IMPROVEMENT OF LIQUEFACTION RESISTANCE OF RECLAIMED SAND IN WATER — AN EXPERIMENTAL STUDY

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ABSTRACT

This study identified mechanical properties, liquefaction mechanisms and improvement effects of cement treated sand during sedimentation in water. In this study, an optimum ratio pattern of cement treated sand to untreated reclaimed sand was established for land reclamation or liquefaction prevention. Danang sand was the primary backfill material. The water sedimentation method was utilized to prepare soil specimens under different contents of cement and coagulant and curing times. A series of unconfined compression tests and cyclic triaxial tests was carried out. Experimental results demonstrate that the unconfined compression strength of cement treated sand was decreased significantly as cement and sand particles separated during backfilling into water. However, by adding polyacrylamide as a coagulant to cement treated sand, the loss of unconfined compression strength was reduced effectively. The main contribution of this study is the application of polyacrylamide to cement treated sand for land reclamation in water. Under 6% cement content, 344 mg/kg coagulant content (polyacrylamide) and curing time of 28 days, the seismic capacity of this cement treated sand on the seismic intensity scale was 6 for Taiwanese standards.

Key words: Liquefaction, cement treated sand, coagulant, cyclic resistance.

1. INTRODUCTION

Due to the high population densities and the rapid economic growth in Taiwan, the land reclamation has become common to obtain enough land. The hydraulic reclamation method is the primary land reclamation method in Taiwan. However, the backfilled soil layers generated by hydraulic reclamation are very loose. These loose sandy soil layers are easy to liquefy during earthquakes. Therefore, ground improvement becomes an important item during construction. In the other word, if the backfilled soil layers are strong enough and difficult to liquefy, the following ground improvement will not be necessary. To achieve this purpose, adding cement to soil will be an ideal method during reclamation. This is so called the Premixing Method.

However, due to the size differences of sand and cement particles, the cement and the sand particles will separate when backfilled into water. This phenomenon may decrease the shear strength and cyclic resistance (CR) of cement treated sand significantly. Therefore, adding a coagulant to cement treated sand may reduce the separation of cement and sand particles via bridging and adsorption, and increase shear strength and cyclic resistance. Thus, this study carried out a series of unconfined compression tests and cyclic triaxial tests by controlling cement content and curing time while using different coagulants. This study discusses the mechanical properties of cement treated sand and assesses the effectiveness of improvements to untreated reclaimed sand via these factors. The goal is to generate an optimum method for improving cement treated sand for backfill in water.

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2. PREMIXING METHOD

Engineering technology for the Premixing Method was developed in 1989 by Japan's Coastal Development Institute of Technology. This method mixes soils (usually sands) with a small amount of cement and coagulant to produce cement treated sand. This cement treated sand can then be backfilled into the sea and form stable artificial land. The technical manual for the Premixing Method (2000) states that this method has the following advantages:

1. Secondary ground improvements are not needed after backfilling cement treated sand; thus, the construction period can be shortened.
2. A soil-transport ship can be used directly for a large-scale land reclamation.
3. The strength of artificial land can be set within a predefined range.
4. Some existing facilities can be used directly, as no special equipment is needed.
5. In addition to preventing liquefaction, this method also reduces lateral earth pressure. Therefore, this method increases economic efficiency.

However, the Premixing Method has the following shortcomings:

1. Improvement effects by different sands differ significantly.
2. Improvement materials, such as cement and coagulant, are expensive.
3. Backfilling with this method will pollute surrounding water.
4. This method can only be used to reclaim land or backfilling on the ground.

3. MECHANICAL PROPERTIES OF CEMENT TREATED SOILS

3.1 Influence of Cement Content

Zen (1990) carried out a series of cyclic triaxial tests on cement treated sand. When double amplitude axial strain of the cement treated specimen exceeded 5%, Fig. 1 showed the relationship between the cyclic stress ratio (CSR) and number of cycles. The cyclic stress ratio increased significantly when 2% cement was added. Although the experimental results in Fig. 1 was not sure to address liquefaction, 5% cement should be recognized as an appropriate amount for transforming loose sand into a non-liquefaction material in engineering practices.

Zen (1994) suggested that an unconfined compression strength of 98 kPa for cement treated sand can be regarded as a non-liquefaction index.

Notably, cement treated sand can prevent liquefaction caused by earthquakes. However, most studies did not consider the separation of cement and sand particles during backfilling in water. Although based on commercial considerations, the technical manual for the Premixing Method does not explicitly mention the coagulant composition, optimum coagulant dosage or chemical reaction among cement, sand, and coagulant. However, coagulant type and content are the most important factors for success or failure in improving the effectiveness of cement treated sand. Therefore, this study carried out a series of interrelated experiments to identify the best coagulant and optimum coagulant dosage.

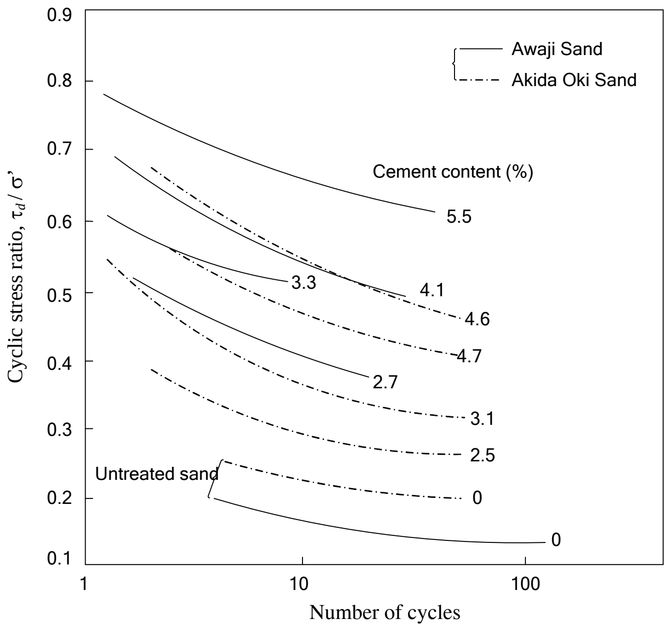


Fig. 1 The relationship between cyclic stress ratio and number of cycles (Zen 1990)

3.2 Influence of the Coagulation Mechanism

In this study, the idea used for selecting coagulants originated from the coagulation, flocculation, and precipitation reactions in the wastewater treatment process. During the treatment process, coagulants and flocculants are added to encourage precipitation of suspended materials and obtain potable water. If an appropriate coagulant is added to cement treated sand, the separation of cement and sand particles can be reduced by adsorption and coagulant bridging; thus, the cement and sand particles will precipitate together. This method will increase the strength of cement treated sand. Generally, aluminum salts, ferric salts, or polymeric flocculants are the three principal categories of coagulants used in wastewater treatment. The coagulation mechanisms of these coagulants are described in the following section.

