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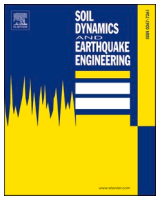

Soil improvement using agar gum polymer for seismic liquefaction mitigation

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ABSTRACT

Liquefaction can cause ground subsidence and structural collapses, which could result in considerable damage. While numerous preventive methods have been proposed to prevent such liquefaction, most of these methods involve cement-based reinforcements, thus potentially introducing other environmental problems, such as groundwater contamination and increased carbon dioxide emissions. Therefore, it is essential to develop and use eco-friendly, ground-reinforcement materials. Agar gum is an eco-friendly biopolymer extracted as a result of the biological activities of microorganisms. Ground-reinforcement of agar gum enhances its effectiveness in improving the unconfined compressive and shear strengths, thus making it a suitable, eco-friendly, ground-reinforcement material. However, while the use of agar gum could (logically) increase the strength of liquefaction resistance, there is insufficient research to support this assumption. Therefore, in this study, the viscosity, unconfined compressive strength, and hardness of agar gum were quantified, and the liquefaction resistance strength was evaluated based on cyclic triaxial tests using agar-gum-treated samples. The hardness, unconfined compressive strength, and liquefaction resistance strength increased with increasing agar gum concentrations, and the change based on a curing time was relatively constant. In addition, the effect of enhancing the liquefaction resistance strength using agar gum was confirmed based on a comparison with previous studies using untreated samples and other reinforcing materials.

1. Introduction

Liquefaction occurs when loose ground is subjected to Earth tremors. This generates excess pore pressure, results in the loss of effective stress, and thus makes the soil behavior similar to that of liquid. When liquefaction occurs, structures built on the ground collapse, thus causing considerable damage. Examples of liquefaction damage abroad include the collapse of the Calaveras Dam as a result of the 1918 California earthquake in the United States, building collapses owing to the 1964 Niigata earthquake in Japan, and the destruction of a city during the 1976 Tangshan earthquake in China. In Korea, traces of liquefaction were first observed in roads, parks, and agricultural lands near the epicenter of the 2017 Pohang earthquake [1–4]. Moreover, liquefaction occurs frequently with more than 10,000 instances reported worldwide [5].

Numerous methods have been proposed and used to prevent ground liquefaction. There have been cases of liquefaction prevention using cement, such as the lattice-shaped ground improvement using cement mixing and grouting of the Yahatagawa floodgate [6,7]. However, the use of cement-based methods can adversely affect the environment. Hence, to address these limitations, eco-friendly ground reinforcements have been actively researched. Representative eco-friendly reinforcements include colloidal silica grouting, bentonite suspension grouting, bio-cementation, induced partial saturation, and laponite grouting. Colloidal silica grouting strengthens the binding of soil particles and significantly increases their resistance to repetitive loads by injecting colloidal silica solutions into the ground, thus increasing the strength of the ground over time [8–10]. Bentonite suspension grouting is a ground-reinforcement method implemented by adding bentonite that prevents excess pore pressure increases and is effective in increasing the liquefaction resistance strength [11–13]. Bio-cementation is a method used to improve the soil through the precipitation of calcium based on the mechanism of microbial-induced calcium carbonate precipitation (MICP), which is a technology used to increase the shear

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strength and liquefaction resistance of the soil [14–16]. Induced partial saturation is a technology that improves the resistance of soil susceptible to liquefaction (by reducing the saturation of soil vulnerable to liquefaction) by injecting air into the empty soil space [17–22]. Laponite grouting is a technique used to increase resistance to liquefaction by injecting a laponite mixture into the soil [23,24].

Biopolymers generated by the biological activities of organisms are emerging as eco-friendly reinforcing materials. Biopolymers are substances that can be extracted from animals, plants, and microorganisms. Animal-based biopolymers include chitosan and casein; plant-based biopolymers include guar gum, beta-glucan, agar gum, and carrageenan, and microorganism-based biopolymers include xanthan and gellan gum [25]. These biopolymers are eco-friendly materials. Research studies conducted on them treat them as eco-friendly, ground reinforcement materials used in a modern society where the environment is important. Biopolymers, such as agar, gellan, and xanthan gum prove effective in improving the unconfined compressive strength when used to reinforce the ground [26,27]. The strengths of water-soluble biopolymers, such as agar and gellan gum, were measured under air-dried and submerged conditions. In the case of biopolymer-treated soil, the water content in the soil affects the strength [28]. Following the evaluations of shear strength by treating the soil with agar, gellan, and xanthan gum, it was found that the biopolymer in the soil increases the bonding force among soil particles, increasing the shear strength [26,27,29–32]. Research was also conducted to confirm the performance effect of biopolymers as an injection material by checking the injection performance of biopolymers [33–35]. In addition, the effects of biopolymer treatment on soil dynamic properties and ground-response analysis were evaluated using the resonant column test [36,37]. Recently, the resistance to liquefaction based on cyclic triaxial tests was explored using a biopolymer treatment. As a result of evaluating liquefaction through strain-controlled, cyclic triaxial tests, it was confirmed that biopolymer treatment fills the voids among soil particles and improves strength, thus suppressing excess pore pressure increases that affect liquefaction resistance [38–40]. As liquefaction evaluations conducted according to the preceding biopolymer treatment are based on strain control, it can be difficult to evaluate the strain behavior of the sample based on the load and to calculate the cyclic resistance ratio (CRR). Accordingly, this makes it necessary to calculate the CRR during stress-control-based liquefaction evaluations using biopolymers.

Biopolymers can dramatically reduce carbon dioxide emissions compared with conventional materials, such as cement, and can be obtained from renewable resources. Moreover, when biopolymers are ground-reinforced, they can effectively promote vegetation [26]. Therefore, the increasing requirement for eco-friendly reinforcements has resulted in increased interest in ground-reinforcement methods using biopolymers. Among biopolymers, agar gum is a thermal gelation polymer that exists in a sol state when heat is applied; however, hardens into a gel state at temperatures below a specific threshold [41–43]. Thus, when agar gum is heated and injected into the ground in the sol state, it hardens into a gel state. When agar gum hardens in the ground, ground reinforcement could be expected to increase the adhesion between the soil particles and increase the strength of the ground. Therefore, in this study, agar gum was selected as an eco-friendly, ground reinforcement material to evaluate and compare the liquefaction resistance strengths of agar-gum-treated and untreated samples obtained using cyclic triaxial tests. Additionally, the viscosity, hardness, and unconfined compressive strength of the agar gum were measured and compared with those of the cyclic triaxial test results.

2. Materials and methods

2.1. Soil

The soil samples used in this experiment were prepared using the particle-size distribution curve data (for samples with sizes that are very easily liquefied) obtained in previous studies [44]. Therefore, the soil particle-size distribution in the Pohang liquefaction area was reproduced using decomposed granite soil, silica sand, and kaolinite [45]. Fig. 1 illustrates the particle-size distribution curve used in the experiment. Based on the particle-size distribution curve, the soil sample created corresponded to poorly graded sand (SP) under the unified soil classification system. Table 1 presents the physical properties of the soil used in the experiments.

