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Technical Note

Evaluation of the effect of induced vibration on early age lightweinght air-trapped soil

Kwang-Suek Oh[1], **Tae-Hyung Kim**[2,*]

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Abstract

This study was conducted to determine the effect of vibration on the curing and compressive strength of lightweight air-trapped soil (ATS). ATS is manufactured by mixing cement with water and sand and injecting bubbles into the mixture. It is light as compared to regular soil, can reduce the weight on the ground, and has high fluidity. If ATS is used at construction sites with many vibration sources, such as pile driving, blasting, and construction machinery, the effect of vibration needs to be seriously considered. If a road is expanded using ATS to reduce traffic congestion, the ATS quality may decrease because of vibration generated by traffic moving on the road. In particular, because ATS contains many air bubbles and needs time for curing, the effect of vibration can be greater than expected. Therefore, the effect of vibration on ATS was evaluated during the curing process by conducting unconfined compression tests on samples prepared with different values of variables including vibration velocity, starting vibration time, and mixing ratio. Vibration velocities of 0.25 and 0.50 cm/s did not greatly affect the strength. However, vibration velocities of above 2.50 cm/s significantly affected the decrease in strength, and the starting vibration time also had a clear effect on specimens cured for less than 2 hours.

Keywords: *Vibration, Air-trapped soil (ATS), Unconfined compressive strength, Curing, Air bubbles*

1. Introduction

The time-dependent settlement of soft soil poses serious maintenance problems to develop along coastal and riverside areas that encounter thick-soft soil deposits. Rehabilitation works for areas suffering settlement problems in soft soil deposits generally face time and facility service constraints. These constraints hamper the selection of remedial methods as these require a longer construction duration and ample land space. The use of lightweight materials is a feasible alternative for overcoming the above constraints. As lightweight materials have lighter densities than general fill materials, post-construction settlement can be minimized [1].

Air-trapped soil (ATS) is one type of lightweight material. It is prepared by mixing air bubbles and water with sand and cement [2, 3]. The density of soil slurry can be adjusted to a range of around 10 kN/m^3. ATS has several advantages. Firstly, it can reduce the stress induced by the overburden load affecting the ground because it is lighter than soil and can be transferred from a batch plant to the site by pumping due to its high fluidity. In addition, ATS is easy to manufacture because it does not require a compaction process. ATS has been recognized as an effective material for embankments on soft ground, backfilling retaining walls, backfilling structures, filling settlement ground, and other applications.

Most studies on lightweight materials, including ATS, focused on the strength and deformation characteristics [4 - 10]. These studies did not examine the effect of vibration on the characteristics of lightweight materials.

However, there have been many studies on protecting curing concrete from vibration for concrete quality management [11- 16]. Many construction sites have seen a rapid increase in the number of vibration-related problems. There are often various types of vibration: blasting in mines or construction sites according to the source; instant shocks due to explosions; constant shocks due to pile driving, excavation, machine tools, and motors; and vibrations caused by transport facilities such as vehicles and machines. Such vibrations affect the safety of existing structures. Thus, most countries have regulations detailing the allowable standard for vibration [17-19]. Many studies have examined the effect

* *Corresponding Author:kth67399@hhu.ac.kr*
1 Associate Professor, Department of Architectural Engineering, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-Gu, Busan 606-791, Korea
2 Professor, Department of Civil Engineering, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-Gu, Busan 606-791, Korea

of vibrations on regular concrete; thus, measures have been developed to control vibration and minimize the damage to structures [20-24]. However, there are no corresponding studies on lightweight ATS with regard to vibration. One weakness of ATS to vibration is during curing, as it contains many air bubbles. ATS also needs a certain amount of time for curing. However, there is no information on the effect of vibration on ATS in the literature and no specific standard for controlling ATS quality. This makes ATS difficult to apply to various fields.

This study was conducted to determine the effect of vibration on the curing and compressive strength of ATS. A series of laboratory experiments were conducted. The variables considered in the tests were the vibration velocity, time when vibrated, and mixing ratio. The unconfined compressive strength was measured and the results were analyzed to examine the effect of vibration.

