

Evaluation of Lime-Stabilized Ariake Clay with Foaming Waste Glass as Pavement Materials

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Foaming waste glass, a new material produced from waste glass, is first briefly introduced. Secondly, the preliminary findings of the engineering properties required for improved pavement materials, namely unconfined compressive strength q_u , compressive splitting strength q_s and the CBR value of the lime-stabilized Ariake clay (LA) with foaming waste glass (LAG) mixture, are presented on the basis of a series of laboratory tests. The potential effectiveness of foaming waste glass as a partial replacement for lime on the strengths of the LAG mixture is indicated by a comparison with lime-stabilized Ariake clay. A process for evaluating stabilized materials as pavement materials is described based on the results of a uniaxial test and pavement structure analysis. It is concluded that foaming waste glass can be effectively applied as a partial replacement for lime for the improvement of soft clay and that the LAG mixture could be used as pavement materials, considering not only its strength but its deformation properties as well.

Keywords: Ariake clay, Foaming waste glass, Unconfined compressive strength, CBR, Deformation modulus

INTRODUCTION

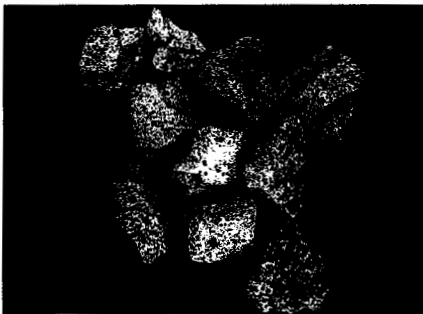
The amount of waste glass such as glass bottles and other industrial glasses is growing every year. It has become such a serious environmental problem that it is time to tackle waste glass. Recently, using special techniques, a new material was produced from waste glass. The newly produced material, called "foaming waste glass", is described in this paper. It takes the shape of a honeycomb originally when it comes from the factory. Surfaces of foaming waste glass are coarse (Yokoo et al., 1998), which increases the internal friction angle, i.e., the strength of the material, see

Fig. 1. Voids are spread throughout the material. Actually, it is a porous material. Thus, it has a low density from 0.3 to 1.5 g/cm³ depending on the presence of different volumes of voids according to the requirement of users. The strength of foaming waste glass can be changed by using a different density. In addition, two kinds of void, namely continuous and discontinuous voids, see Fig. 2, which can control the water absorption ability, are available (see Onitsuka et al., 1999). The continuous voids inside the materials make it possible for foaming waste glass to have good absorption and water-holding capability.

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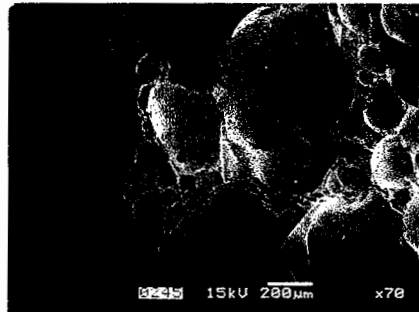


A With discontinuous voids

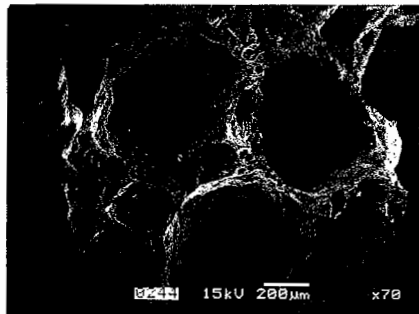


B With continuous voids

FIGURE 1 Shape of foaming waste glass (density: 0.4) (See Color Plate V at the back of this issue)



A With discontinuous voids



B With continuous voids

FIGURE 2 Microstructures of foaming waste glass

Due to its engineering properties, such as a coarse surface, water absorption, low density, and a relatively high strength, foaming waste glass has successfully found some applications in some fields since it was initially manufactured (Onitsuka and Hara, 1998). Research on its application for the improvement of soft soil has been preliminarily reported. The effectiveness of foaming waste glass on treated soft soil was illustrated by the increase in CBR value (Yoshitake et al., 1998).

On the other hand, Ariake clay is a special soft clay deposited in the northern Kyushu island of Japan. The natural water content may be as high as 200%. Its unconfined compressive strength is far less than 0.1 MPa, even if its water content is less than 100% (Onitsuka, 1983). Therefore, most Ariake clay could not be used as a pavement material without improvement. Ariake clay from construction excavations in this region is a problem from an environmental point

of view. Research on improving Ariake clay by stabilizing it mainly with lime and cement has been documented (Nanri, 1997; Nishida, 1995; Onitsuka and Shen, 1998).

A laboratory investigation aimed at utilizing foaming waste glass to improve Ariake clay as a pavement material was undertaken at Saga University. The strength properties, namely unconfined compressive strength q_u , compressive splitting strength q_s and the CBR value of lime-stabilized Ariake clay (LA) mixtures, were investigated. By comparison and evaluation of the physical-mechanical behaviors, the effectiveness of the addition of foaming waste glass in improving the strength of the lime-stabilized Ariake clay (LAG) mixture was illustrated, and the possibility of using foaming waste glass as a partial replacement for quicklime was explicitly realized. A procedure for evaluating stabilized soft clay to be used as pavement materials, based on the uniaxial test and pavement structure analysis, was described.