2.2. Biopolymer

The biopolymer used in the experiment was agar gum. Agar gum is a plant-based biopolymer, usually a polysaccharide extracted from several types of Rhodophyta. The chemical structure of agar gum is formed of polysaccharides linked to galactose molecules [26,46,47]. Fig. 2 illustrates the chemical structure of agar gum. Agar gum is used in various fields, such as food, cosmetics, research, and industry [41,46]. Agar gum is a water-soluble biopolymer and dissolves in water. Additionally, agar gum is composed of agarose and has thermogelation properties [29,48]. Therefore, when an aqueous solution containing agar gum is heated, it dissolves and maintains a sol state. The sol state of the aqueous solution of agar gum has the characteristics of a thermogelling polymer that forms a gel state when the temperature falls below a specific threshold. The dissolution temperature of the aqueous agar gum solution is in the range of 85–90 °C and the gelation temperature is 32–45 °C [26,32,41–43,48]. Therefore, the aqueous agar gum solution exists in a gel state at room temperature. Fig. 3 shows agar gum in the sol and gel states. Gelled agar gum has high-mechanical strength and produces increased cohesion and adhesion among soil particles [48]. Thus, when an aqueous solution of agar gum in a heated sol state is injected into the ground, the solution falls below a certain temperature over time, and agar gum gel is formed. The agar gum gel forms a hydrogel among the soil particles, thus increasing the adhesion between the soil particles and preventing an increase in excess pore pressure and a decrease in effective stress [38,40]. Moreover, the strength of the agar gum increases at increasing concentration. A denser network is evident as the concentration of agar gum increases, thus resulting in a decrease in the size of the voids and high-compression resistance [42].

In this study, an aqueous solution of agar gum was prepared by mixing agar gum powder with distilled water, which was then heated to dissolve the powder to prepare an aqueous polymer solution in the form of a sol. The agar gum concentration is based on the water volume. Consequently, it could be defined as the weight of the agar gum powder/weight of the aqueous solution.

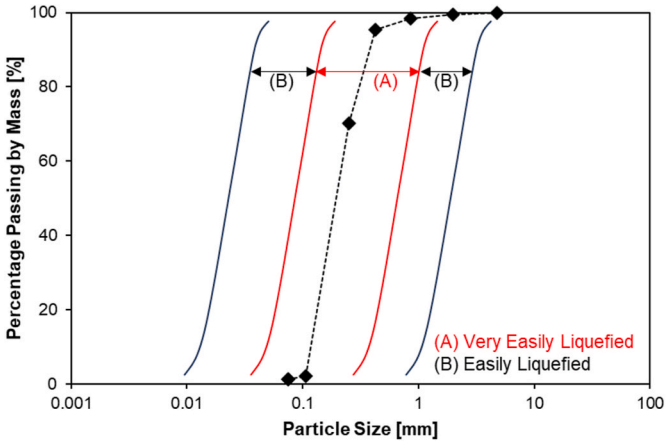

Fig. 1. Particle-size distribution curve with liquefiable boundary (Iwasaki, 1986).

Table 1
Physical properties of the soil.

G_s	D_{60} [mm]	D_{30} [mm]	D_{10} [mm]	C_u	C_c
2.66	0.22	0.15	0.12	1.83	0.85

2.3. Characteristics of pure agar gum

Aqueous solutions of agar gum exhibit properties that exist in the sol state at high temperatures. Consequently, to understand the material properties of a heated sol state agar gum aqueous solution, the change in viscosity was measured based on the agar gum concentration. Additionally, as the temperature of the agar gum solution decreased, the agar gum changed into a gel state. The viscosity of the gel state was also measured; however, after the gel changed to a solid state, it was not possible to measure the viscosity. Therefore, the aqueous solution of the gel-type agar gum was subjected to separate unconfined compressive strength and hardness tests.

2.3.1. Viscosity of aqueous solution of agar gum

To measure quantitatively the viscosity of the aqueous solution of agar gum, the viscosities of agar gum (concentrations of 2 %, 4 %, and 6 %) were measured using a DVE viscometer. The concentration of agar gum was calculated as the weight of agar gum powder/weight of aqueous solution. To prevent the gelation of the solution during the experiment, the viscosity of the aqueous polymer solution was maintained at 70 °C (which is a temperature at which agar gum can exist in a sol state), and the viscosity was measured. The experimental conditions used for the viscosity tests are listed in Table 2.

2.3.2. Measurement of unconfined compressive strength of agar gum gel

An aqueous solution of agar gum, in the form of a sol at high temperatures, changes into a gel form as the temperature decreases. The agar gum gel formed can stand on its own, thus exhibiting strength. Additionally, as the concentration of agar gum increases, a higher strength can be expected because a dense network is formed. Consequently, an unconfined compressive strength test was conducted to determine quantitatively the compressive strength of the agar gum gel based on the changes in its concentration. To measure quantitatively the compressive strength of the agar gum gel, its unconfined compressive strength was measured using an unconfined compressive strength tester (Universal testing two-column type, Model TD-U02).

The sample was manufactured with a diameter of 55 mm and a height of 40 mm. The sample was prepared by pouring the heated agar

Table 2
Experimental conditions for pure agar gum.

Test Type	Solution Type	Experimental Temperature [°C]	Concentration [%]	Curing Times [days]
Viscosity	Pure Sol	70	2	0
			4	0
			6	0
UCS	Pure Gel	25	2	1/8
			4	1/8
			6	1/8
Fall Cone	Pure Gel	25	2	1/8
				7
				28
			4	1/8
				7
				28
			6	1/8
				7
				28

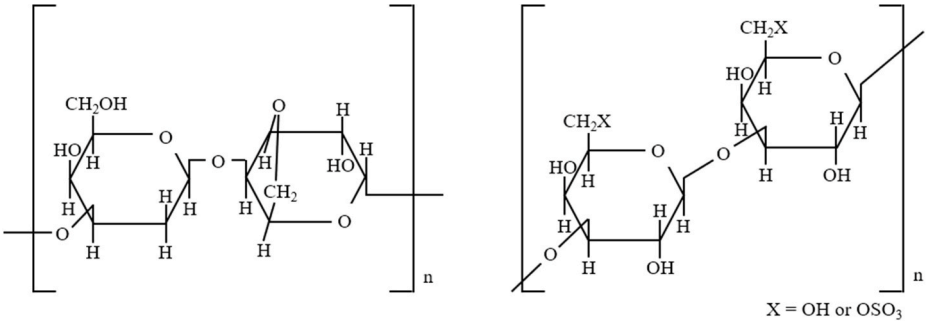

Fig. 2. Chemical structure of agar gum.