2. Experimental investigation

2.1 Experiment variables

2.1.1 Vibration velocity

The minimum reference vibration velocity of 0.25 cm/s was selected from the vibration regulations generally used for concrete. Three more velocities were then selected: 0.50, 2.50, and 4.20 cm/s. These vibration velocity ranges were set by referencing previous published studies of Hulshizer and Desai [17] and Song [19]. For instance, Hulshizer and Desai [17] from their laboratory and field testing suggested vibration limits of 0.16, 0.59, 0.79, 1.57, 2.71 cm /sec for concrete cast in less than 3 hours, within 3-11 hours, within 11-24 hours, within 1-2 days and over 2 days, respectively. Even though vibration velocities of above 2.5 and 4.2 cm/s and are not likely to occur onsite, a comprehensive vibration velocity range was set as the purpose was study the effects of vibration on lightweight ATS.

2.1.2 Starting vibration time

The effect of the starting vibration time on the hardening of lightweight ATS is also an important factor. Five starting vibration times were selected: 0, 1, 2, 4, 6, and 12 h. A starting time of 0 h means that vibration was applied immediately after production of the specimen. A starting time of 12 h was the upper limit because the specimen was almost cured by then. Each specimen was vibrated for 30 min.

2.1.3 Mixing ratio

The mixing ratios shown in Table 1 were selected to determine the effect of vibration on the curing of lightweight ATS. Specimens were produced with three cement–sand mixing ratios of 1:0, 1:1, and 1:2 for unit weights of 6, 8, and 10 kN/m³. The mixing ratios for each unit weight were taken from previous studies regarding the construction of road embankments using ATS [2]. These three mixing ratios are frequently used in practice. Hereafter, specimens with cement–sand ratios of 1:0, 1:1, and 1:2 are referred to as 6, 8, and 10 kN/m³ specimens, respectively.

2.2 Materials

2.2.1 Cement and sand

Common Portland cement was used in this study. Table 2 presents the physical characteristics. Manufactured sands were used to produce relatively uniform-quality lightweight ATS. The particle size distribution curve of the sand is shown in Fig. 1, and the effective particle size (D_{10}) was approximately 0.15 mm. D_{10} refers to the soil particle diameters for which

Table 2 Properties of Portland cement

Specific gravity		3.15
Fineness		3.354
Solidification (min)	Initial Set	205
	Final Set	275
Stability (%)		0.09
Compressive strength (MPa)	3 days	28.8
	7 days	39.1
	28 days	52.2

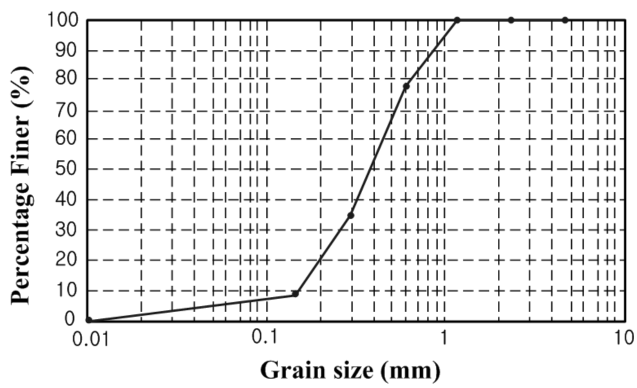


Fig. 1 Particle size distribution curve of sand

Table 1 Mixing ratios (unit: kg)

Items		Cement slurry				Weight of cement slurry: ①	Bubble slurry			Density of mixing slurry:①+② (kN/m³)
γ (kN/m³)	C-S*	Cement	Sand	Water	Water /Cement		Foaming agent	Water	Weight of bubble slurry:②	
6	1-0	380	0	190	0.50	570	0.55	27.02	27.57	6
8	1-1	294	294	194	0.66	782	0.46	22.45	22.91	8
10	1-2	253	506	227.7	0.90	986.7	0.36	17.68	18.04	10

* C-S =cement-sand

10% of the particles are finer. The absorptivity and specific gravity of sand are 1.18 and 2.65, respectively. The sands should be clean and hard without natural cleavage planes such as those that occur in slate or shale.

2.2.2 Foaming agent

Foaming agents are generally classified into animal, vegetable, and synthetic types, and they should generate stable air bubbles in a mixture with other materials. In this study, an animal-type forming agent was used because its air bubbles are stronger than those of vegetable agents. This agent was manufactured by extracting protein from horns, claws, fur, and other animal residue after they are hydrolyzed, making it a highly eco-friendly foaming agent. The chemical composition and physical characteristics of this agent are given in Tables 3 and 4. In addition, heavy metal detection experiments were conducted for the animal foaming agent to guard against the possibility of environmental contamination. Heavy metals were not detected.