Liou (2006) described the coagulation mechanisms of aluminum salts and ferric salts as follows.

1. Aluminum salts

Due to its cheapness and non-toxicity, aluminum sulfate is the most common aluminum salt in the conventional coagulation process. The primary coagulation mechanism of aluminum sulfate is sweep flocculation, and the subsequent coagulation mechanisms are adsorption and electrical-charge neutralization. The suitable pH range for aluminum sulfate application is roughly 6 ~ 7.8. However, floccules produced by the coagulation process of aluminum sulfate are extremely light. Moreover, when the amount of sodium salts or potassium salts in water exceeds a threshold, floccules are destroyed into very small particles that cannot precipitate.

2. Ferric salts

The coagulation mechanism of ferric salts is generally the same as those of aluminum salts. When pH exceeds 6, sweep flocculation is the principal coagulation mechanism for ferric salts; when pH is ≤ 6, the primary coagulation mechanisms of ferric salts are adsorption and destabilization. The suitable pH range is about 4 ~ 10. Compared with that of aluminum salts, the suitable pH range for ferric salts is wider.

Feng *et al*. (2002) identified the reaction principle of organic polymeric flocculants in a cement paste system via analysis of the flocculation mechanism. On the one hand, organic polymeric flocculants (*e.g.*, propylene flocculants containing the hydroxyl functional group) can be adsorbed onto cement particles through activated functional groups located in the long carbon chains of organic polymeric flocculants and, on the other hand, a molecule can adsorb a significant amount of cement particles. Therefore, bridging among cement particles can be constructed by organic polymeric flocculants, thereby promoting precipitation of floccules generated by cement particles and organic polymeric flocculants. Consequently, cement particles are not easily washed away or dispersed by surrounding water molecules.

According to experimental results obtained by Yan and Zhang (2008), Fig. 2 describes the synthesis of polyacrylamide (PAM). The polymer chain in PAM has large amounts of carboxyl and amino functional groups.

Figure 3 shows the reaction diagram of the PAM flocculation mechanism. Jiang *et al*. (2006) demonstrated that carboxyl functional groups can absorb calcium ions in cement via the coordination bonds (Fig. 3(a)). Liao (2000) determined that carboxyl functional groups can be absorbed onto soil particle surfaces via water bridging (Fig. 3 (b)) and amino functional groups can combine their hydrogen atom with oxygen in soil to form hydrogen bonds by bridging (Fig. 3 (c)); thus, PAM and soil particles can be combined to form floccules. Chen (2005) noted that calcium ions produced by cement hydration can be used as a medium that bridges PAM and sand particles or PAM and itself to enhance PAM flocculation efficiency (Fig. 3(d)).

Jiang *et al*. (2007) carried out coagulation tests with wastewater generated from washing coal (wastewater contained large amounts of SiO_2 and Al_2O_3) by adding PAM and calcium carbide. They demonstrated that the isolation rate of freshwater from 500 mL wastewater was about 40% after adding a fixed dosage of solution which contained 6% calcium carbide solution in 50 mL and 1% PAM in 20 mL.

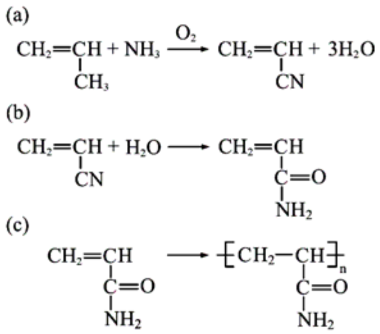
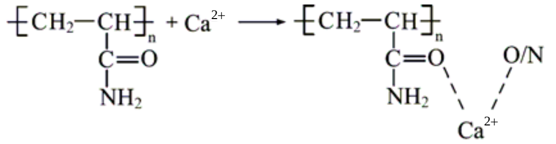
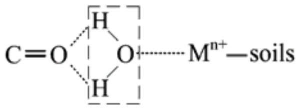


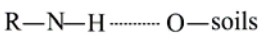
Fig. 2 The synthesis of polyacrylamide (Yan and Zhang 2008)



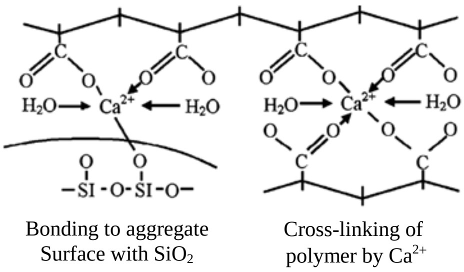
(a) The reaction diagram of coordination bond between carboxyl functional groups of PAM and calcium ions in cement (Jiang *et al.* 2006)



(b) The reaction diagram of adsorption between carboxyl functional groups and soils through the bridging of water molecule (Liao 2000)



(c) The reaction diagram of adsorption between amino functional groups and soils through the bridging of hydrogen bond (Liao 2000)



(d) The reaction diagram of the flocculation efficiency reinforced by calcium ions for PAM (Chen 2005)

Fig. 3 The reaction diagram of flocculation mechanism for polyacrylamide

According to these studies, both the carboxyl and amino functional groups are effective in bridging and adsorption between cement and sand particles, and promote simultaneous settling of cement and sand particles. Therefore, PAM can effectively resolve the problem of cement and sand particle separation during backfilling in water.

4. EXPERIMENTAL PROCEDURES

The test materials, experimental equipment, and test methods are described in the following sections.

4.1 Test Materials

Danang sand, a quartzose sand, was obtained from Vietnam. The Danang sand had been processed by crushing, such that the shape of sand grains was rounded to near subangular. Table 1 lists the basic physical properties of Danang sand. Figure 4 shows the grain-size distribution of Danang sand.

The type I Portland cement was obtained from the Taiwan Cement Corporation. In this study, cement content a_w (%) is defined as follows:

$$a_w(\%) = \frac{W_c}{W_s} \times 100 \quad (1)$$

where W_c is the mass of cement (g), and W_s is the mass of dry sand (g)

4.2 Specimen Preparation

This study designed a backfilling tube to simulate reclamation of land with cement treated sand in water. The backfilling tube was 230 cm high with an inner diameter of 17.4 cm. Specimen preparation was as follows.