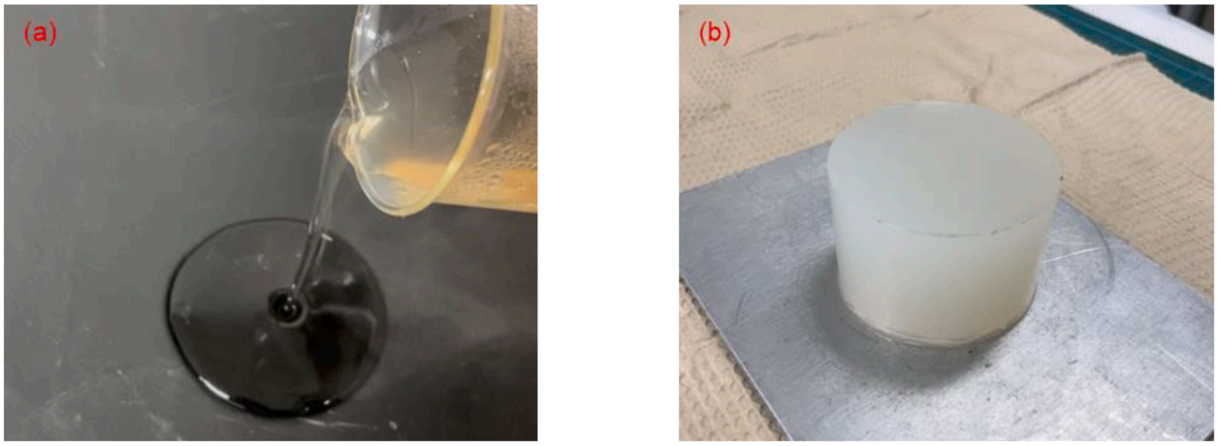

Fig. 3. State of agar gum. Agar gum in (a) sol and (b) gel states.

gum aqueous solution into a mold and storing it at a laboratory temperature of 25 °C for a certain time to ensure the gelation time of the aqueous solution of the agar gum. Thereafter, the unconfined compressive strengths for agar gum (concentrations of 2 %, 4 %, and 6 %) were measured to determine the impact of changes in the agar gum concentration. The concentration of agar gum was calculated as a function of the weight of agar gum powder/weight of aqueous solution. The experimental conditions used for the unconfined compressive strength tests are listed in Table 2.

2.3.3. Evaluation of the relative hardness of agar gum gel

In addition to strength, which is a mechanical property of solids, hardness was also measured. Various methods exist that can measure hardness, including scratch, penetration, or bounce tests. In this study, the fall-cone test—similar to a penetration test—was used. Although the value measured using the fall cone test cannot represent the exact hardness of the agar gum gel, it can be used to represent a change in the relative hardness depending on the concentration of agar gum and curing time. To confirm the change in hardness based on the agar gum concentration, fall-cone tests were conducted on agar gum samples (2 %, 4 %, and 6 %). The concentration of agar gum was calculated as the weight of agar gum powder/weight of aqueous solution. Additionally, to confirm the long-term hardness maintenance of agar gum, a fall-cone test was conducted after various curing times (1/8, 7, and 28 days) based on the agar gum concentration.

The sample was manufactured with a diameter of 55 mm and a height of 40 mm. During sample preparation, the heated agar gum aqueous solution was poured into a mold. It was maintained at 20 °C for a certain time to ensure the gelation of the aqueous agar gum solution. Additionally, wet curing was used to cure the samples. The DA-564 Fall Cone Liquid Limit Tester was used for the fall-cone tests. The experimental conditions for the test are listed in Table 2.

2.4. Evaluation of liquefaction resistance strength based on cyclic triaxial tests

The cyclic triaxial tester (GDS Enterprise Level Triaxial Testing System) was used for the cyclic triaxial test in this study. The experimental equipment comprised an accurate electromechanical actuator, a load cell that

Pressure, a piezometer for collecting sample pore pressure data, a strain gauge for collecting sample strain data, software for data calculation, and a personal computer.

The sample used in the cyclic triaxial test was molded to a diameter of 70 mm and a height of 140 mm. The sample was formed using a five-layer compaction with a dry unit weight of 13.43 kN/m^3. The sample molding method was divided into two types—that is, untreated and agar-gum-treated samples. The untreated sample was molded by mixing distilled water corresponding to a water content of 25 % compared with that of the dried soil. The agar-gum-treated sample was molded by mixing an aqueous solution of agar gum that corresponded to 25 % of the water content of the dried soil. After heating the agar gum aqueous solution to dissolve the agar gum powder completely in the distilled water, the sample was molded to obtain a homogeneous mixture by mixing it with dried soil. Additionally, to prevent gelation of the agar gum aqueous solution during the sample molding process, the temperature was maintained at 60 °C during the mixing and molding processes.

In this study, the liquefaction resistance strength based on the agar gum concentration and the long-term liquefaction resistance strength of agar gum were evaluated. To analyze the liquefaction resistance strength based on the agar gum concentration, experiments were conducted at the concentrations of 0 %, 2 %, 4 %, and 6 % agar gum. Additionally, to analyze the long-term reinforcing effect of the agar-gum-treated samples, experiments were conducted for 1/8, 7, and 28 days of curing at an agar gum concentration of 4 %, and the samples were cured by wet curing. The experimental conditions used for the cyclic triaxial tests are listed in Table 3.

The sequence of cyclic triaxial tests consisted of sample saturation, sample consolidation, and deviator stress loading. After the molded sample was placed in the cell, the membrane was wrapped and the sample was saturated by injecting water using a back-pressure pump. Complete saturation was confirmed using Skempton's B value. If the B value was 0.95, the sample saturation step was complete. Following saturation, consolidation of the sample was performed. The confining stress during consolidation was generally 100 kPa [49,50]; therefore, the confining stress during consolidation in this study was set to 100 kPa—that is, consolidation was performed by setting the difference between the back and cell pressures to 100 kPa using a cell pressure pump. Consolidation was performed until the sample volume remained unchanged. Subsequently, an actuator was used to load the deviator stress in the form of a sine wave. For the load control form, the deviator stress was loaded through stress control and the frequency used was 0.1 Hz. The experiment was terminated when the number of loading cycles reached 500 or the axial strain of the sample exceeded 5 % [51]. In the cyclic triaxial test, more than three experiments are required to calculate the CRR. Consequently, the three samples were molded under the same conditions and tested three times at different deviator stresses.

3. Experimental results

3.1. Viscosity

The viscosity of the aqueous agar gum solution was measured to determine the change in viscosity as a function of the shear rate. Fig. 4 illustrates the viscosity of the agar gum aqueous solution as a function of the shear rate at different concentrations. At all concentrations, that is, 2 %, 4 %, and 6 %, the viscosity of the agar gum aqueous solution decreases rapidly as the shear rate increases and then tends to converge to a constant value. Additionally, as the concentration of the agar gum aqueous solution increases, the viscosity increases—that is, the viscosity of the aqueous agar gum solution increases at increasing concentrations. Additionally, it behaves as a non-Newtonian fluid whose viscosity changes based on the shear rate at all concentrations; the increase in viscosity coincides with an increase in strength and hardness based on the agar gum concentration when the temperature of the agar gum aqueous solution is lowered to form a gel. It also exhibits the general tendency of non-Newtonian fluids according to which viscosity decreases at increasing shear rates.