2.3 Specimen Preparation

2.3.1 Production process

To produce the specimens for laboratory tests, the foaming agent was diluted with water at a ratio of 1:19. A pre-foaming method was used to make ATS. In this method, the air bubbles are first foamed by a bubble generator and then mixed with cement slurry. This pre-foaming method can easily control the amount of air bubbles. A bubble generator was made and used for this test (Fig. 2). This device is composed of a high-pressure pump, air compressor, mixer tube, and foam tube. The high-pressure pump is used to pump out diluted foaming agent. The diluted foaming agent and air are mixed in the mixer tube. During this process, the air compressor supplies pressure to make bubbles in the foam tube.

The specimens were prepared by mixing the bubbles generated by a bubble apparatus with the cement slurry (Fig. 3). The cement slurry is a mixture of cement, sand, and water. The mixed slurry of cement and bubbles was formed in cylinder molds. The specimens were ideally 5 cm in diameter and 10 cm in height for the unconfined compression test. It was especially important that the unit weight of the bubbles be verified after foaming because they significantly affect the strength of the lightweight ATS. The air bubbles were foamed at an air compressor pressure of 400 ~ 450 kPa, and the unit weight of the air bubbles was about 0.5 ± 0.05 kN/m³.

Table 3 Chemical composition of an animal foaming agent (unit: %)

H_2O	36
Protein	32
NaCl	10
NH_4Cl	1
$CaCl_2$	6
$MgCl_2$	5
$FeSO_4$	10

Table 4 Physical characteristics of animal foaming agents

Specific gravity	1.18
Viscosity (cP)	37.3
Solids (%)	39.1
pH	6.29
Unit weight of foaming (kN/m^3)	0.5±0.05

2.3.2 Vibration measuring device and vibration device

Prior to the experiment, the relevant vibration velocity was found by using the blasting noise vibration measuring device BLASTMATEIII. A low frequency range of 10–30 Hz was used. The vibration measuring device and vibration sensor are shown in Fig. 4.

The motor (Fig. 4) fixed on a 60 cm × 120 cm iron plate was used to produce vehicle vibration under actual road conditions. The motor can be controlled by a regulator to 10 different speeds by varying the revolution per minute. The motor revolution per minute and relevant vibration velocity were measured at several separation distance locations from the motor. Based on test results, vibration condition for velocities of 0.25, 0.50, 2.50, and 4.20 cm/s were set for testing.

Specimens prepared with unit weights of 6, 8, and 10 kN/m³ were vibrated for 30 min at the relevant vibration velocities (0.25, 0.50, 2.50, and 4.20 cm/s) for each starting vibration time. Vibration was started when the specimen was placed on the vibration table connected to the vibration motor. Table 5 shows the experimental conditions and cases.

3. Test results and analysis

The vibration tests were conducted on specimens based on the experimental conditions (Table 5). The specimen were prepared at three different mixing ratios (cement:sand = 1:0 (6 kN/m³), 1:1 (8 kN/m³), 1:2 (10 kN/m³)). The vibrated specimens were cured for either 14 or 28 d.