EXPERIMENT

Materials

Foaming waste glass

The strength properties of the LAG mixture were investigated by means of an unconfined compression test, a compressive splitting test and a CBR test. The maximum size of the foaming waste glass particles for the samples was restricted due to the size of the testing mold being 5 cm in diameter and 10 cm in depth. Most of the foaming waste glass particles used were in the range 2.00 mm to 4.75 mm in size and they were obtained by using a compaction rammer to crush coarser-size foaming waste glass 40–70 mm in diameter. The properties of the coarser foaming waste glass used in the study are listed in Table I. The unit density was tested in self-weight condition without compaction, but the CBR was obtained under standard compaction specified by the Japanese Road Association (1987). The voids of the foaming waste glass are discontinuous.

Ariake clay

Ariake clay from different locations showed a certain variation in physical and mechanical properties. The Ariake clay used in the study was dug from 0.5–2.0 m deep in the ground, in Ashikari Machi, Saga Prefecture, Japan. Properties of the Ariake clay are listed in Table II. Clay minerals in the Ariake clay used are montmorillonite, illite, hydro halloysite and metahalloysite. The clay also contains a lot of diatom remains. It is necessary to note that the ignition loss of the Ariake clay is 7.4%. Compared with those of Ariake clay from other places, this is not a very big value (Nanri, 1997). The value of ignition loss is an indication of the presence of organic materials in clay. A high content of organic material, as much as 5% measured by the Dichromic Acid Method in Ariake clay, significantly affected the effectiveness of improving Ariake clay using lime (Nishida, 1995). The value of organic content measured by the Dichromic Acid Method is approximately twice that of ignition loss for the Ariake clay (Japanese Geotechnical Association, 1979). The sand content in the Ariake clay used is a little higher than in average Ariake clay. On the other hand, the clay content is less than in average Ariake clay.

TABLE I Properties of the coarser foaming waste glass

Dry unit density	(g/cm ³)	0.355
Wet unit density	(g/cm ³)	0.355
Size of particle	(mm)	4.75
Average CBR	(%)	30.9
Unconfined compressive strength	(MPa)	3.5

TABLE II Physical properties of Ariake clay

Natural water content (%)		110.0
Density of particle (g/cm ³)		2.54
Grading (%)	Gravel	0.0
	Sand	37.0
	Silt	44.0
	Clay	19.0
Liquid limit	(%)	89.5
Plastic limit	(%)	39.6
Plastic index		49.9
Loss on ignition	(%)	7.4

Test Programme

To ascertain the strength properties of the mixture, the following laboratory tests with duplicate samples were carried out for 7-day and 28-day curing conditions. The additive content was defined by the ratio of the dry mass of the additive to the dry mass of the natural clay, expressed as a percentage.

- (1) An unconfined compression test of the LAG mixture to understand the influence of the size and content of foaming waste glass on the unconfined compressive strength q_u . Lime contents of 5, 10, 15, and 20% and foaming waste glass contents of 10, 15, 20, and 25% were used in the study.
- (2) A CBR test of the LAG mixture to verify the influence of foaming waste glass on the CBR. Lime content of 10% and foaming waste glass contents of 10, 15, 20, and 25% were used.
- (3) A compressive splitting test to verify the influence of foaming waste glass on the compressive strength q_s . Lime content of 10% and foaming waste glass contents of 10, 15, 20, and 25% were used.

A comparative evaluation was done mainly on the basis of the following criteria: 1) water content reduc-

tion of the mixture, 2) density of the mixture, 3) unconfined compressive strength q_u and compressive splitting strength q_s , 4) deformation modulus E_{50} , which is defined by the ratio of half the ultimate compressive strength to the strain at that stress, 5) the relationship between E_{50} and q_u , and 6) CBR value.

A soil mixer with a maximum mixing volume of 5 liter was used to mix all the materials uniformly. The LA mixtures were blended by mixing Ariake clay with lime for 10 minutes. Mixtures of the LAG were made by mixing LA with foaming waste glass for another 10 minutes. The mixing speed was 60 rpm for the first 5 minutes and 120 rpm for the second 5 minutes for each of the 10-minute periods. The mixtures were extremely wet when the mixing was finished, so that the relationship between the optimum moisture content and dry density could not be obtained. All the samples were compacted by hand vibrating in three layers into cylindrical molds immediately. The objective of the vibrating is to expel as much entrapped air from the mixture as possible. Samples used for the unconfined compression test are 5 cm in diameter and 10 cm in depth, and for the compressive splitting test 10 cm in diameter and 5 cm in depth. CBR test samples are standard size, i.e., 15 cm in diameter and 12.5 cm in depth. Completely sealed in the molds, the samples were cured in a curing room with temperature $20^\circ\text{C} \pm 3$ and humidity 90% for the required length of time before the tests were carried out.

Both the unconfined compression test and the splitting test were controlled by strain at a speed of 1% per minute. The splitting test is performed under specified loading strips to develop a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plan. The sample was loaded until it was broken to get a maximum value of its strength. The q_s was calculated from the following equation (1), according to the Japanese Road Association (1987):

$$q_s = 2p/\pi Dh \quad (1)$$

where p is the maximum splitting load of the specimen, D and h are the diameter and height of the specimen respectively.