3.2. Unconfined compressive strength

The unconfined compressive strength test was conducted to determine the compressive strength of the agar gum gel. The results are shown in Fig. 5. The experimental results confirm that the unconfined compressive strength also increases as the concentration of agar gum increases, thus indicating that as the concentration increases, the agar gum gel forms a hydrogel with a denser structure that results in a higher unconfined compressive strength.

3.3. Determination of penetration depth using fall-cone tests

The fall-cone test was conducted to determine the hardness of the agar gum gel. The cone penetration depth was determined based on the curing times of 1/8, 7, and 28 days at the agar gum gel concentrations of 2 %, 4 %, and 6 %, the hardness of the agar gum gel was determined based on the agar gum concentration and curing time. Fig. 6 shows the cone penetration depth plots of the agar gum gel at different concentrations.

Fig. 6 shows the cone penetration depth based on curing times, thus confirming that the cone penetration depth decreases as the concentration of agar gum increases. These results suggest that as the concentration of agar gum increases, the hardness of the agar gum gel also

Table 3
Experimental conditions of the cyclic triaxial test.

Solution Content W_{sol}/W_s [%]	Experimental Temperature [C°]	Consolidation Stress [kPa]	Concentration [%]	Curing Times [days]	Deviator Stress [kPa]
25	25	100	0	0	30
					40
					50
			2	1/8	50
					60
					70
			4	1/8	70
					80
					90
				7	70
					80
					90
				28	70
					80
					90
			6	1/8	80
					90
					100

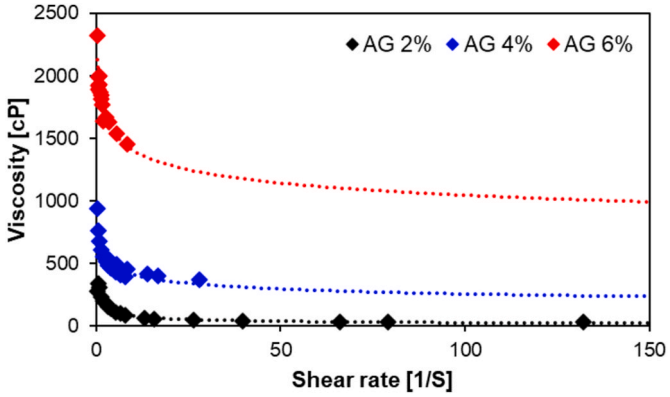

Fig. 4. Viscosity plots of aqueous agar gum solution as a function of the shear rate at different concentrations.

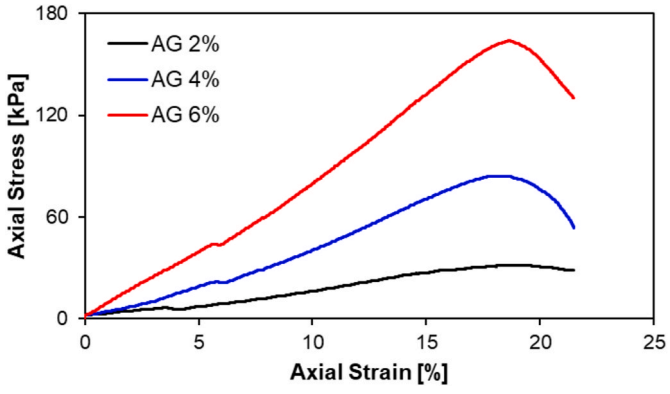

Fig. 5. Unconfined compressive strength of agar gum gel.

increases. Additionally, the agar gum gel can maintain the same hardness from 1/8 to 28 days as there is no difference in the cone penetration depth based on the curing time.

3.4. Cyclic triaxial tests

Cyclic triaxial tests were conducted based on the agar gum concentration, curing time, and deviator stress (Table 3). Fig. 7 shows the cyclic triaxial test of the 2 % agar-gum-treated sample vs. the untreated sample

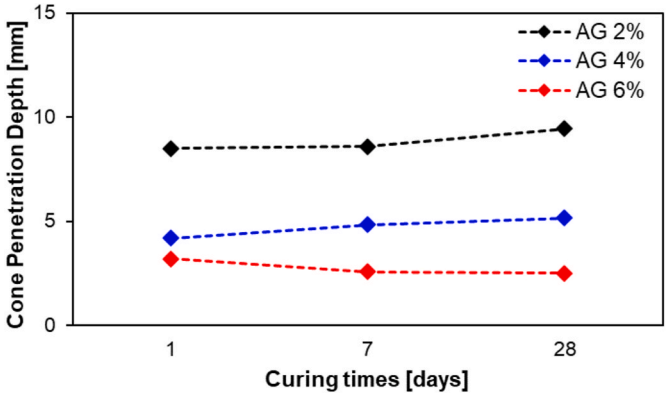

Fig. 6. Cone penetration depth of agar gum gel as a function of curing times at different concentrations.

(deviator stress = 50 kPa).

Fig. 7(a) shows the axial strain vs. the number of cycles. Both the agar-gum-treated (2 %) and untreated samples exhibit a tendency based on which the axial strain increases as the number of cycles increases. The untreated and agar-gum-treated (2 %) samples reached an axial strain of 5 % after 7 and 88 cycles, respectively. This means that the agar-gum-treated sample has higher liquefaction resistance than the untreated sample. Fig. 7(b) shows the plots of excess pore pressure vs. the number of cycles. Both the agar-gum-treated (2 %) and the untreated samples tend to lead to excess pore pressure increases as the number of cycles increases. However, for the untreated sample, the excess pore pressure increases by nearly 100 kPa after 7 cycles, whereas that of the 2 % agar-gum-treated that the agar-gum-treated sample has higher liquefaction resistance than the untreated sample. Additionally, the occurrence of a low excess pore pressure suggests that the degree of liquefaction of the ground is low. Fig. 7(c) shows the plots of the deviator stress vs. axial strain. The agar-gum-treated (2 %) and untreated samples exhibit a tendency for the axial strain to increase gradually as the deviator stress is applied. However, the untreated sample exhibits more deformation in the direction of compression than the 2 % agar-gum-treated sample. Fig. 7(d) shows the plots of q vs. p'. The 2 % agar-gum-treated and untreated samples exhibit a tendency according to which the effective stress decreases as the deviator stress is loaded. However, in the untreated sample, the effective stress decreases to values close to 0 kPa, whereas in the 2 % agar-gum-treated sample, it decreases to approximately 15 kPa. Based on this, the agar-gum-treated sample has a residual