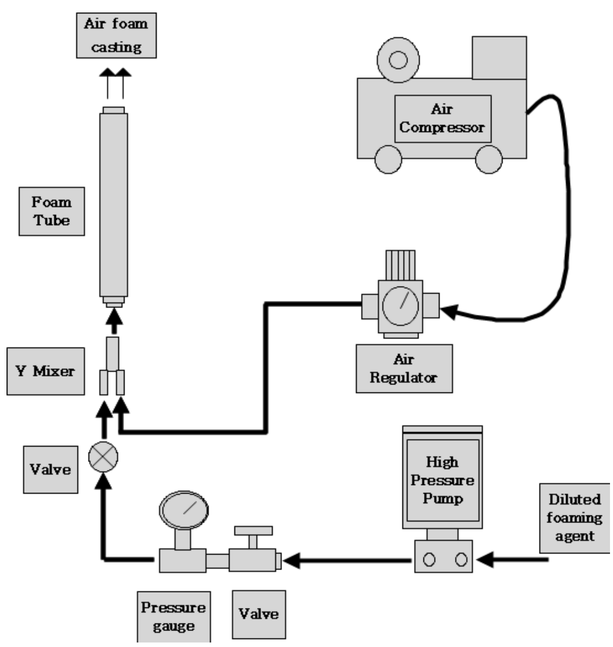


Fig. 2 Air bubble generator

(a) cement slurry mixing

(b) bubble discharge

(c) bubble + cement slurry mixing

(d) mixing slurry

Fig. 3 Lightweight ATS production process

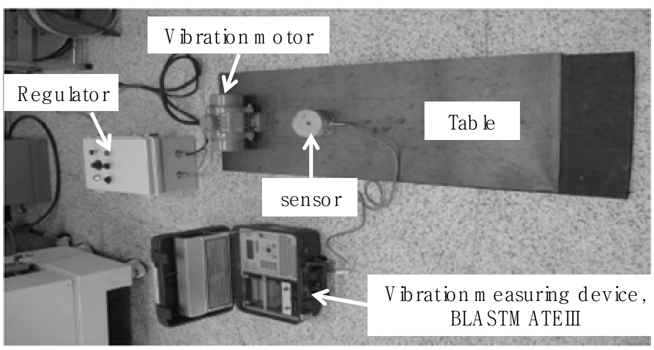


Fig. 4 Composition of vibration experiment device

Table 5 Experimental conditions and cases

Unit weight (kN/m^3)	Vibration Velocity (cm/s)	Starting time vibration (h)	Remarks
6, 8, 10	0.25 0.50 2.50 4.20	0, 1, 2, 4, 6, 12	Referred as 0=T0 1=T1 2=T2 4=T4 6=T6 12=T12

The state of cured specimens vibrated with different vibration magnitudes was checked to determine the effect of vibration on ATS. Unconfined compression tests were then conducted according to KS F 2314 [25] to examine the strength characteristics of lightweight ATS according to the mixing condition, vibration velocity, and starting vibration time. The variations in unconfined compressive strengths for different unit weights, vibration velocities, and starting vibration times were analyzed. The strengths of lightweight ATS specimens cured 14 d and 28 d were measured. Equation (1) indicates the variation in unconfined compressive strength depending on the vibration condition.

$$\text{Strength variation rate} = \frac{q_u(S) - q_u(T)}{q_u(S)} \times 100 \tag{1}$$

where:
q_u(T): unconfined compressive strength obtained from the vibrated specimen;
q_u(S): unconfined compressive strength obtained from the non-vibrated specimen.

3.1 Specimen state after vibration

Figure 5 shows specimens cured with different vibration velocities and starting vibration times. Figure 5(a) shows a specimen that was not vibrated. The picture shows a sleek and homogenous surface. When medium-magnitude vibration (2.50 cm/s) was applied to the specimen or vibration was applied to a specimen with little curing, a white wave pattern appeared on the specimen surface, as shown in Fig. 5(b). When large-magnitude vibration (4.20 cm/s) was applied to a specimen or vibration was applied to a specimen in the fresh slurry state, a large crack occurred in the specimen, as shown in Fig. 5(c). In addition, dispassion of air bubbles in the specimen occurred during vibration, which decreased the height of the specimen was decreased. Material segregation also occurred since the air bubbles in the bottom layer could not escape from the mold while those in the upper–middle layers were emitted during the vibration process.

3.2 Effect of unit weight

(a) vibration free

(b) medium- magnitude of Vibration at fresh state

(c) large- magnitude of vibration at little cured state

Fig. 5 State of specimen according to vibration velocity and staring time vibration

For the 6 kN/m^3 specimen, weak vibration did not change its strength (Fig. 6(a)). However, for the 8 kN/m^3 specimen, a weak vibration of less than 0.50 cm/s resulted in a small increase in compressive strength. This was due to the sand acting as a frame for lightweight ATS. However, the strength increase due to this effect was limited to a weak vibration velocity range of less than 0.50 cm/s; the strength decreased with vibrations above this range due to rearrangement of the sand particles and dissipation of the air bubbles (Fig. 6(b)). The 10 kN/m^3 specimen showed similar behavior as the 8 kN/m^3 specimen, but the strength decrease was much more significant than that for the lighter densities, as shown in Fig. 6(c). This result indicates that the vibration effect on the strength of ATS increases with increase in the unit weight of specimen. In particular, when the ATS unit weight is over 10 kN/m^3, special attention may be required for applications in a construction site exposed to vibrations. The number of curing days had no significant effect on the strength. As shown in Fig. 6, the variations in strength for the 14- and 28-d cured specimens showed similar tendencies.