1. The cement content was set to 1.0%, 2.0%, 3.0%, 4.0%, 6.0% and 8.0%.
2. This study utilized aluminum sulfate, ferrous sulfate, and PAM as coagulants. The coagulant solution concentration was 0.2%. Coagulant content is derived as follows:

$$a_f = \frac{W_f}{W_s} (\text{mg/kg}) \quad (2)$$

   where W_f is the mass of dry coagulant (mg), and W_s is the mass of dry sand (kg). The coagulant content was set at 0, 34, 86, 172, 344, 602 and 860 (mg/kg).
3. First, sand, cement, and water (mass ratio of water to sand was 15%) was mixed in a mixer. The coagulant was then added to the above cement treated sand and mixed for 20 min under a rotational speed of 100 rpm.
4. Second, the cement treated sand was dumped directly from the water surface. Cement treated sand was sampled after 24 hours. This preparation method is called the water sedimentation method. The specimen was 10 cm high and had a diameter of 5 cm.
5. After sampling, a cement treated sand specimen was placed into a tank for curing. Curing time (t_c) was 7, 14, 28 and 56 days.
6. Table 2 shows the basic physical properties of cement treated sand containing PAM.

4.3 Test Methods

To discuss the shear strength and dynamic properties of cement treated sand, this study carries out a series of unconfined compression tests and cyclic triaxial tests.

1. Unconfined compression test

Under different cement contents, curing times, and coagulant contents, a series of unconfined compression tests was carried out to determine the unconfined compression strength (q_u) of cement treated sand. According to ASTM D2166-00e1, the test compression rate was 0.5%/min.

2. Cyclic triaxial test

The cyclic triaxial test apparatus used in this study belongs to a stress control system, which can produce a sine wave axial

Table 1 The basic physical properties of Danang sand

D_{50} (mm)	0.26
Uniformity coefficient, C_u	2.10
Coefficient of gradation, C_c	1.13
Specific gravity, G_s	2.69
Maximum dry unit weight, $\gamma_{d,\max}$ (kN/m^3)	16.48
Minimum dry unit weight, $\gamma_{d,\min}$ (kN/m^3)	13.29
Maximum void ratio, $e_{\max}$	0.99
Minimum void ratio, $e_{\min}$	0.60

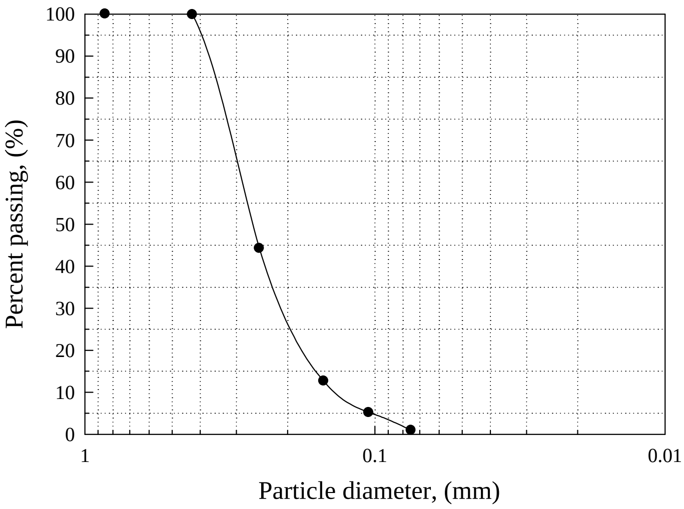


Fig. 4 The grain-size distribution of Danang sand

load at a frequency of 1.0 Hz by controlling the electronic pressure regulator. Cell pressure and back pressure (u_b) were 147 kPa and 98 kPa, respectively. Therefore, the initial confining pressure (σ_c) was 49 kPa. The axial load, axial displacement, and excess pore water pressure were measured simultaneously during the test process.

5. EXPERIMENTAL RESULTS AND ANALYSIS

5.1 Properties of Reclaimed Sand

Untreated reclaimed sand is typically very loose, and easily liquefied during earthquakes. However, adding a small amount of cement increases the cyclic resistance of reclaimed sand.

This study defines liquefaction as initial liquefaction status. In the cyclic triaxial test, when a specimen is initially liquefied under the action of a specific cyclic load, the cyclic resistance ratio (CRR) can be expressed as

$$\text{CRR} = \frac{\sigma_d}{2\sigma'_c} \tag{3}$$

where σ_d is the deviator stress (kPa), and σ'_c is the effective confining pressure (kPa). The number of cycles for reaching initial liquefaction is N_c.

In this study, the cyclic strength curve is the relationship curve of the cyclic resistance ratio to number of cycles (N_c) needed to reach initial liquefaction. The cyclic strength curve can be derived through inverse first-order polynomial regression using experimental data. When the number of cycles (N_c) needed to reach initial liquefaction is 15, the relative CRR is defined as cyclic resistance (CR).

Figure 5 compares the cyclic strength curves of untreated reclaimed sand, cement treated sand backfilled on land, and cement treated sand without coagulant reclaimed in water. The cyclic resistance of untreated reclaimed sand was very low; however, the cyclic resistance of cement treated sand backfilled on land increased significantly after adding 2% cement content. However, the cyclic resistance of cement treated sand without coagulant reclaimed in water declined dramatically. The reason for this phenomenon is that cement and sand particles in cement treated sand separated during the water sedimentation process (Fig. 6(a)). This phenomenon decreased the effect of cement on the strength development. Therefore, preventing separation of cement particles by adding coagulants is necessary.

5.2 Shear Strength of Cement Treated Sand

After adding cement to sand, sand pores fill with gels produced from cement hydration and these gels strengthen the structure of sand. Thus, the shear strength of sand increases. Conversely, the primary mechanisms of the coagulant are bridging and electrical-charge adsorption, which can cause cement and sand particles to be combined into a group, thereby reducing separation. To investigate this effect of cement treated sand, unconfined compression strength was measured and adopted as a basic indicator of the shear strength of cement treated sand.

1. Improvement effect of coagulant

Figures 6(a) ~ 6(d) compare differences in improvement effect to cement treated sand by adding different coagulant. Under a cement content of 4%, cement and sand particles in cement treated sand without a coagulant were almost completely separated into two layers (the upper layer was a cement layer and the lower layer was a sand layer) after sedimentation (Fig. 6(a)). The loss amount of cement that separated from cement treated sand contained aluminum sulfate or ferrous sulfate (coagulant content was 344 mg/kg) was slightly lower than that of cement treated sand without coagulant. Therefore, the improvement effect of cement treated sand via inorganic salts was insufficient. However, when PAM was used as a coagulant (coagulant content was 344 mg/kg), cement and sand particles did not separate nearly (Fig. 6(d)). This phenomenon means that the PAM is a better coagulant than inorganic salts for preventing cement and sand particle separation. The major reason is that the molecular weight of PAM is roughly $10^6 \sim 10^7$, much greater than that of aluminum sulfate or ferrous sulfate. The size of floccules generated by PAM was greater than those of inorganic salts. Notably, these floccules settle easily. Furthermore, in terms of the molecular pattern, the electrical charges of positive or negative ions in PAM were located on the surface of the long linear molecular chain. This pattern increased the effectiveness of electrical-charge adsorption and bridging and reduced separation of cement and sand particles. Therefore, PAM was adopted as the primary coagulant to examine the effects of coagulant on cement treated sand.