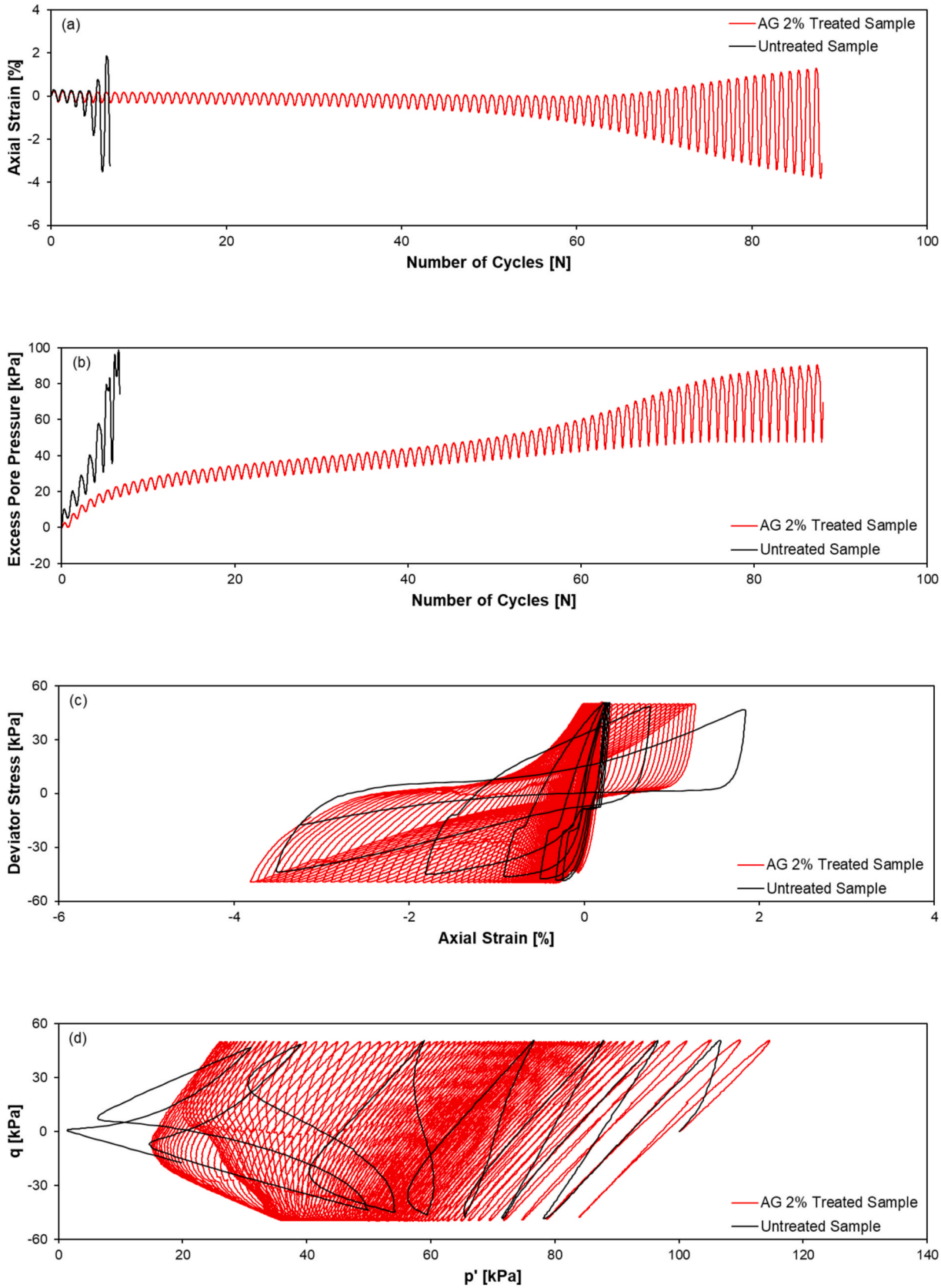

Fig. 7. Cyclic triaxial test of 2 % agar-gum-treated vs. untreated samples. Plots of (a) axial strain vs. number of cycles, (b) excess pore pressure vs. number of cycles, (c) deviator stress vs. axial strain, and (d) q vs. p'.

effective stress, unlike the untreated sample. The existence of residual effective stress in the agar-gum-treated sample means that the treatment of the agar gum increases the resistance to liquefaction.

Treatment with agar gum increases the physical strength of the sample such that liquefaction occurs after an increased number of loading cycles (even though the same deviator stress loading was applied), thus increasing the liquefaction strength. The excess pore pressure of the 2 % agar-gum-treated sample increases to a value that is smaller than that of the untreated sample, and the effective stress decreases to values that are smaller in the 2 % agar-gum-treated than in the untreated sample, thus resulting in residual effective stress. This means that the agar gum forms a hydrogel between the soil particles to increase the binding force between them, thereby preventing an increase in the excess pore pressure and a decrease in the effective stress. These results suggest that the agar gum treatment effectively prevents liquefaction.

To confirm the dynamic behavior based on the agar gum concentration, the results of the cyclic triaxial test of the 6 % and 2 % agar-gum-treated samples were compared. The 6 % agar gum-treated sample was tested using a deviator stress of 90 kPa, and the 2 % agar-gum-treated sample was tested at a deviator stress of 60 kPa. Fig. 8 illustrates the cyclic triaxial test results for the agar gum 6 % treated sample and the 2 % agar gum-treated sample.

Fig. 8(a) shows the axial strain vs. the number of cycles. The agar-gum-treated samples (6 % and 2 %) reach the 5 % strain values at 33 and 13 cycles, respectively. The 6 % agar-gum-treated sample reaches the 5 % strain value after a higher number of cycles, even though the experiment was conducted with a deviator stress that was 1.5 times higher than that of the 2 % agar-gum-treated sample. Fig. 8(b) shows the excess pore pressure vs. the number of cycles. The excess pore pressure (approximately equal to 88 kPa) of the 6 % agar-gum-treated sample was reached after approximately 33 cycles, whereas that of the 2 % agar-gum-treated sample was approximately 92 kPa and was reached after 13 cycles. Fig. 8(c) shows the deviator stress vs. axial strain. The compressive strain of the 6 % agar-gum-treated sample is considerably lower than that of the 2 % agar-gum-treated sample. Fig. 8(d) shows the plots of q vs. p'. The effective stress of the 6 % agar-gum-treated sample drops to approximately 16 kPa, while that of the 2 % agar-gum-treated sample drops to approximately 14 kPa. In the case of the sample treated with 6 % agar gum, a deviator stress was applied which was equal to 1.5 times that of the sample treated with 2 % agar gum. However, the axial strain reached the 5 % value after a larger number of cycles in the case of the sample treated with 6 % agar gum. In addition, the strain in the compression direction was significantly reduced in the sample treated with 6 % agar gum even though the applied deviator stress was 1.5 times greater than that of the sample treated with 2 % agar gum. These findings show that as the concentration of agar gum increases, the binding force of soil particles increases, and the physical strength of the sample increases. In addition, it can be observed that the density of the hydrogel formed between soil particles increased, thus resulting in higher liquefaction resistance even though a higher deviator stress was applied. These results suggest that the higher the concentration of agar gum is, the more effective it is in preventing liquefaction.

4. Analysis and discussion

4.1. Concentration effects of agar gum on the cyclic resistance ratio (CRR)

The liquefaction resistance strength of the samples could be determined by calculating the CRR using the cyclic shear ratio (CSR) from a stress-control-based cyclic triaxial test. CSR can be calculated using Equation (1). To calculate CRR_{15}, three experiments were conducted on each sample, and CRR_{15} was calculated as the CSR which corresponded to 15 cycles.

$$CRS = \frac{\pm\sigma_{dc}}{\sigma'_{3c}} \quad (1)$$

where $\pm\sigma_{dc}$ denotes the cyclic deviator stress, and σ'_{3c} denotes the effective isotropic consolidation stress.