The penetration test for CBR was performed at a penetration speed of 1 mm per minute. More detailed information about the test procedures can be found in the specifications (Japanese Road Association, 1987).

RESULTS AND DISCUSSION

Water Content Reduction

The strength of soils is related closely to their water content. A high water content in Ariake clay is a main factor in its low strength. It is important to reduce a large amount of the water content in Ariake clay, so that it can achieve the required strength. In addition, the shrinkage property, a durability index of cement or lime-treated materials, is affected predominantly by the water content in the mixture (NG et al., 1988).

The water content of the Ariake clay in the LAG mixture is hard to measure directly. But the water content can be estimated from that of the LAG mixture because it is affected mainly by Ariake clay. The reduction of the water content of the Ariake clay in the LAG mixture is caused by the reaction of hydration, the reaction of lime pozzolan, and the absorption of the porous foaming waste glass as well. In addition, as a result of increasing the proportion of foaming waste glass, the amount of Ariake clay in the LAG mixture will decrease for a fixed lime content. Therefore, the water content of the mixture will be decreased as the amount of foaming waste glass increases, as shown in Fig. 3. For a fixed lime content, the water reduction varies linearly with the content of foaming waste glass added. The water reduction of the mixture caused by the addition of up to 25% foaming waste glass reaches 10–15% for lime content varying from 5 to 20%. The efficient water reduction contributes to the increase in strength of the mixture.

Unit Density

Figure 4 shows the variation of the unit density of the LAG mixture with the addition of foaming waste glass. The density of the mixture changes from 1.43

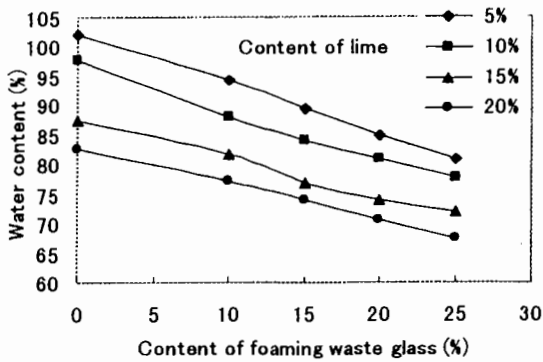


FIGURE 3 Water reduction with the content of foaming waste glass

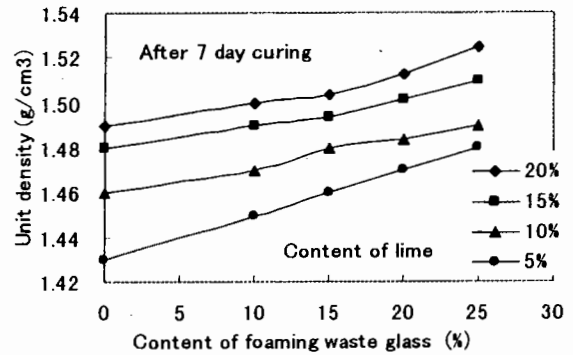


FIGURE 4 Unit density with the content of foaming waste glass

to 1.53 g/cm³. The density increase is insignificant with the addition of foaming waste glass, and it was found to be less than 5% in the study. It seems unlikely that a slight change in density will be large enough to be a factor influencing the strength.

The unit density of a mixture is affected by factors such as the specific gravities of the constituents, the ratio of the constituents and compaction energy. In the study, the specific gravities of the constituents are the same. Compaction energy will not be effective in changing the density due to the high water content of the mixture. The change in density mainly resulted from the decrease in water content of the mixtures.

Unconfined Compressive Strength

Unconfined compressive strength q_u is currently used as a criterion for selection of cement and lime-stabilized material for road material in Japan. The effectiveness of foaming waste glass in improving q_u is important, and it is interesting to discuss the possibility of the partial replacement of lime. To understand the influence of foaming waste glass on the q_u of the LAG mixture, it is necessary to investigate the influence of lime on the q_u at the same time.

Influence of lime on q_u

Figure 5 shows the influence of lime on the q_u of the LAG mixture after 7 days, curing. The influence of

lime on the q_u of LA (foaming waste glass=0%, in the LAG case) can also be evaluated as in Fig. 5. When the lime content is less than an effective value, around 10% in the study, the q_u increases rapidly. When lime added to the Ariake clay exceeds the effective amount, the influence of the extra addition of lime on the q_u of the LA will be relatively ineffective.

Lime content in the LAG mixture is still a prominent factor affecting the q_u of the mixture. The lime-improved q_u of the LAG mixture changes with the addition of lime in the same way as in LA discussed above. Thus, all of the curves in Fig. 5 show a similar tendency to LA for lime content from 5 to 20%.