3.3 Vibration velocity

Figure 7 shows the effect of vibration velocity on the strength variation of ATS. Vibration velocities of 0.25 and 0.50 cm/s did not greatly affect the strength. There were almost no changes in the 6 kN/m^3 specimen. However, a vibration velocity of above 2.50 cm/s caused a significant effect; the compressive strength decreased with increased vibration velocity. This result shows that the critical vibration that affects the ATS strength is 2.50 cm/s. Thus, if a construction site is exposed to a vibration velocity of over 2.50 cm/s, special attention may be required. For the 10 kN/m^3 specimen, the strength variation was slightly unstable compared to those of the 6 and 8 kN/m^3 specimens. The overall trends in the effect of vibration velocity was essentially similar for all three unit weights. As shown in Fig. 7, the 14 and 28 days cured specimens had similar tendencies for the variation in strength.

3.4 Starting time variation

To determine the effect of varying the starting time on the specimens, six cases were selected: 0, 1, 2, 4, 6, and 12 h (Table 5). These cases are referred to as T0, T1, T2, T4, T6, and T12, respectively. The test results show similar behaviors for different cases, as shown in Figs. 6 and 7.

Vibration velocities of 0.25 and 0.50 cm/s did not have a significant effect on the specimens; thus, starting time variation is not an important influence at low vibration velocities. However, when a vibration velocity of over 2.50 cm/s was applied to a specimen 2 h after its production, there was a clear effect. This was caused by the dissipation of air bubbles and segregation of materials in the specimen, as shown in Fig. 5. Specimens vibrated 4 h after production were not significantly affected by vibration because they were already more or less cured. These results show that the critical timeframe for vibration having an effect on the ATS strength is 0–2 h after production. Consequently, if a construction site uses ATS, vibration should be strictly restricted for 2 h to secure the quality.

The strength variation of the 10 kN/m^3 specimen was relatively unstable compared to those of the 6 and 8 kN/m^3 specimens. This may be related to sand, which has a high specific gravity relative to the materials comprising ATS. When vibration is applied to a specimen, sand particles in slurry-state ATS easily sink. The sinking speed or arrangement of each particle can differ according to the particle weight, size, and shape of the sand; thus, the strength decrease rate is unstable.