The liquefaction resistance strengths of the untreated and agar-gum-treated samples were compared to determine their effects on the liquefaction resistance of the agar gum. First, cyclic triaxial tests were conducted on agar gum at the concentrations of 2 %, 4 %, and 6 % to determine the change in liquefaction resistance strength based on the agar gum concentration. Fig. 9 illustrates the liquefaction resistance curve based on the agar gum concentration. The agar-gum-treated sample yields a liquefaction resistance curve exhibiting higher values than those in the respective curve of the untreated sample. Additionally, as the concentration of the agar gum increases, the liquefaction resistance curve increases. Fig. 10 shows the normalized CRR_{15} as a function of the agar gum concentration. The CRR_{15} of the agar-gum-treated sample is higher than that of the untreated sample, and as the concentration of agar gum increases, the CRR_{15} also increases.

Agar gum treatment exhibits an increase in liquefaction resistance strength of approximately 1.44–2.23 compared with that of the untreated sample. As the concentration of agar gum increases, the strength of the resistance to liquefaction increases; and as the concentration of agar gum increases, the content of agar gum per unit volume of the sample increases. This increases the physical strength of the agar gum and the binding force between the soil particles. Additionally, as the concentration of agar gum increases, a dense agar gum hydrogel forms; this creates a denser network in the voids of the sample, suppresses the increase in excess pore pressure and decreases the effective stress of the agar-gum-treated sample. The action of the agar gum soil particles is effective in improving the liquefaction resistance strength. Consequently, increasing the concentration of agar gum increases the liquefaction resistance.

4.2. Curing time effect of agar gum on the CRR

Reinforcement applied to prevent liquefaction is not only important for increasing the resistance strength but is also responsible for maintaining the resistance strength for a long time. Consequently, to determine whether agar gum treatment influences long-term strength, cyclic triaxial tests were conducted at the curing times of 1/8, 7, and 28 days at a 4 % agar gum concentration. Fig. 11 shows the liquefaction resistance curves of the agar-gum-treated samples with respect to the curing time. The deviator stress was set at 70 kPa, 80 kPa, and 90 kPa. Fig. 12 shows the plots of CRR_{15} with respect to the curing time of the agar-gum-treated samples.

The results of the experiment with the same deviator stress show that the samples treated with agar gum exhibit similar CRR_{15}, regardless of the curing time. Although there are slight differences depending on the curing time, the agar-gum-treated samples exhibit a considerably higher CRR_{15} than the untreated samples—that is, they lead to improvements which are 1.81–1.97 times the liquefaction resistance compared with the resistance of the untreated samples. At the agar gum concentration of 4 % in Fig. 6, the cone penetration depth according to the curing times remains constant. Additionally, in Fig. 12, it can be observed that CRR_{15} is maintained according to the curing times at 4 % agar gum concentration. Therefore, it can be confirmed that the cone penetration depth and CRR_{15} are maintained linear regardless of the curing period. Additionally, as a result of the unconfined compressive strength study, it was confirmed that the unconfined compressive strength of the agar-gum-treated sample under submerged conditions remained constant regardless of the curing times and that it had a significantly higher unconfined compressive strength than that of the untreated sample [46]. This shows that CRR_{15} maintains its strength consistently regardless of the curing times. Consequently, the agar gum maintains the binding force of the

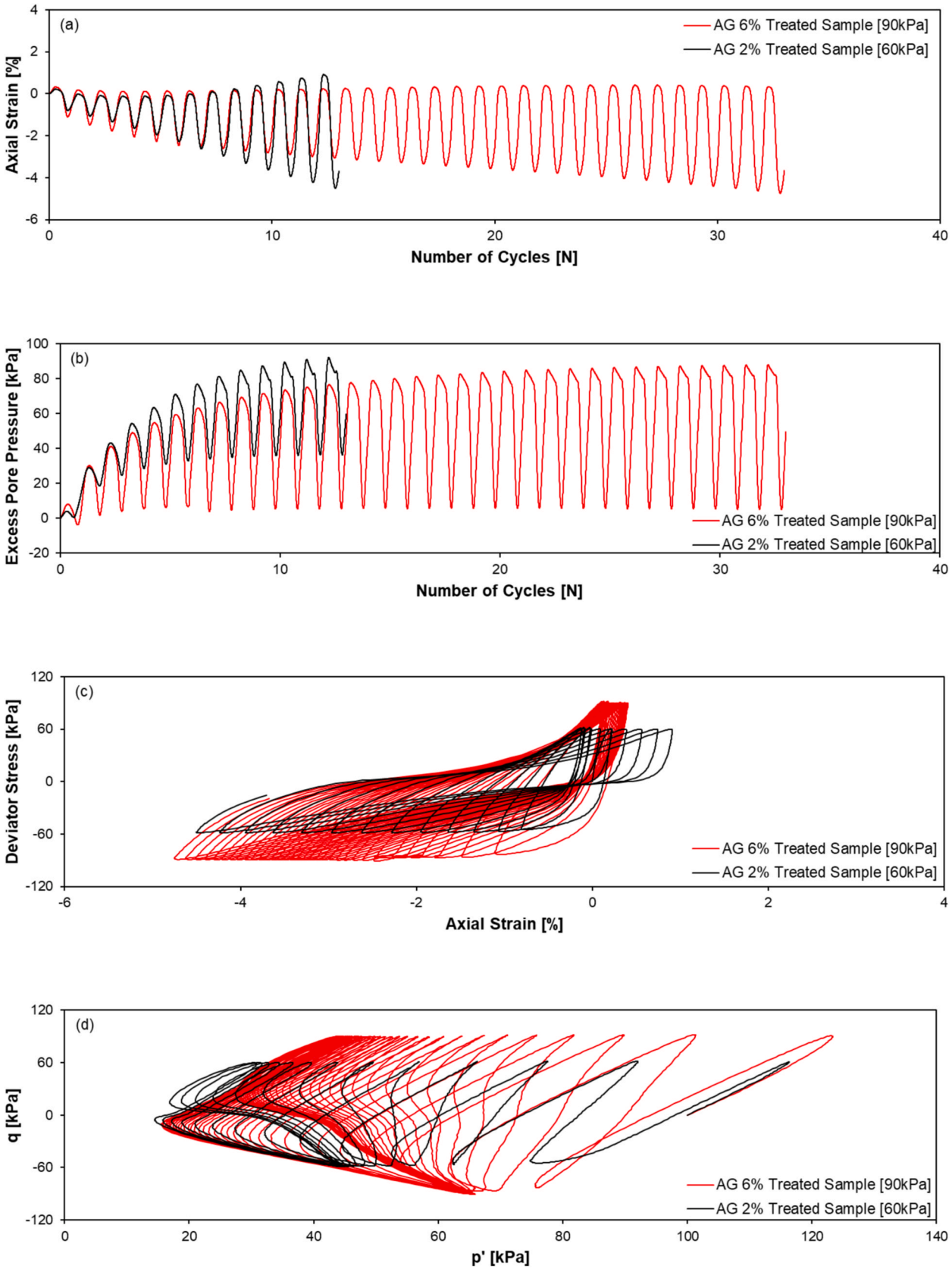

Fig. 8. Cyclic triaxial tests of 6 % vs. 2 % agar gum-treated samples. Plots of (a) axial strain vs. number of cycles, (b) excess pore pressure vs. number of cycles, (c) deviator stress vs. axial strain, and (d) q vs. p'.

