture lightweight soil specimens cured under open and closed system conditions (T_{ic}=90℃)

closed system conditions (Fig. 16). In comparison with Fig. 16 and Fig. 8, the water content decreased greatly from 1 day to 28 days when initial curing temperature was 40^{o}C or less. This decrease reflects consumption of water in the sample due to progressive cement hydration. In contrast, at initial curing temperatures of 60^{o}C or more, water content hardly changes, even with longer curing, and cement hydration may hence be retarded.

6. Internal structure of foamed mixture lightweight soils

As previously noted, a one-to-one relation between unconfined compressive strength and dry density in the closed system condition was not observed. One of the reasons that the unconfined compressive strength cannot be predicted from dry density is the structural change induced by heating.

To investigate the influences of initial high temperature curing on the internal structure of foamed mixture lightweight soil at constant volume, we first observed the structure with the naked eye. Photographs of sections of foamed mixture lightweight soil specimens cured at initial high curing temperature (T_{ic}=90^{o}C) show that under open system conditions the specimen expanded considerably, and many large cavities were present throughout (Fig. 17). Under closed system conditions, even though almost no volume change was observed, the overall internal structure was similar to that formed under open system conditions.

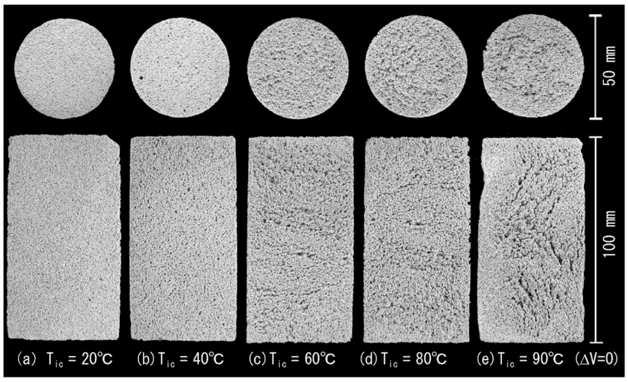

Fig. 18 Cross sections of foamed mixture lightweight soil specimens cured at five differing initial temperatures under closed system condition

Figure 18 shows the influence of initial curing temperature on the internal structure of foamed mixture lightweight soil cured under closed system conditions. When initial curing temperature was comparatively low (20 to 40°C), small air bubbles were uniformly distributed throughout the entire specimen. At initial curing temperature of 60°C or more, large, scattered, and deformed air bubbles were formed. In the 90°C specimen, worm-like cavities were especially evident. Small air bubbles formed and expanded by heating, and subsequently connected to each other. Accordingly, when the specimens are subjected to high temperature in the early curing period, this heat changes the structure and affects the unconfined compressive strength, although dry density remains almost constant.

To investigate the internal structures in detail, typical microstructures of specimens cured under closed system conditions were observed using a stereo microscope (Fig. 19). The microstructures in the sample cured at T_{ic}=20°C, contained uniformly distributed air foams. Individual cavities were small and circular. In contrast, the microstructure formed at T_{ic}=90°C, contained larger air bubbles, many of which were connected, thereby forming large cavities. The microstructures observed at T_{ic}=90°C were similar to the actual microstructures observed in FCB ground. Consequently, variation in unconfined compressive strength of FCB ground originates from changing structure by heating produced by cement hydration. If FCB grounds are to be constructed, careful evaluation of the design strength is necessary, and strict management of the temperature is crucial.

7. Conclusions

The following conclusions were reached

(1) The unconfined compressive strength of foamed mixture lightweight soil decreases linearly with decreasing initial curing temperature. Unconfined compressive strength of specimens cured at 80°C or more is about 20% of that of specimens cured at 20°C.

(2) Observation of internal structures suggests that decrease in unconfined compressive strength with increased initial curing temperature is attributable to structural change induced by heating. In which small uniformly distributed air bubbles become connected to each other and form large cavities.

It is therefore necessary to reevaluate design strength to meet the standard desired, and to manage temperature strictly during construction of FCB grounds.

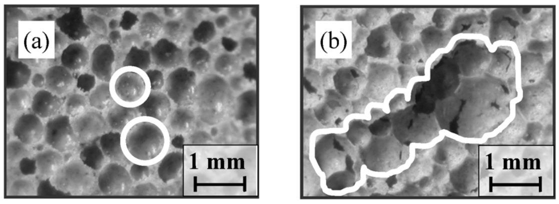

Fig. 19 Typical microstructure of foamed mixture lightweight soil specimens cured under closed system conditions: (a) T_{ic}=20℃; (b) T_{ic}=90℃

Acknowledgements

The authors would like to express their gratitude to Dr. B. P. Roser of Shimane University for his proofreading of this paper. This study was supported by a Grant-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Sciences (No. 17560444 to T. Kamei).

References

Frydenlund, T.E. and Aaboe, R. (1993): Expanded polystyrene - a light way across soft ground, *Proceedings of the 13th International conference on Soil Mechanics and Foundation Engineering*, New Delhi, 1287-1292.

Goto, T., Chaen, T., Suzuki, N., Kakimoto, Y., Kasai, J. and Matsuo, T. (2002): Effects of the temperature rise on strength development of foam mixed mortar or cement milk in embankment, *Proceedings of the International Workshop on Lightweight Geo-materials*, Tokyo, 91-96.

Japan Highway Public Corporation (1996): Design and execution guide for lightweight embankment method using air-foamed mixed lightweight soil, 58p. (in Japanese).

Kamei, T. and Takashima, J. (2005): Unconfined compressive strength of foamed mixture lightweight soil subjected to initial high temperature curing under constant volume condition, *Ground Engineering*, 23(.1), 51-58(in Japanese).

Maekawa, H., Kamei, T., Yamazaki, H., Matsuda, T. and Kitagawa, K. (2003): Effects of curing temperature on unconfined compressive characteristics of foamy mixture lightweight soil, *Proceedings of the 48th Geotechnical Engineering Symposium*, 53-60 (in Japanese).

Miki, H. (2002): Cost reduction effect due to lightweight embankment, *Proceedings of the International Workshop on Lightweight Geo-materials*, Tokyo, 1-16.

Nakase, A. (1974): New technologies in the field of soil engineering, *Kouwan*, 2, 21-25.

Sano, Y. Ogata, K., Kitamura, Y., Matsumura, K. and Sato, M. (2002): Current status of the embanking method using air-mixed lightweight soil for expressways, *Proceedings of the International Workshop on Lightweight Geo-materials*, Tokyo, 207-214.

Yasuhara, K. (2002): Recent Japanese experiences with lightweight geomaterials, *Proceedings of the International Workshop on Lightweight Geo-materials*, Tokyo, 35-59.