3.5. Curing days

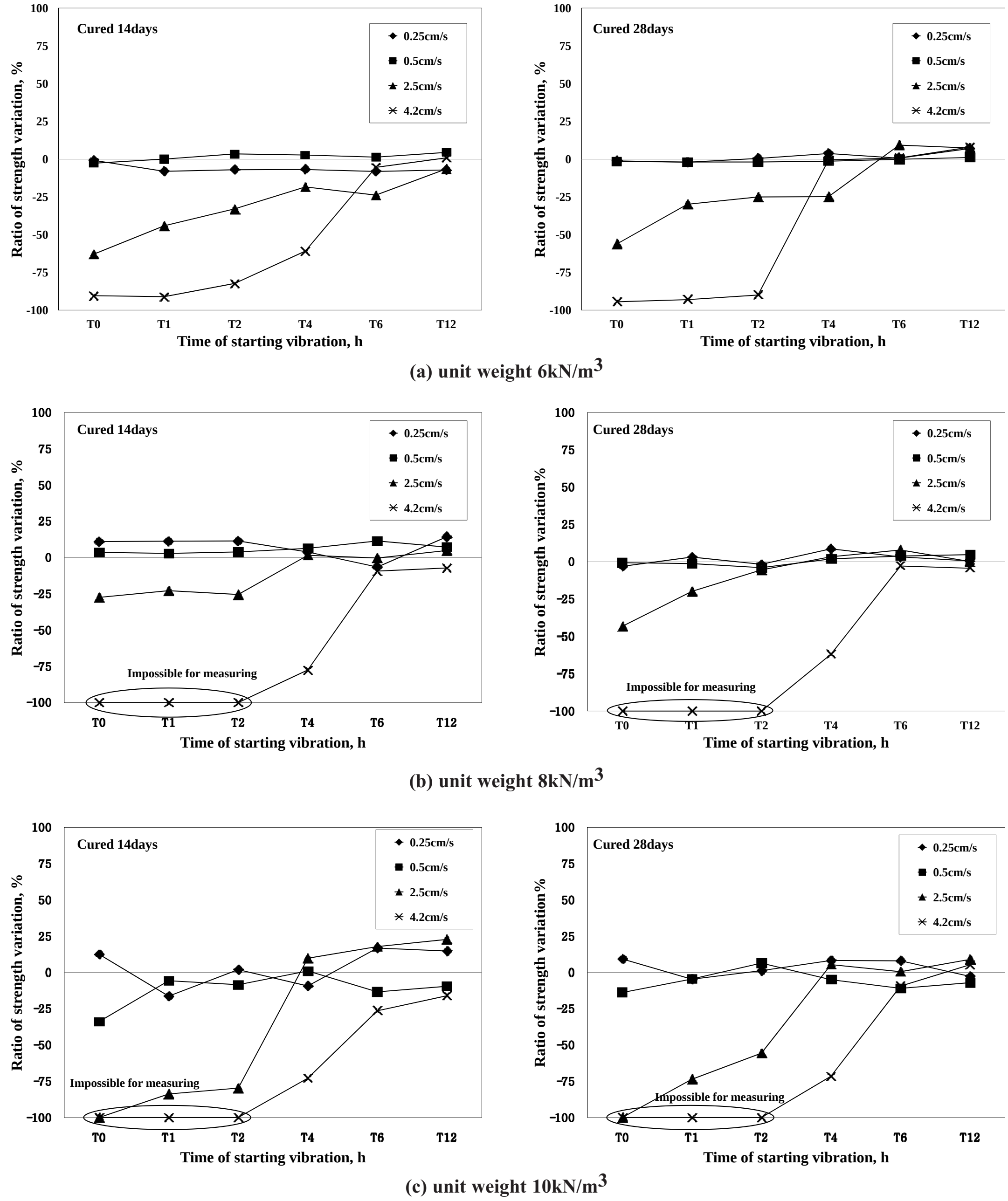


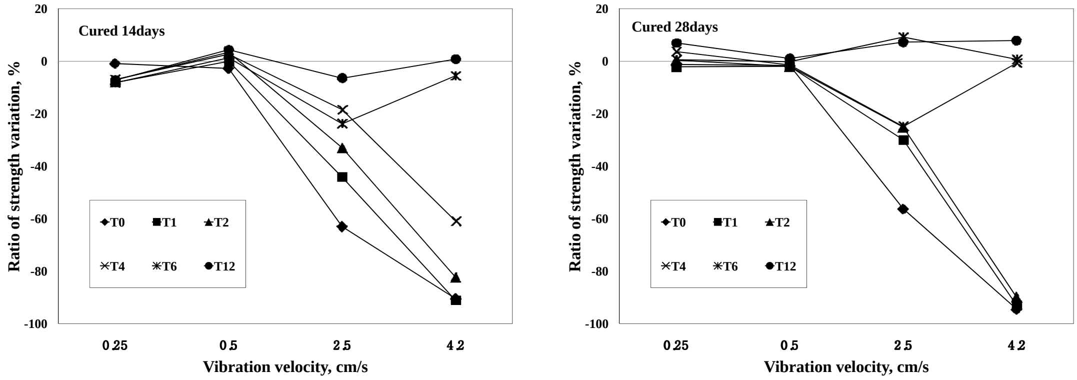
Fig. 6 Relation between starting time variation and strength variation

To determine the effect of curing days on vibrated ATS specimens, the unconfined compression test results of specimens cured for 14 and 28 days were compared. The unconfined compressive strength of the 14 days cured specimen showed slightly lower strength than the 28 days cured specimen [1, 2, 8]. There was no large difference in strength based on the curing days, and the strength variation of both specimens showed similar tendencies.