Notably, different coagulants generate entirely different results for the relationship between shear strength and strain for cement treated sand. The advantages and shortcomings of different coagulant were also determined by comparing the

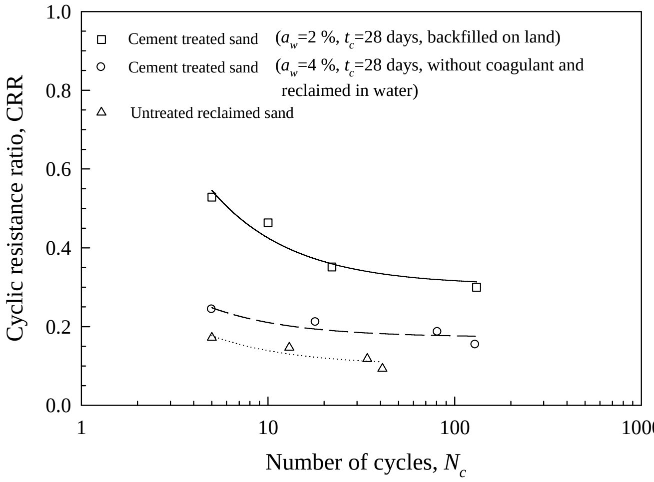
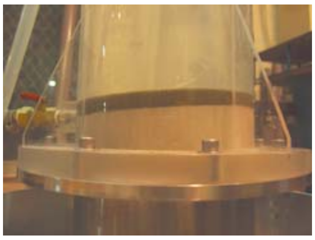
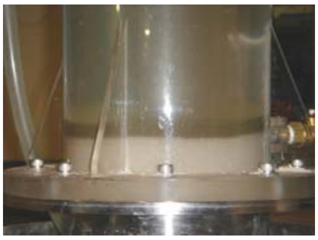


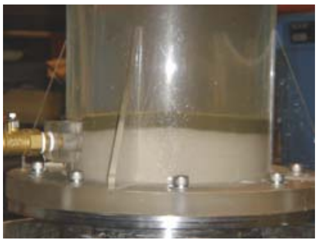
Fig. 5 The comparison among cyclic strength curves of untreated reclaimed sand, cement treated sand backfilled on land and cement treated sand without coagulant reclaimed in water



(a) Without coagulant



(b) Adding aluminum sulfate



(c) Adding ferrous sulfate

(d) Adding polyacrylamide

Fig. 6 The improvement effect of different coagulant type

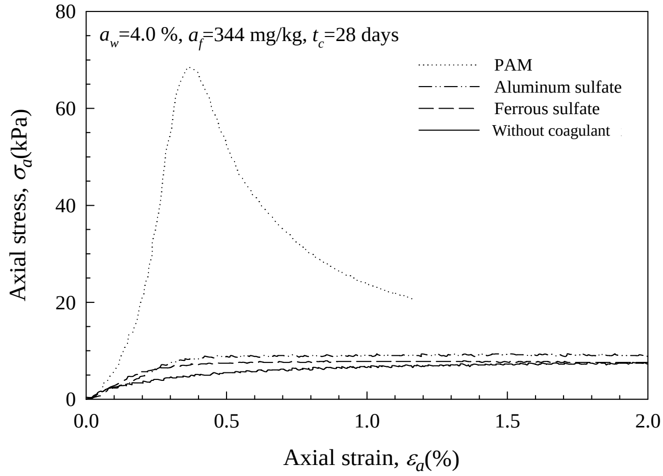


Fig. 7 The relationship between axial stress and axial strain of cement treated sand contained different coagulants

relationship between axial stress and axial strain from unconfined compression tests (Fig. 7). When no coagulant was added, the axial stress of cement treated sand increased initially as axial strain increased, and finally approached a specific value. No peak strength existed. When aluminum sulfate or ferrous sulfate was added, the experimental result was similar to that with no coagulant. The strength of cement treated sand containing aluminum sulfate or ferrous sulfate is slightly higher than that with no coagulant. However, when PAM was added, peak strength existed and its value was much larger than that of untreated reclaimed sand or cement treated sand containing other two coagulants.

The main reason for this finding is that PAM contains carboxyl and amino functional groups. These two functional groups can effectively increase shear strength and reduce cement loss during backfilling via bridging and electrical-charge adsorption, while the other two coagulants, aluminum sulfate and ferrous sulfate, do not have this effect. Furthermore, solution pH in the backfilling tube was about 11.7 after backfilling cement treated sand; this value exceeds the limits of aluminum salts and ferric salts. Hou *et al*. (2003) demonstrated that the molecular chains of PAM are prone to curl naturally in highly alkaline environments, which can easily result in sedimentation of PAM floccules. Therefore, the effectiveness of PAM for cement treated sand was better than that of aluminum salts or ferric salts; that is, cement treated sand containing PAM had the highest peak strength.

2. Relationship between unconfined compression strength and cement content

Figure 8 shows the variation in unconfined compression strength of cement treated sand. When the coagulant content of PAM was constant, unconfined compression strength of cement treated sand increased as cement content increased. The reason is that the source of unconfined compression strength of cement treated sand was mainly derived from cementation between cement and sand particles. Therefore, when the cement content increased, cementation increased, and the unconfined compression strength of cement treated sand increased. Furthermore, the increases of the unconfined compression strengths under different coagulant contents have a similar trend.

Additionally, to compare strength differences of cement treated sand in different backfilling scenarios (in water or on land), this study adopted the wet tamping method for specimen preparation, which represented reclamation of cement treated sand on land (without coagulant). The water sedimentation method was adopted to simulate land reclamation of cement treated sand in water. Unconfined compression strengths of cement treated sand for reclamation on land were much larger than those of reclamation in water (Fig. 9). Furthermore, as cement content increased, the difference in strength between the wet tamping method and water sedimentation method increased. On the other hand, experimental results demonstrate that the unconfined compression strength of cement treated sand without coagulant was decreased by over 80% as a result of separation of cement and sand particles after sinking in water. The loss ratio of strength (a_L) is defined as follows:

$$a_L = \frac{q_{u\_L} - q_{u\_W}}{q_{u\_L}} \times 100\% \quad (4)$$

where q_{u_L} is unconfined compression strength of cement treated sand backfilled on land, and q_{u_W} is unconfined compression strength of cement treated sand reclaimed in water.