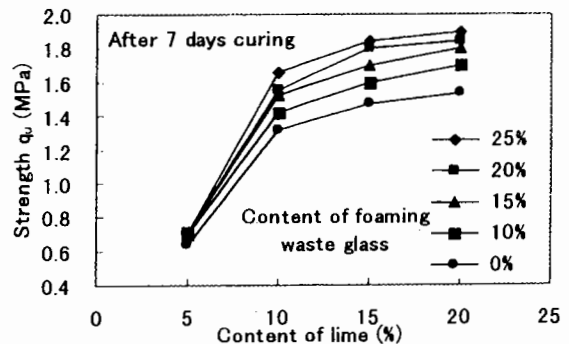


FIGURE 5 Influence of lime content on unconfined compressive strength

The q_u of the Ariake clay is about 0.03 MPa, and the natural water content of the Ariake clay is 110%. A small amount of lime content can cause hydration in such a wet clay completely and quickly, but the pozzolan reaction may not complete and will take a longer time. The changes in strength for a low lime content of 5% are very large due to the hydration and pozzolan reaction, compared with the strength of the Ariake clay without stabilization. The q_u of the LA in the LAG mixture is still very low. The q_u of the LAG mixture is predominately affected by the weak LA mixture. Consequently, the q_u of the LAG mixture is not changed significantly by the addition of foaming waste glass, whereas, for a high lime content case, the q_u of LA in the LAG mixture is much higher and the foaming waste glass can work together with the LA to resist the applied load. The influence of the addition of foaming waste glass on the q_u of the LAG mixture is then apparent.

It was observed in the present study that when a 5% lime content was used, the q_u of the LAG mixture is about 0.7 MPa. Any addition of foaming waste glass has little influence on the q_u . When the lime content was increased to 10%, the q_u of the LAG mixture increased to 1.3 MPa and also increased significantly with increased foaming waste glass. Further addition of lime content in the mixture changes the q_u only a little.

Influence of foaming waste glass on q_u

Figure 6 shows the variation of the q_u of the LAG mixture with the foaming waste glass content after 7 days, curing. Lime content varies from 5 to 20% in the four cases. Generally, the q_u of the LAG mixture increases linearly with the addition of foaming waste glass, from 10 to 25% in the four cases. However, the increase is determined to some extent by the lime content available in the mixture.

The following factors contribute to the increase in q_u for an addition of foaming waste glass. 1) For a fixed lime content, an increase of foaming waste glass in the mixture is equal to a decrease in the content of Ariake clay. The ratio of lime to Ariake clay (L/A) increases and benefits the strength of the LA-consti-

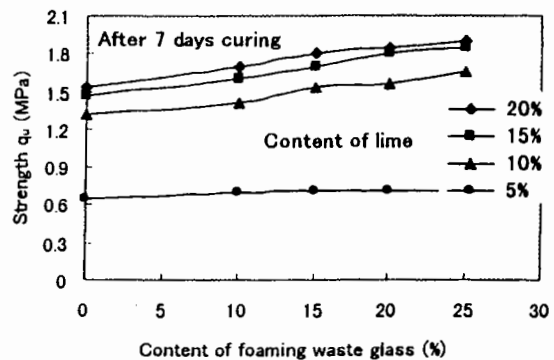


FIGURE 6 Influence of foaming waste glass content on unconfined compressive strength

tuted part of the LAG mixture. 2) A decrease in the water content of the LAG mixture due to the increase of the amount of the foaming waste glass is inevitable, as shown in Fig. 1, which is also helpful to the increase in q_u . 3) The aggregate interaction effect of foaming waste glass in the mixture increases the q_u with an increase in the content of foaming waste glass.

Another factor that plays an important role in the influence of foaming waste glass on the q_u is the curing time the samples experienced before testing. A long curing time will help the increase in q_u of LA in the LAG mixture. Similar to cases of high lime content in the mixture, addition of foaming waste glass has a more efficient benefit on q_u for a long curing time than for a short curing time. Figure 7 shows the q_u of the LAG mixture for a 10% lime content, for two curing times. The values of the q_u after 28 days' curing are twice as high as those after 7 days.

The increase of q_u after 28 days' curing is the same as that after 7 days. But, the q_u increase rate with same addition of foaming waste glass is much bigger after 28 days' curing than after 7 days' curing. This is because the q_u of LA in the LAG has increased so strongly that the foaming waste glass of the LAG mixture can resist the applied loads. Upon close inspection, cracking was observed across not only the LA but also the foaming waste glass inside the tested samples after 28 days' curing.

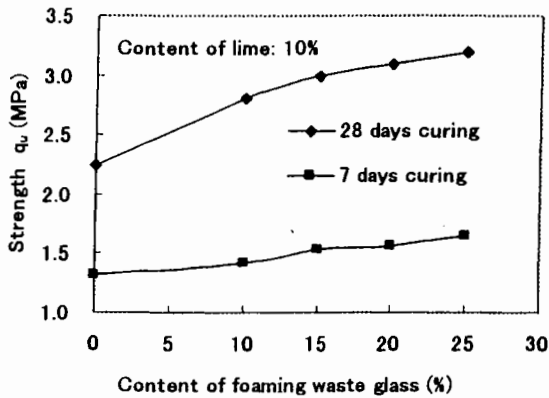


FIGURE 7 Influence of curing date on unconfined compressive strength

In the study, the results from samples after 7 days' curing are as follows: for a lower lime content of 5%, a 10% increase in q_u was achieved by a 10% addition of foaming waste glass. But only 1.5% change in q_u was observed for a further increase of foaming waste glass up to 25%. However, at a higher lime content of 10%, a 10% increase in q_u was achieved for 10% of foaming waste glass, and a 20% increase in q_u for up to 25% of foaming waste glass. The results after 28 days' curing show a 24% increase in q_u for 10% addition of foaming waste glass, and a 40% increase in q_u for 25% addition of foaming waste glass. Therefore, a partial replacement of lime with foaming waste glass in the mixture can effectively increase its strength.