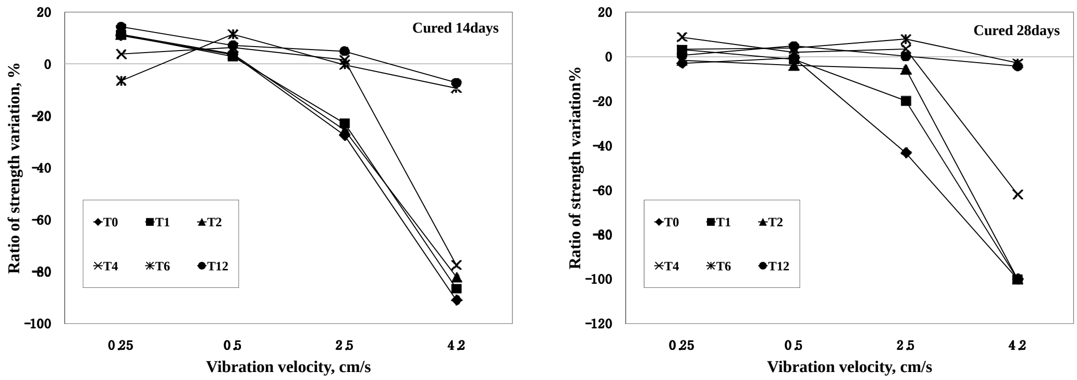
To compare the rate of strength decrease for the 14 and 28 days cured specimens, the T0 cases for both were compared, as shown in Fig. 8. As indicated in Table 5, T0 means that the vibration was immediately applied after the specimen was prepared in the mold. We expected the largest strength changes in these specimens. The results show that the strength is significantly affected, but the trends in strength change based on the curing days are very similar.

4. Conclusions

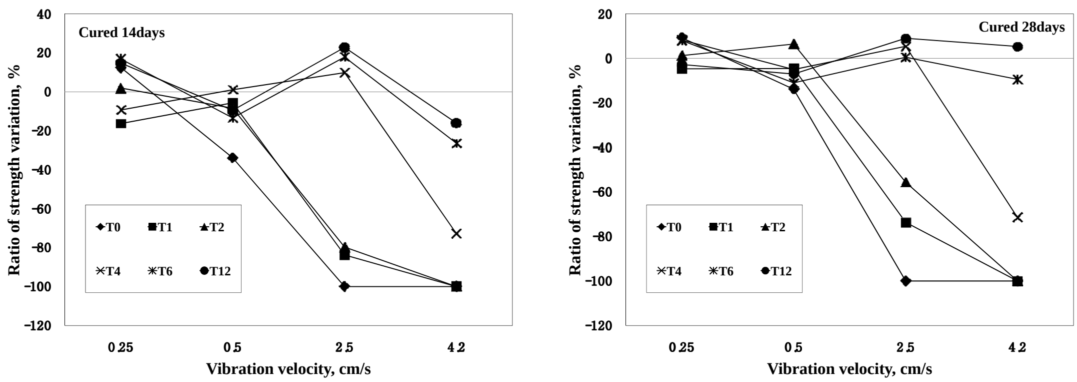
This study was conducted to determine the effect of vibration on the quality of lightweight ATS, especially the compressive strength. In the field, vibration can be caused by pile driving, blasting, construction machines, and vehicle movements. To study the effect of vibration on the strength of lightweight ATS, three experiment variables were selected: vibration velocity, starting vibration time, and mixing ratio. The overall experiments results of the unconfined compression tests



(a) unit weight 6kN/m^3



(b) unit weight 8kN/m^3



(c) unit weight 10kN/m^3

Fig. 7 Relation between vibration velocity and strength variation

show that the vibration significantly affects the ATS properties and that the effect of vibration on ATS strength increases with the density. The concluding remarks are given below in detail.

(1) Specimens that did not experience vibration had a sleek and homogenous surface, whereas specimens exposed to medium-magnitude vibrations or less-cured specimens that were vibrated had a white wavy pattern on the surface. Specimens exposed to high-magnitude vibrations or specimens that were vibrated in the slurry state had large cracks. In addition, the height of the specimen decreased with material segregation of the sand and air bubbles because the air bubbles in the bottom layer of the specimen in the mold could not escape, while air bubbles in the upper–middle layers were emitted when vibrated.

(2) The 10 kN/m^3 specimen containing a higher proportion of sand shows similar behavior to the other lighter specimens, but the decrease in strength is much more significant. The variation in strength of the 10 kN/m3 specimen is relatively unstable compared to that of the other specimens. This may be because the sand had a high specific gravity compared to the other materials comprising ATS. When the specimen was vibrated, sand particles in slurry-state ATS easily sank.

(3) Vibration velocities of 0.25 and 0.50 cm/s did not greatly affect the strength. However, vibration velocities of above 2.50 cm/s significantly affected the decrease in strength. The overall trend for the effect of vibration velocity was similar for all three unit-weight specimens.