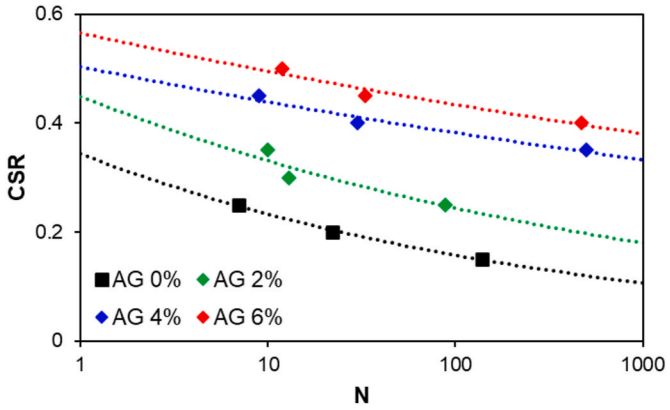

Fig. 9. Liquefaction resistance curve based on the agar gum concentration.

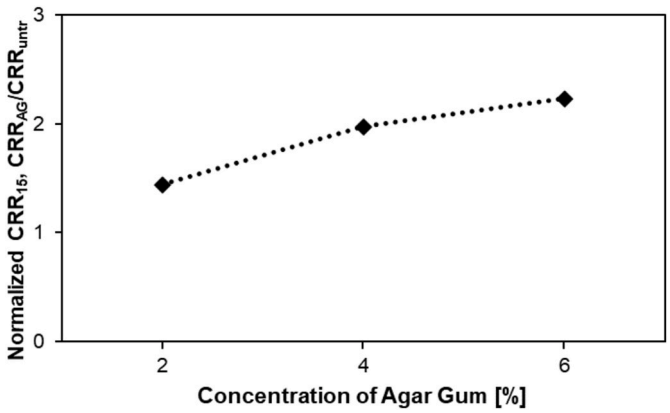

Fig. 10. Normalized CRR_{15} based on the agar gum concentration.

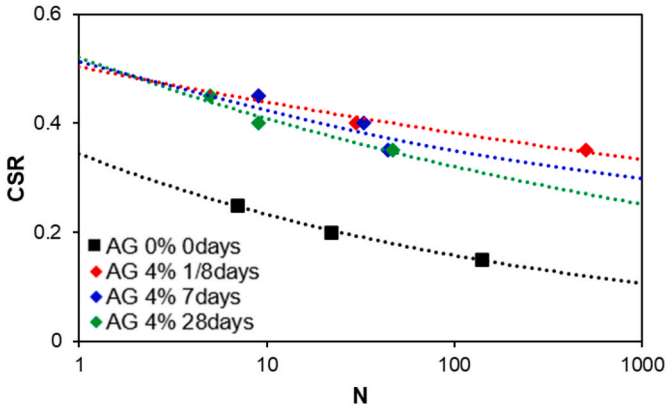

Fig. 11. Liquefaction resistance curve based on the curing times of the agar-gum-treated samples.

soil particles for a long time. Additionally, the hydrogel formed in the sample established a network for a long time without elution or falling off, and thus suppressed the increase in excess pore pressure and decreased the effective stress of the agar-gum-treated sample to prevent liquefaction. These findings suggest that the agar gum is effective in improving long-term liquefaction resistance.

4.3. Mechanism of agar gum properties

Agar gum has thermogelling properties [26,32,41–43,48]. As shown in Fig. 3, when heat is applied, agar gum dissolves and exists in a sol

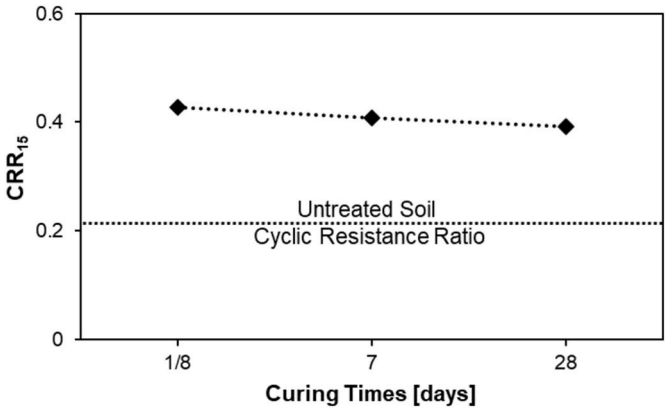

Fig. 12. CRR_{15} based on the curing times of the agar-gum-treated samples.

state, and when the temperature falls below a certain temperature, it forms a gel. The formed agar gum gel (as shown in Fig. 5) has its strength. In addition, when reinforced in the ground, it improves strength by increasing the bonding force between soil particles [26,29,32,43]. As the aqueous agar gum solution gels below a certain temperature, maintaining this solution at a high temperature (so that it does not gel) and reinforcing the ground are effective measures to improve strength [46].

Agar gum has the property of increasing strength as concentration increases [26,29,32,43,46]. Fig. 13 shows unconfined compressive strength and CRR_{15} according to agar gum concentration. Based on this, it can be observed that as the concentration of agar gum increases, the unconfined compressive strength and CRR_{15} also increase. As the concentration of agar gum increases, a denser hydrogel is formed with greater bonding between soil particles, and the unconfined compressive strength increases. Additionally, as the concentration of hydrogel increases, the void in the soil is filled more densely, thus preventing an increase in excess pore pressure. This results in a higher CRR_{15} as the concentration of agar gum increases.

Agar gum has the property of increasing viscosity as its concentration increases. As shown in Fig. 4, as the concentration of agar gum increases, the viscosity also increases. Considering the injection characteristics, as the viscosity of the fluid increases, injection becomes more difficult [24]. However, the viscosity properties of agar gum show a tendency toward shear thinning, with the apparent viscosity decreasing as a function of shear rate [35]. Analysis of the change in shear rate in the fluid flow within the void will result in a relatively low viscosity value during high-pressure injection by utilizing the parameters of apparent viscosity and the characteristics of injection pressure and shear thinning [35,52]. Therefore, the 2 % aqueous agar gum solution is expected to be injected into the ground at a high pressure owing to its shear-thinning

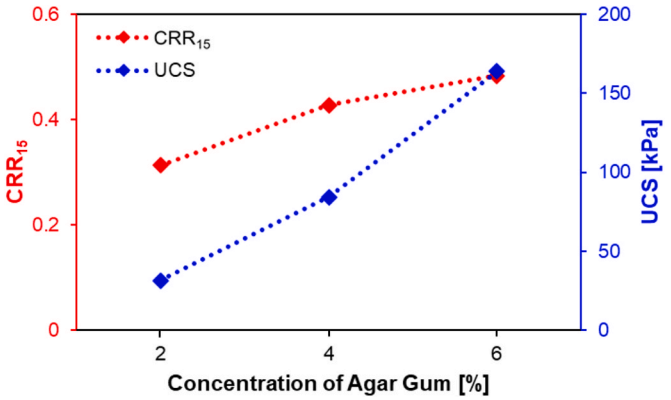

Fig. 13. Plots of CRR_{15} and UCS as a function of the agar gum concentration.

properties. However, it is thought that it will be difficult to completely inject high-viscosity fluids, such as 4 % or 6 % aqueous agar gum solutions, into the ground. Therefore, it is necessary to consider using injection methods of high-viscosity suspension-type injection materials, such as cavity filling, deep-cement mixing, and vibration methods, or adding additives to lower the viscosity [24,53].