The influence of curing time on the strength of the mixtures has been investigated in detail (Kawabe, 1999). The strengths of the samples after 1 and 90 days' curing are about 10% and 200% of those after 7 days' curing, respectively.

Size effect of foaming waste glass

The size effect of foaming waste glass on the LAG mixture was investigated based on samples made by mixing lime, Ariake clay, and fly ash with foaming waste glass (LAFG) with different ratios instead of the LAG mixture. Here it is assumed that the influence of the particle size of the foaming waste glass on the LAG and LAFG mixtures should be similar. The fly ash used in the mixture is just as a partial replace-

ment for lime. The properties of the fly ash used here are listed in Table III.

Table IV shows the test results of the q_u variation of the mixture after 7 days' curing with different foaming waste glass sizes. The foaming waste glass used in the mixture is 2, 4.75 and 10 mm in maximum size. It was indicated that the q_u of the LAFG mixture increased with the particle size for all three cases with different foaming waste glass content. The q_u of the mixture with 10 mm foaming waste glass is about 10% higher than that with 2 mm foaming waste glass, and about 5% higher than that with 4.75 mm foaming waste glass.

The unit density of fine-sized foaming waste glass is a little larger than that of bigger-size foaming waste glass under the same compaction conditions. This will lead to the difference in volume of foaming waste glass in samples with the same dry mass, which means that the sample containing big particles will be composed of a little more volume of foaming waste glass and therefore less volume of Ariake clay. The water content of the sample mixed with less Ariake clay becomes smaller and results in higher strength in the sample. This is consistent with the findings in the study that the sample with a bigger size of foaming waste glass shows a higher strength.

TABLE III Chemical properties of fly ash

Loss on ignition (%)		3.02
Chemical Constituents (%)	Si ₂ O ₃	61.21
	Al ₂ O ₃	21.85
	Fe ₂ O ₃	5.15
	TiO ₂	1.06
	CaO	4.65
	MgO	1.32
	Na ₂ O	0.70
K ₂ O		0.93

TABLE IV Variation of q_u with sizes of foaming waste glass (MPa)

Particle size (mm)	10-4.75	4.75-2	<2
A:G:F:L=4:2:3:1	1.354	1.303	1.208
A:G:F:L=4:3:2:1	1.271	1.241	1.154
A:G:F:L=4:4:1:1	1.228	1.108	1.086

Compressive Splitting Strength

Figure 8 shows the test results of the compressive splitting strength, q_s , of the LAG mixture with 10% lime content. The testing specimens were cured for 7 days and 28 days. Each value in Fig. 8 is an average for the three replicate specimens tested.

The addition of foaming waste glass to the LAG mixture also improves the q_s in the two curing conditions. But, the effect of foaming waste glass on the q_s is larger after 28 days' curing than after 7 days' curing. Compared with the q_s of the LA mixture, those of the LAG mixtures reached an increase of 30 to 45% for a 25% addition of foaming waste glass after 7 and 28 days' curing, respectively. A close observation of the tested samples indicated that the failure surfaces of the samples after 7 days' curing happened in the LA of the LAG mixture only, but in the LA and the foaming waste glass after 28 days' curing. The reason that the effect of foaming waste glass on q_s is larger for the longer period than the shorter period is the same as for the influence on q_u .

The ratio of the compressive splitting strength q_s at 28 days to 7 days is about 1.40 for the LAG mixture, a little higher than that of the LA, at 1.17. The ratio of compressive splitting strength q_s to the unconfined

compressive strength q_u is about 7. That is to say, the splitting strength is about 1/7 of the unconfined compressive strength.

CBR

The CBR of the LAG mixture is also of concern in pavement engineering and is used to evaluate the strength properties. Figures 9a and b present the relationship between the penetration and the penetration load of the LAG mixture for the 10% lime case. Figure 10 shows the average CBR values from 2.5 mm and 5 mm penetration. The benefit of the addition of glass stone in the mixture to the penetration load or CBR value is obviously indicated. Compared with the CBR of the LA mixture, those of the LAG mixture increase by 65% and 72% after 7 and 28 days' curing for a 25% addition of foaming waste glass. The values of the CBR after 28 days' curing are nearly 1.5 times as much as those after 7 days' curing. Thus, curing time is also important for the CBR of the LAG mixture. The increase rate in CBR is bigger than that of unconfined compressive strength, especially in the early stages. Furthermore, the increase rates get bigger with the depth of penetration.