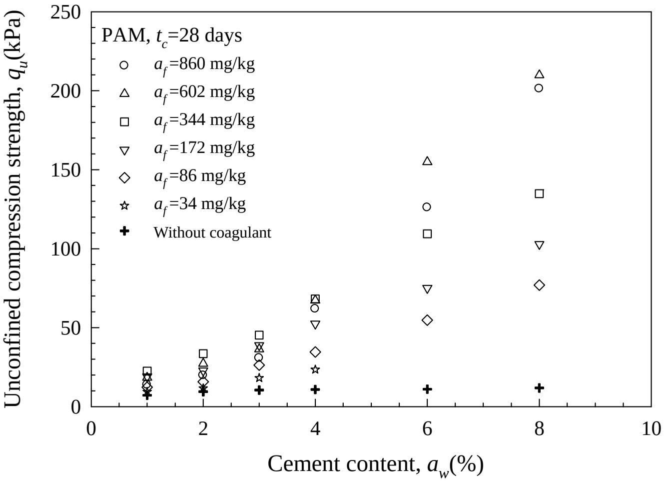


Fig. 8 The relationship between unconfined compression strength of cement treated sand and cement content

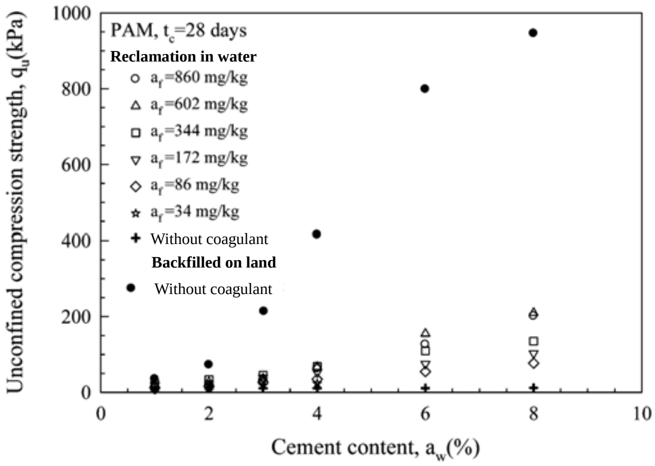


Fig. 9 The difference of unconfined compression strength of cement treated sand between backfilled on land and reclamation in water

Experimental data indicate that PAM effectively reduced the loss ratio for unconfined compression strength and had the lowest loss ratio of about 41% in this study (Fig. 10).

3. Relationship between unconfined compression strength and coagulant content of PAM

Figure 11 shows the relationship between unconfined compression strength and the coagulant content of PAM. Unconfined compression strength of cement treated sand initially increased and then decreased as coagulant content of PAM increased. The reason is that when PAM content was low, the amount of bridging and adsorption between cement and sand particles was insufficient for restraining separation of cement and sand particles; thus, unconfined compression strength was not enhanced. However, when the PAM content exceeded a specific threshold, the effectiveness of flocculation also declined. Because the surfaces of cement and sand particles were entirely covered by PAM, the dispersion effect occurred due to electrical-charge repulsion produced from PAM and itself. This phenomenon results in loose sedimentation (dry unit weight of cement treated sand decreased as coagulant content of PAM increased (Table 2)) and reduced unconfined compression strength. Therefore, an optimum coagulant content of PAM exists.

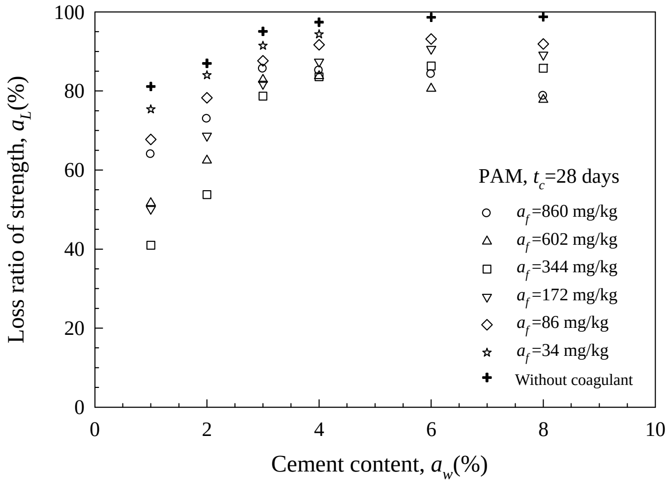


Fig. 10 The relationship between the loss ratio of unconfined compression strength and cement content for cement treated sand

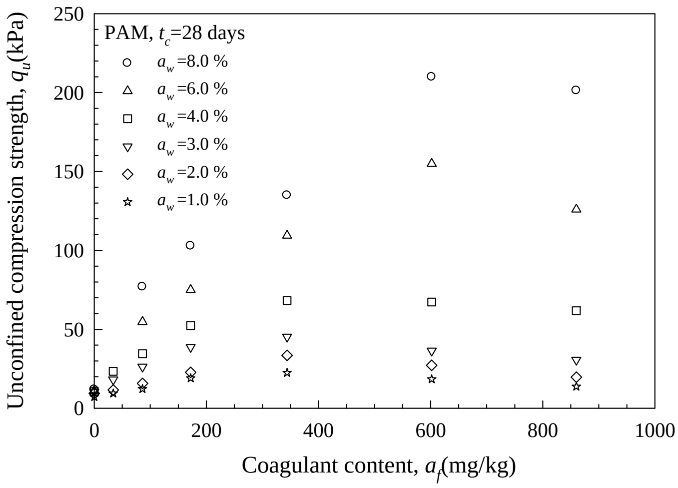


Fig. 11 The relationship between unconfined compression strength of cement treated sand and coagulant content of PAM

Table 2 The basic physical properties of the cement treated sand contained PAM

Coagulant content (mg/kg)	0	34	86	172	344	602	860
Dry unit weight (kN/m^3)	13.29	13.27	13.25	13.13	13.01	12.75	12.56
Moisture content (%)	27.43	30.50	31.54	33.05	34.40	35.31	37.64

Comparison of the interaction of coagulant content with cement indicates that the optimum coagulant content of PAM was of 344 mg/kg when cement content was ≤ 4%; when cement content was 6% and 8%, the optimum coagulant content of PAM was 602 mg/kg. This is because when cement treated sand contained a large amount of cement, an increased amount of coagulant was needed to cover cement and sand particles completely. These experimental results are similar to those obtained by Zhu *et al*. (2007).

5.3 Dynamic Properties of Cement Treated Sand

1. Results of cyclic triaxial tests

With a CRR of 0.5, coagulant content of 344 mg/kg, and curing time of 28 days, Figs. 12 and 13 show the time histories of axial strain (ε_d) and excess pore water pressure (u_d), respectively. When cement content was 4%, N_c was 9; when cement content was 6%, N_c was 33; and when cement content was 8%, liquefaction of the specimen did not occur. A high cement content assisted specimens in developing high shear strength, and reduced axial strain with the same number of loading cycles (Figs. 12 (a) ~ 12(c)). Furthermore, a comparison of the three curves for 4%, 6% and 8% cement content (Figs. 13 (a) ~ 13(c)) indicates that the amount of excess pore water pressure in a single cycle and the accumulation rate of excess pore water pressure decreased as cement content increased. Therefore, a high cement content restrained the generation of excess pore water pressure and reduced the occurrence of liquefaction.