4.4. Comparison of agar gum with other reinforcement materials

As interest in the environment has increased, numerous eco-friendly liquefaction prevention methods have been developed. Consequently, liquefaction reinforcement was studied using various eco-friendly injection materials and the CRR_{15} was calculated using cyclic triaxial tests.

Fig. 14 shows the CRR_{15} based on the eco-friendly reinforcement type, thus making it possible to confirm the enhancement effect of the CRR_{15} for each concentration of eco-friendly reinforcing materials. In the case of colloidal silica grouting, the liquefaction resistance strength increases by approximately 1.52–1.86 times compared with that of the untreated sample [54]; in the case of highly diluted colloidal silica grouting, the liquefaction resistance strength increases by approximately 1.29–1.59 times compared with that of the untreated sample [55]; in the case of bentonite suspension grouting, the liquefaction resistance strength increases by approximately 1.14–1.36 times compared with that of the untreated sample [56]; in the case of laponite treatment, the liquefaction resistance strength increases by approximately 1.68 times compared with that of the untreated sample [23]; in the case of biocementation, the liquefaction resistance strength increases by approximately 1.14–1.36 times compared with that of the untreated sample [57]; and in the case of agar gum treatment, the liquefaction resistance strength increases by approximately 1.44–2.23 times compared with that of the untreated sample.

Fig. 15 shows the CRR_{15} using the concentration calculation based on the soil weight. This shows that, like other eco-friendly reinforcing materials, the liquefaction resistance strength increases as the concentration of agar gum increases. Therefore, agar gum treatment is effective in preventing liquefaction. As a result, agar gum can be expected to have potential as an eco-friendly ground reinforcement material.

5. Conclusions

In this study, the viscosity, unconfined compressive strength, and hardness of agar gum were measured. Additionally, the liquefaction resistance strength was evaluated (using a cyclic triaxial test) by reinforcing the ground with an agar gum biopolymer, an eco-friendly material. The following conclusions could be drawn.

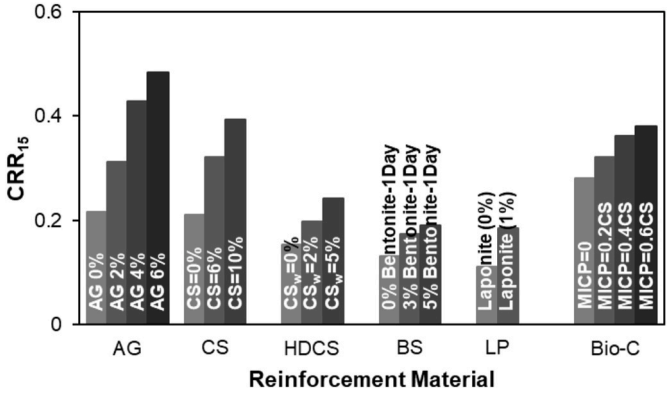

Fig. 14. CRR_{15} values based on the eco-friendly reinforcement type (AG: agar gum, CS: colloidal silica grouting, HDCS: high-diluted colloidal silica grouting, BS: bentonite suspension grouting, Bio-C: biocementation, LP: laponite).

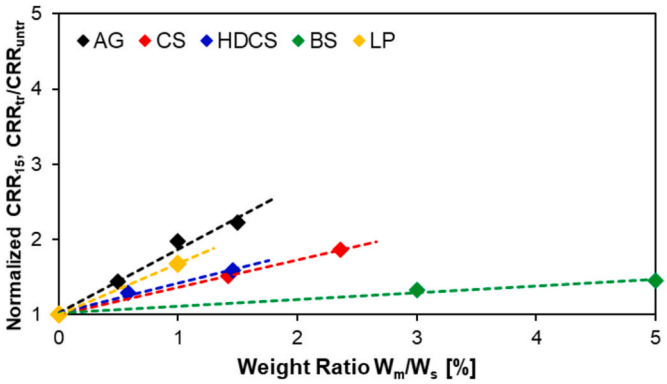

Fig. 15. Plots of normalized CRR_{15} as a function of the weight ratio based on the concentration calculation by soil weight.

1) All the agar gum aqueous solutions tended to be non-Newtonian fluids, and as the shear rate increased, the viscosity decreased rapidly and tended to converge to a constant value. Additionally, as the concentration of the agar gum aqueous solution increased, the viscosity increased.
2) In the case of gel-state agar gum, as the concentration of the agar gum increased, the unconfined compressive strength increased and the cone penetration depth decreased. Additionally, agar gum gels of the same concentration have similar cone penetration depths from 1/8 to 28 days. Accordingly, it can be demonstrated that as the concentration of agar gum increases, it has higher physical strength and hardness, and also maintains hardness for a long period.
3) In the cyclic triaxial test, the agar-gum-treated sample exhibited deformation at higher deviator stress than the untreated sample. Additionally, the magnitude of the strain in the compression direction appeared to be extremely small, and the increase in excess pore pressure and dissipation of the effective stress were suppressed. This result indicated that treatment with agar gum increased the physical strength of the sample by increasing the binding force of the soil particles, the strength of the agar gum hydrogel generated in the sample increased the resistance to liquefaction. Consequently, treatment with agar gum could prevent the complete loss of effective stress, thus suggesting that the agar gum was effective in preventing liquefaction.
4) As a result of the evaluations of CRR_{15} of agar gum-treated samples, CRR_{15} also increased as the concentration of agar gum increased. Additionally, it was confirmed that there was almost no change in CRR_{15} depending on the curing period. This suggests that as the concentration of agar gum increases, a denser hydrogel is formed per unit volume, thus increasing the bonding force and strength of soil particles; correspondingly, the agar gum treatment maintains liquefaction resistance strength over a long period.
5) Comparisons of the CRR_{15} of the agar gum-treated sample with other reinforcing materials showed that the agar gum treatment was as effective in preventing liquefaction as other reinforcing materials. Consequently, agar gum could be used as an eco-friendly ground-reinforcement material to prevent liquefaction.

CRediT authorship contribution statement

Chaewoon Jang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Beomjoo Yang:** Validation, Writing – review & editing. **Won-Taek Hong:** Methodology, Project administration, Resources, Supervision. **Jaehun Ahn:** Methodology, Project administration, Resources, Supervision. **Jongwon Jung:** Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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