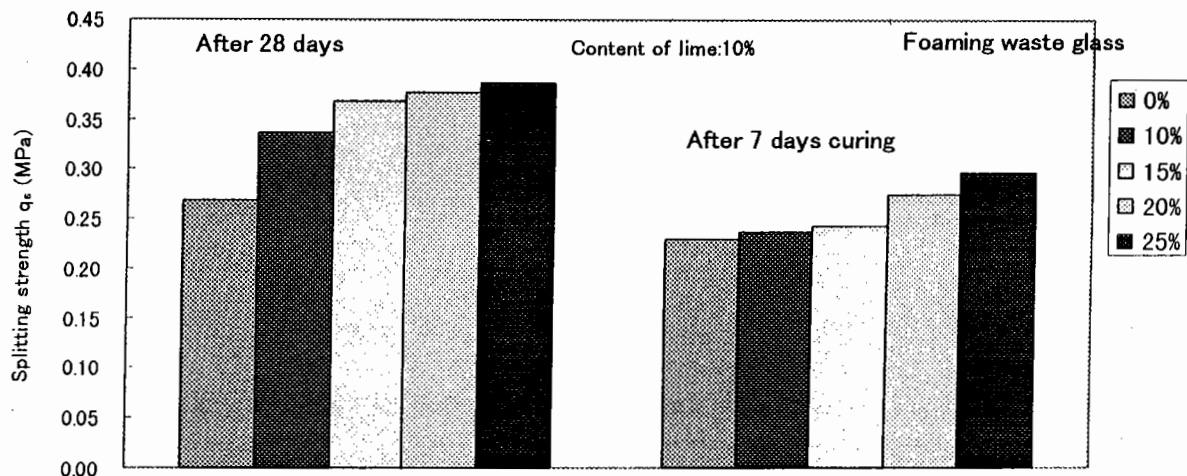


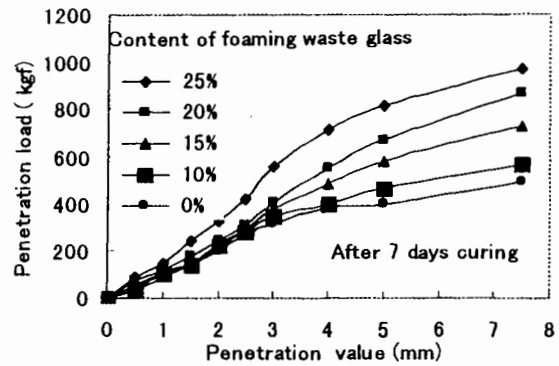
FIGURE 8 Influence of curing date on unconfined splitting strength

Figure 11 indicates the relationship between the CBR and q_u of the LAG mixtures. It also shows that the increase in CBR is faster than q_u . The reason that the CBR test shows a bigger increase potential than unconfined compressive strength is due to the difference of the loading stress states of the samples. Unlike the unconfined compressive test, the CBR test is a confined test and the state is more like a direct shear test. The CBR value is more sensitive to the internal frictional angle than to the cohesion of a mixture. On the other hand, the unconfined compressive strength is more sensitive to the cohesion than to the internal frictional angle. An addition of foaming waste glass to the mixture can enhance the internal friction at angle more than the cohesion of the mixture, especially at an early stage. This was verified by the unconfined compression test. At a later stage, both the internal friction and cohesion of the mixture can be improved by an addition of foaming waste glass. That is why q_u and CBR increase at later stages when foaming waste glass is added.

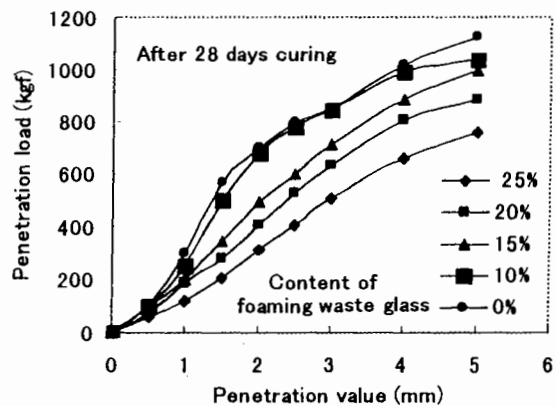
Deformation Modulus

The deformation property of a lime-stabilized material as a pavement material is important to reduce load-induced deformation. Furthermore, in mechanistic analyses of pavement structures, a deformation modulus must be adopted for a pavement material. A widely used index in pavement engineering is the resilient modulus, which is the elastic modulus based on the recoverable strain under repeated loads (Huang, 1993). In geotechnical engineering, in Japan, a common index to evaluate the resistance to deformation is E_{50} , as was defined in a previous section. It is not the same as the resilient elastic modulus in definition. But E_{50} indicates the deformation properties of the average state of the relationship between stress and strain in the mixture.

The deformation resistance ability of the whole pavement is dependent on that of every constituent pavement material. The larger the deformation modulus of the pavement structure, the smaller the deformation of the pavement structure under a particular loading. In that sense, a strong modulus of the pave-



a After 7 days curing



b After 28 days curing

FIGURE 9 Relationship between penetration and penetration load

ment material is always desirable. However, in a layered pavement, the load-induced stresses in a certain layer are determined by the ratio of the modulus of every layer, and the location of the layer dealt within the pavement structure as well. The larger the deformation modulus of the material of the layer and the higher the location of the layer in a pavement structure, the higher the load-induced stresses of the material will be (Shen, 1997). If the strength does not increase properly with the modulus of the materials, failures such as plastic deformation and cracking in