2. Effects of adding cement

Figure 14 shows the cyclic strength curves of cement treated sands with different amounts of cement. The cyclic strength curve moved upward as cement content increased. Furthermore, the cyclic resistance also increased as cement content increased. These trends exist because additional cement can produce an increased amount of gels among sand particles, thereby increasing shear strength.

Additionally, the improvement ratio (IR) of cyclic resistance is defined as follows:

$$\text{IR} = \frac{\text{The cyclic resistance of cement treated sand containing PAM}}{\text{The cyclic resistance of untreated reclaimed sand}} \tag{5}$$

where untreated reclaimed sand means that the sand did not contain cement and coagulant (PAM). The IR value increased as cement content increased (Table 3).

3. Effects of adding coagulant

Figures 16 and 17 show the cyclic strength curves and cyclic resistances of cement treated sands with different amounts of coagulant, respectively. The cyclic strength curve initially moved upward as coagulant content of PAM increased; however, the curve moved downward when PAM content exceeded 344 mg/kg (Fig. 16). Furthermore, the cyclic resistance of cement treated sand increased initially and then decreased as coagulant content of PAM increased (Fig. 17). The highest cyclic resistance was with 344 mg/kg PAM. Table 4 shows the various IR values with different amounts of PAM. The reasons leading to this phenomena are the same as those discussed in Section 5.1(3).

4. Relationship between unconfined compression strength and cyclic resistance

Seed and Idriss (1971) developed a simplified procedure for assessing soil liquefaction potential. When the local magnitude of an earthquake is 7.5 with an equivalent 15 cycles, average cyclic stress ratio (CSR) of soil generated by an earthquake can be expressed as follows:

$$\text{CSR} = 0.65 \frac{a_{\max}}{g} \frac{\sigma_v}{\sigma'_v} r_d \tag{6}$$

where $a_{\max}$ is peak ground surface acceleration, g is gravitational acceleration, σ_v is total vertical stress, σ'_v is effective vertical stress, and r_d is the stress reduction factor at a depth of interest.

If we assume the maximum possible magnitude of an earthquake in Taiwan is 7.5, and maximum ground surface acceleration is 0.33 g (According to the earthquake intensity table by the Central Weather Bureau, Ministry of Transportation and Communications (2008) in Taiwan, the range of ground acceleration in intensity scale 6 is 220 ~ 400 gal. Therefore, this value of 330 gal is within the range of ground acceleration in intensity scale 6 for Taiwanese standards.), reclaimed depth of 10 meters and experimental conditions in this study (total vertical stress of 147 kPa and effective vertical stress of 49 kPa), the average cyclic stress ratio (CSR) is roughly 0.547 by Eq. (6). The CSR is utilized as a basis for assessing liquefaction of cement treated sand. A comparison of data for cyclic strength curves (Fig. 14) and cyclic resistances (Fig. 15) indicates that the liquefaction of cement treated sand did not occur when curing time was 28 days, coagulant content of PAM was 344 mg/kg and cement content was 6%.

Figure 18 shows the relationship between unconfined compression strength and cyclic resistance. After linear regression, the relationship between unconfined compression strength and cyclic resistance can be expressed as follows:

$$\text{CR} = 0.0044 q_u + 0.126 \text{ (PAM)} \tag{7}$$

where the unit of q_u is kPa.

The CSR of 0.547 was regarded as the cyclic resistance of cement treated sand without the risk of liquefaction and this value was substituted into Eq. (7), yielding an unconfined compression strength of 96 kPa. This means that risk of liquefaction disappeared when unconfined compression strength of cement treated sand was ≥ 96 kPa. This experimental result corresponds with those obtained by of Zen (1994) with a non-liquefaction index.

Table 3 The improvement ratio of cyclic resistance for different cement contents

Coagulant	Coagulant content a_f (mg/kg)	Curing time t_c (days)	Cement content a_w (%)	Improvement ratio of cyclic resistance IR
PAM	344	28	3	2.46
			4	3.58
			6	4.33
			8	5.06
Untreated reclaimed sand				1.00

Table 4 The improvement ratio of cyclic resistance for different coagulant contents

Coagulant	Cement content a_w (%)	Curing time t_c (days)	Coagulant content a_f (mg/kg)	Improvement ratio of cyclic resistance IR
PAM	4	28	0	1.57
			34	1.95
			86	2.65
			344	3.58
			602	3.50
			860	3.05
Untreated reclaimed sand				1.00

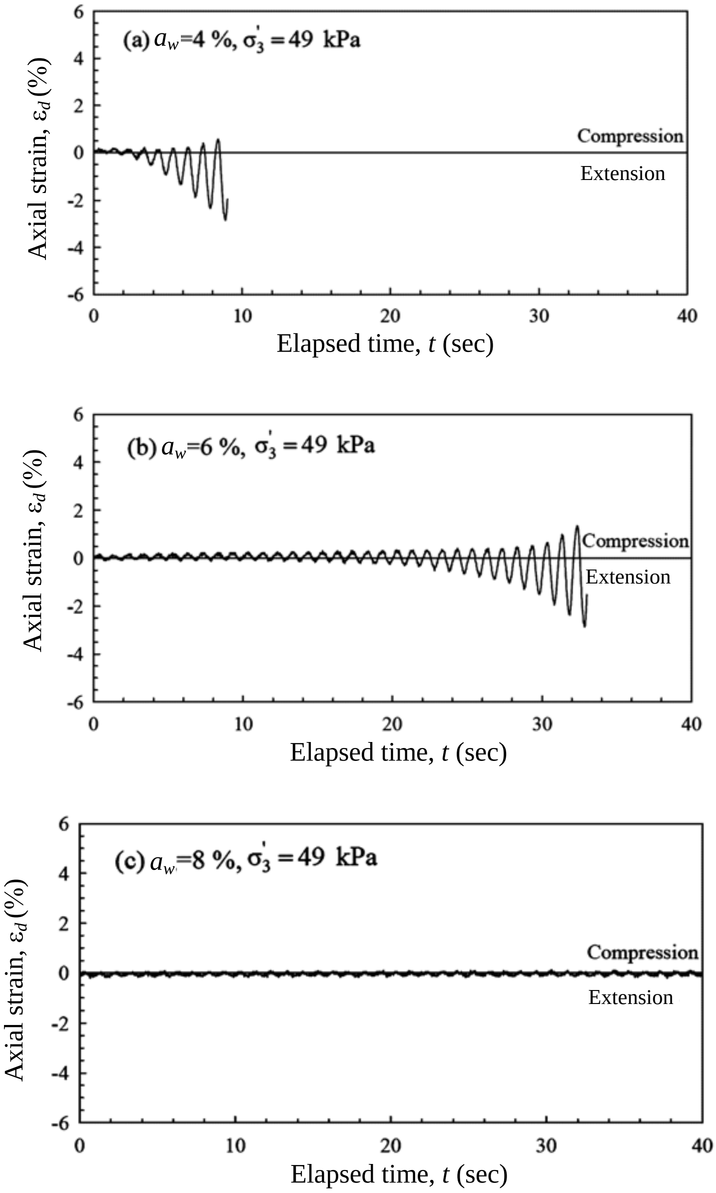


Fig. 12 The time history of axial strain for cement treated sand containing PAM (CRR = 0.5, a_f = 344 mg/kg, t_c = 28 days)

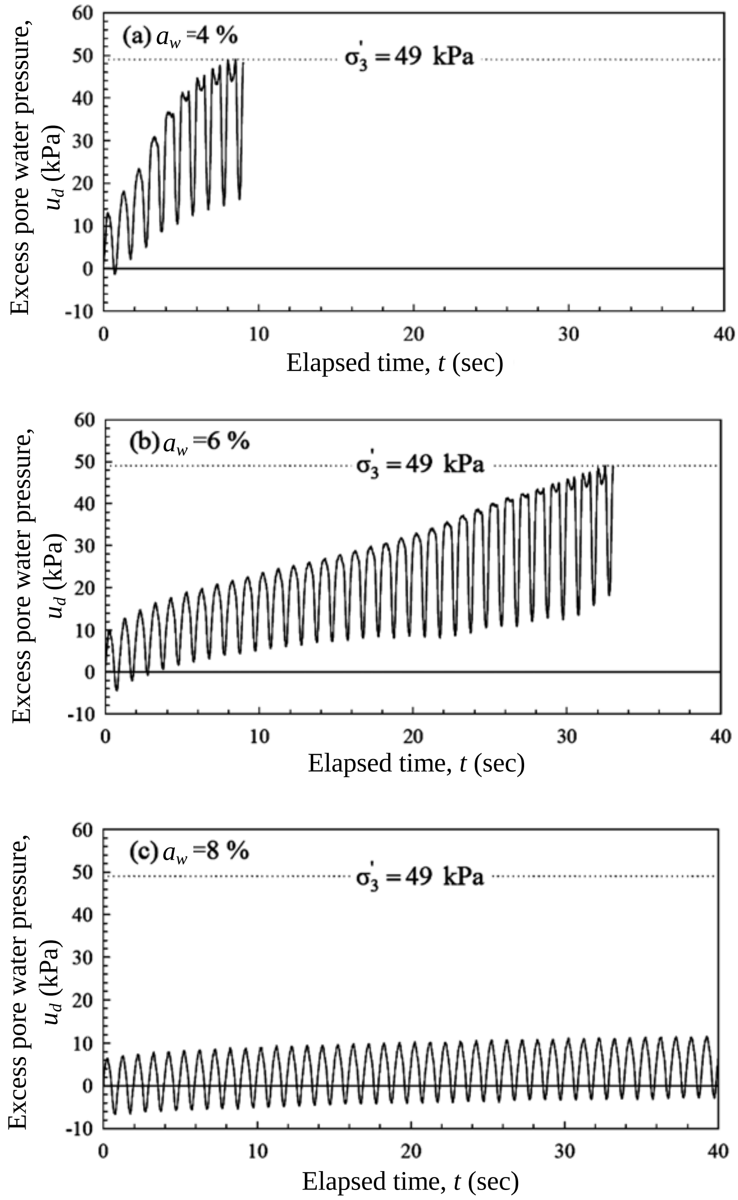


Fig. 13 The time history of excess pore water pressure for cement treated sand containing PAM (CRR = 0.5, a_f = 344 mg/kg, t_c = 28 days)

6. CONCLUSIONS

In this study, Danang sand was used as the primary material for backfilling in water. Danang sand was transformed into cement treated sand by adding cement and coagulant. The water sedimentation method was utilized to prepare specimens. Unconfined compression tests and cyclic triaxial tests were carried out after employing different curing times. The principal conclusions are as follows.

1. Untreated reclaimed sand is usually very loose and easily liquefied during an earthquake. However, adding a small amount of cement increased the cyclic resistance of reclaimed sand. However, cement and sand particles in the cement treated sand separated during sedimentation in water. This phenomenon decreased the beneficial effects of cement. Therefore, preventing separation of cement particles by adding a coagulant is necessary.
2. The shear strength of cement treated sand backfilled on land or in water without separation can be increased significantly. However, cement particles separated from cement treated sand while sinking, and the strength of the cement treated sand was lost. In this study, by adding PAM as a coagulant, the loss of unconfined compression strength for cement treated sand was reduced effectively and substantially.
3. The development of unconfined compression strength for cement treated sand was affected primarily by cement content and coagulant content of PAM. Unconfined compression strength of cement treated sand increased as cement content increased. However, unconfined compression strength of cement treated sand increased initially and then decreased as coagulant content of PAM increased. Thus, an optimum coagulant content of PAM exists. The optimum coagulant content of PAM was 344 mg/kg when the cement content was ≤ 4%; under 6% and 8% cement content, the optimum coagulant content of PAM was 602 mg/kg.

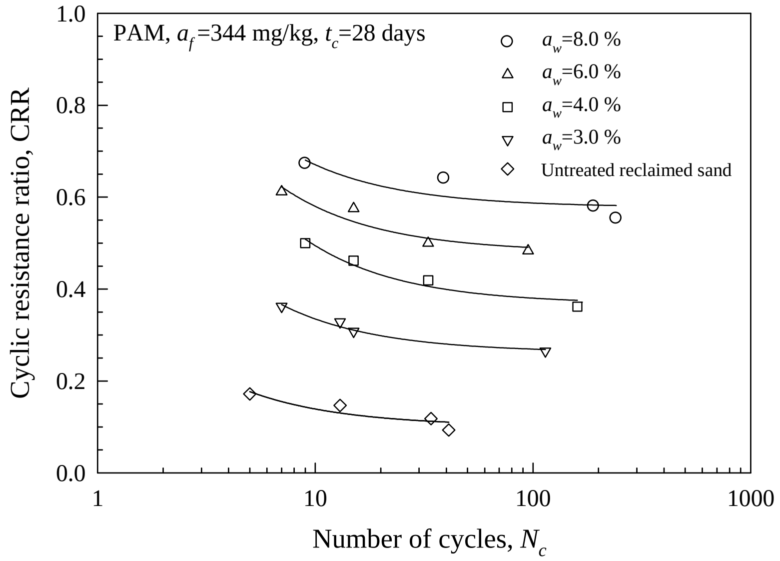


Fig. 14 The cyclic strength curves of cement treated sands for different cement contents