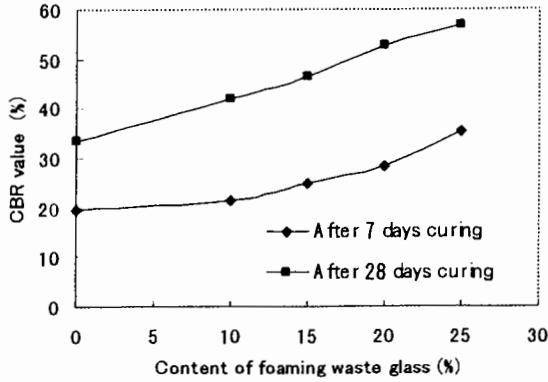


FIGURE 10 Influence of curing date on CBR of LAG mixture

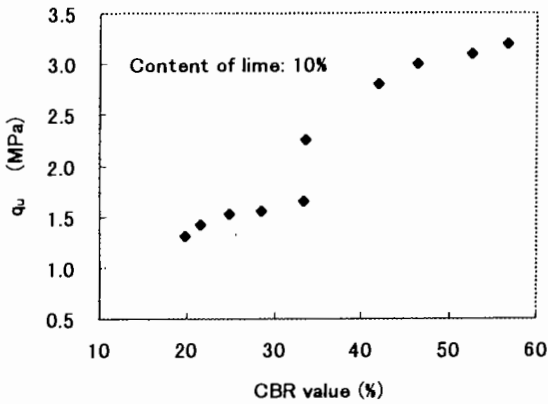


FIGURE 11 Relationship between CBR and unconfined compressive strength

the material of the layer will happen. Therefore, the demand for the deformation modulus as a pavement material considering the two aspects is in conflict.

It is a well-known fact that the deformation modulus and the strength of stabilized materials are related to each other, but not uniquely related (Nishida, 1995). Generally, the greater the strength, the bigger the deformation modulus of the material. The relationship between E_{50} and q_u of a stabilized material is, however, affected by many factors, such as the type of stabilizers and their contents, and the properties of the materials to be stabilized. Therefore, it is necessary to make clear the relationship when the materials are applied in engineering practice. Figure 12 shows the

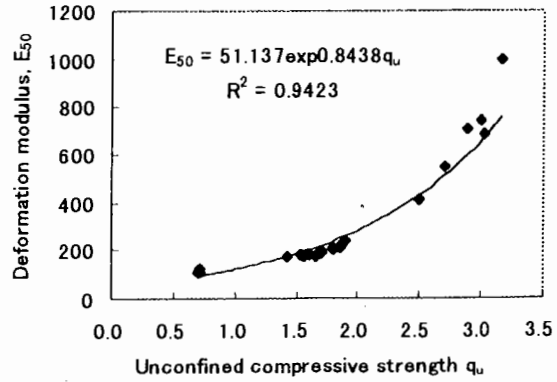


FIGURE 12 Relationship between deformation modulus and unconfined compressive strength

relationship between the modulus and the strength of the LAG mixture from the data in the study. An empirical regression equation was obtained in equation (2). The average values of E_{50} of the LAG, 200 MPa and 600 MPa, can be adopted corresponding to the strengths after 7 and 28 days' curing respectively.

In order to compare the results with those from other stabilizers and soils stabilized, empirical regression equations from cement-treated Ariake clay and from other cement-treated soils are listed in equation (3) (Sakka et al., 1998), and equation (4) (Richardson, 1996). Both equations (3) and (4) show a quick increase in deformation modulus with the strength q_u .

$$E_{50} = 51.137 \exp 0.8438 q_u \quad (R^2 = 0.9423) \quad (2)$$

$$E_{50} = 1000 q_u \quad (0.1\text{MPa} < q_u < 0.8\text{MPa}) \quad (3)$$

$$E_{50} = -34.367 + 2006.8q_u^{0.7748} \quad (3.0\text{MPa} < q_u < 8.0\text{MPa}) \quad (4)$$

Evaluation of the stabilized materials as pavement materials

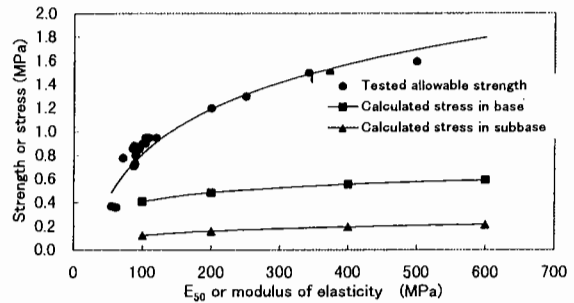
In pavement engineering, both the strength and the modulus of a stabilized material are important, as mentioned above. An evaluation considering both of

these is reasonable. In the study, the applicability of the LAG material to be adopted as a pavement layer was evaluated. It was implemented by comparing the relationship between the deformation modulus E_{50} and the allowable strength from the laboratory tests, with that between the modulus of elasticity and the traffic load-induced stress of a pavement layer from pavement structure analyses. They are shown together in Fig. 13.