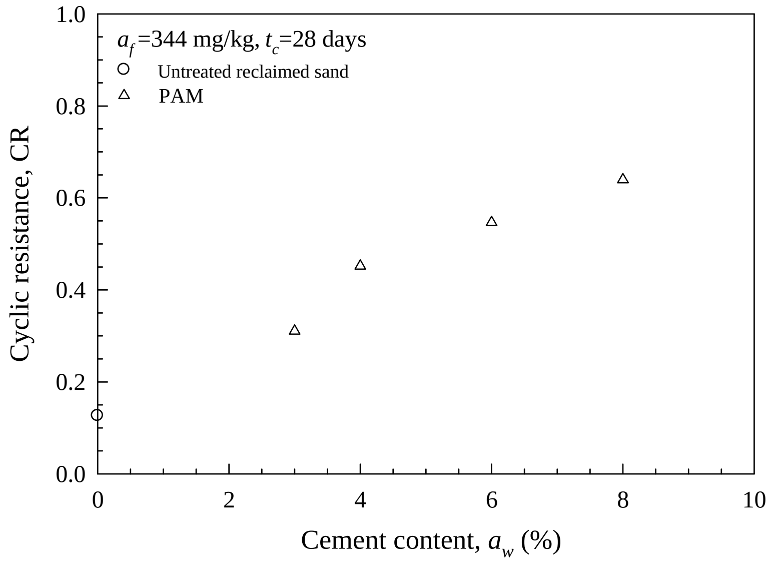


Fig. 15 The relationship between cyclic resistance of cement treated sand and cement content

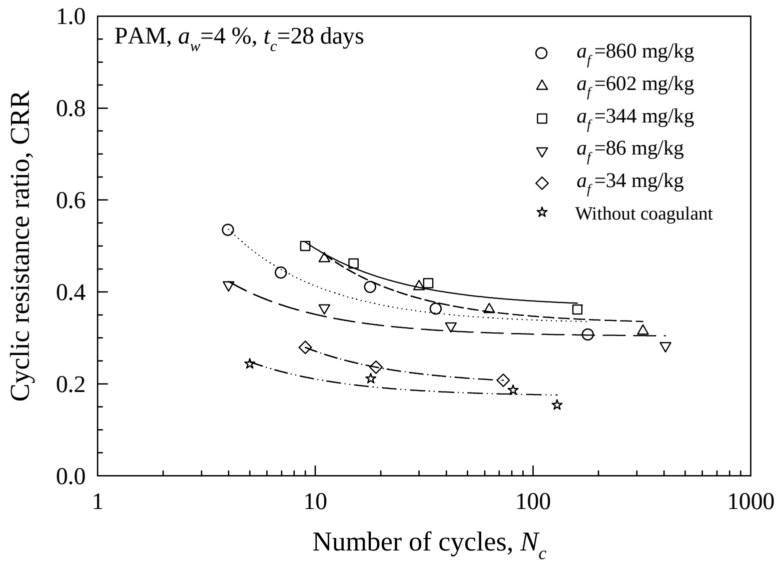


Fig. 16 The cyclic strength curves of cement treated sands for different coagulant contents of PAM

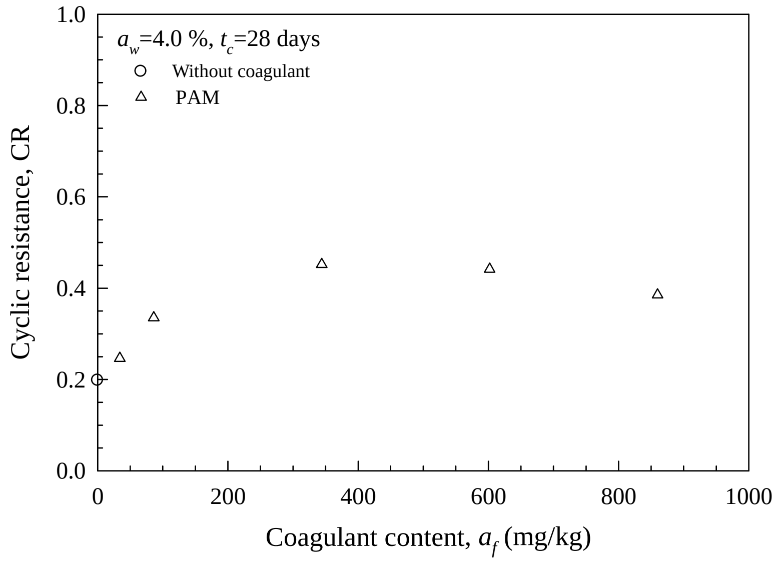


Fig. 17 The relationship between cyclic resistance of cement treated sand and coagulant content of PAM

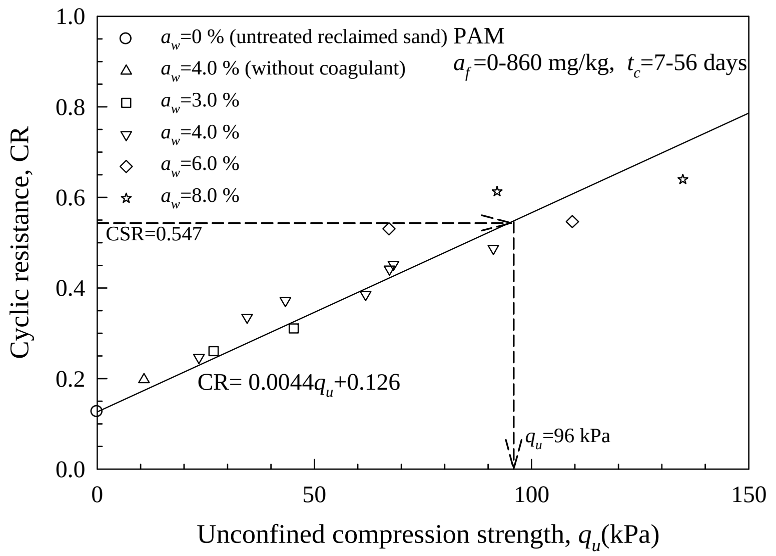


Fig. 18 The relationship between cyclic resistance and unconfined compression strength for cement treated sand

4. Under curing time of 28 days, coagulant content of 344 mg/kg (PAM), and cement content of 6%, the cyclic resistance of this cement treated sand was 4.33 times that of untreated reclaimed sand. Furthermore, seismic capacity of this cement treated sand on the seismic intensity scale was 6 for Taiwanese standards.

The primary contribution of this study is the application of polyacrylamide for land reclamation using cement treated sand in water. The optimum coagulant content of PAM was established for non-liquefaction artificial land and to prevent liquefaction.

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