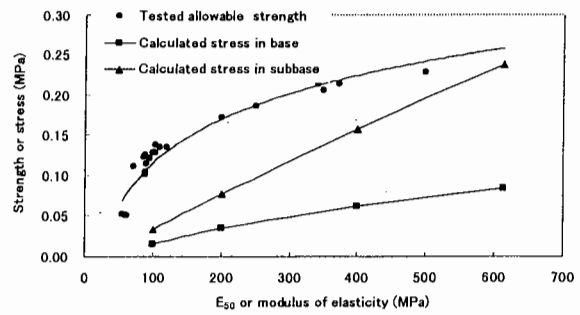
The base and subbase layers are in a five-layer asphalt concrete pavement structure corresponding to traffic volume "A" of the Japanese design code (Japanese Road Association, 1992). According to material fatigue theory, a material can survive without cracking from an infinite number of repeating loads if half of the maximum static strength is used as fatigue strength for the material. The allowable compressive strength is here simply taken as half of the q_u in order to avoid fatigue cracking, because no repeating load data of the mixture is available at this moment. Thus, this will be on the safe side. The q_u and E_{50} from 7 and 28 days' curing were used for illustration. The allowable tensile strength is taken to be 1/7 of the compressive strength, which is based on the empirical data of the study. Stresses concerned in pavement engineering are the vertical compressive stress on the top of the layer and the horizontal tensile stress at the bottom of the layer discussed. The stresses in the study were calculated by the program KENLAYER (Huang, 1993).

As indicated in Fig. 13a, the curves of the calculated compressive stress on the top of both base and subbase layers are far lower than the strength curve of the mixtures. The compressive stress on the top of the base and subbase is not sensitive to the modulus of elasticity. Therefore, the increase in q_u of the mixture with curing will provide a big margin in strength, although the E_{50} will increase also.

The tensile stresses at the bottom of the base and subbase are sensitive to the modulus of elasticity of the layers, especially for the subbase, see Fig. 13b. Thus, it will be crucial for the tensile stress at the bottom of the base layer if a large modulus of the mixture is adopted. If the deformation modulus becomes too



a Compressive strength and stress on the top of the layers



b Tensile strength and stress at the bottom of the layers

FIGURE 13 A comparison between the material strength from test and the stress by traffic load

high then tensile stress-induced cracking is inevitable. In this respect, the LAG mixture will have a better behavior than cement-treated Ariake clay and other cement-treated soil due to the relationship between E_{50} and q_u expressed in the above section.

SUMMARY AND CONCLUSIONS

The amount of waste glass is increasing worldwide and will soon become a serious environmental problem. Foaming waste glass, a new material made from waste glass, has properties such as low density, rough surface, good water absorption capacity, and relatively high strength. Ariake clay, a very soft clay, has a very low strength and cannot be used as a pavement material.

A series of experiments was carried out on the utilization of foaming waste glass in the improvement of Ariake clay, based on the strength properties of the LAG mixture. A process for evaluating stabilized soft clay to be applied in pavement engineering was described. It becomes clear from the testing results that foaming waste glass can effectively replace some of the lime in the improvement of soft clay in respect of strength. The LAG mixtures can be used as pavement material in respect of their strength properties.

Water content and unit density are the two main factors influencing the strength of a material. The water content of the LAG mixture decreases significantly with the addition of foaming waste glass for a fixed lime content, but the unit density of the mixture changes slightly. The changing of the unit density of the mixture due to an addition of foaming waste glass is not as important as water reduction to the strength variation of the LAG.

The influence of lime on the strength of the LA mixture is significant, due to a rapid elimination of water in the Ariake clay by hydration and pozzolan reaction. It is also crucial to the influence of foaming waste glass on the strength of the LAG mixture. A relatively large amount of lime is necessary for the stabilization of Ariake clay to reach the required strength as a pavement material. However, above a certain lime content, adding more lime is not economical because of its ineffectiveness in further increasing the strength. Partial replacement of lime with the newly produced foaming waste glass in the LA mixture can increase the strength effectively.

A potential increase in unconfined compressive strength q_u due to an addition of foaming waste glass was observed, especially for the cases where the amount of lime in the mixture is a little high and the curing period is relatively long. A 20% and 40% increase in q_u after 7 and 28 days' curing respectively were observed for a 25% addition of foaming waste glass in the LAG mixture with a lime content of 10%.

An increase of foaming waste glass content in the mixture is also greatly beneficial to the compressive splitting strength q_s . An increase of 30 to 45% after 7 and 28 days' curing, respectively, was obtained for a 25% addition of foaming waste glass in the LAG mixture

with a 10% lime content, compared with the LA mixture. The compressive splitting strength q_s is about 1/7 of the unconfined compressive strength q_u . The splitting strength after 28 days is 1.4 times as much as after 7 days.

The LAG mixture shows a higher increase in CBR with the addition of foaming waste glass than that in q_u . Compared with an increase of 20–40% in q_u , the increase in CBR is observed to be up to 65–72% for a 25% addition of foaming waste glass after 7 and 28 days' curing. This is partly due to the stress state difference between the confined and unconfined loading tests.

Strength q_u and deformation modulus E_{50} of an improved material are the main factors of concern in pavement engineering, and related to each other. The relationship differs not only with the stabilizers used but also with the materials to be improved and added. An empirical regression of the relationship between E_{50} and q_u is obtained, which is used to evaluate the mixture as a pavement material. The average values of E_{50} change between 200 and 600 MPa, corresponding to 7–28 days' curing in the study. The increase rate of the deformation modulus with strength q_u is slower than cement-treated Ariake clay and other soils. It will make the pavement structure behave well under traffic loads, especially with regard to tensile cracking. The LAG mixture can be used as both base and subbase layers by comparing the test results with that from structure analysis.

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