(4) The starting vibration time was not an important factor for vibration velocities of 0.25 and 0.50 cm/s. However, when the vibration velocity was over 2.50 cm/s, the starting vibration time had a clear effect on specimens cured for less than 2 h. This was caused by the dissipation of air bubbles and segregation of materials. However, specimens vibrated 4 h after production were not significantly affected because they were already more or less cured.

(5) The unconfined compressive strength of the 14 days cured specimen shows slightly lower strength than the 28-d cured specimen. There was no large difference in strength based on the curing days, and the strength variation of both specimens showed similar tendencies.

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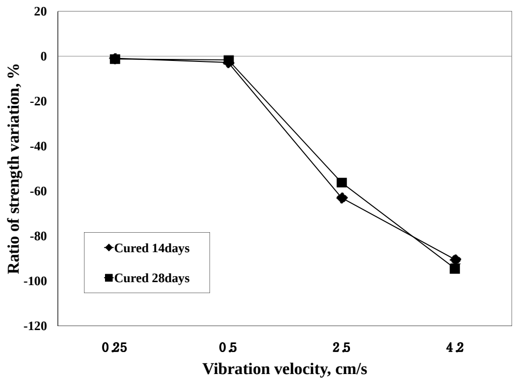
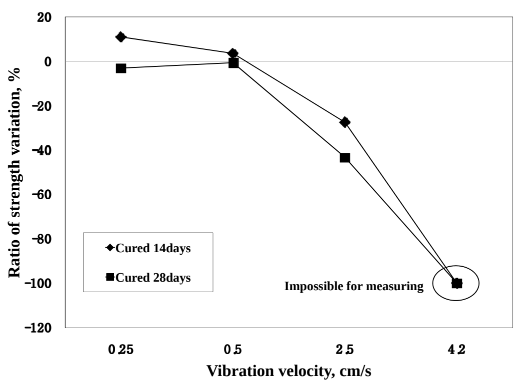
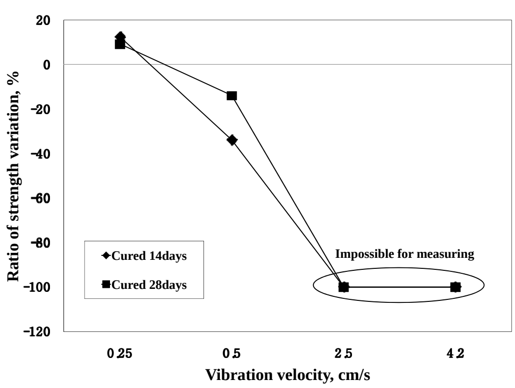


(a) unit weight 6kN/m^3



(b) unit weight 8kN/m^3



(c) unit weight 10kN/m^3

Fig. 8 Comparison of strength variation to curing days of T0 specimens

References

[1] Tsuchida T, Takeuchi D, Okumura T, Kishida T. Development of lightweight fill from dredgings, Proc. of Environmental Geotechnics, Balkema, 1996. p. 415-420.

[2] Hwang J-H. A study of mechanical characteristics of air–trapped soils, Master thesis, Korea Maritime University, 2009.

[3] Lee Y-J, Kim S-W, Park L-K, Kim T-H. Compression and tensile characteristics of lightweight air-trapped soil. J of the Korean Geotechnical Society, 2010; 26(9): p. 59- 69.

[4] Highgrade Soil Research Consortium. Technical data for construction method of air-mixed soil, Technical report, 2005. p. 158

[5] Japanese Highway Public Corporation (1996), Design and construction guidelines of foamed cement banking method using foamed mixture light-weight soil, Technical document No. 225 1996, p.61

[6] Miki H, Mori M, Chida S. Trial Embankment on soft ground using lightweight-foam mixed in-situ surface soil. In Proc. XXIInd PIARC World Road Congress, Durban, 2003.

[7] Park L-K, Kim T-H, Seo Y-K. Engineering characteristics of the lightweight air-mixed soil (LWS) containing silty marine sediment. Marine Georesources and Geotechnology 2011; 29: p. 202-217.

[8] Song J-H. Analysis of compressive strength of lightweight air-mixed soil according to the properties of soil. Master Thesis, Pusan National University, 2009.

[9] Tsuchida T. Development and use of foamed treated soil in port and airport project, Report of port and harbor research institute 1999; 38(2): 131-167 (in Japanese)

[10] Yajima, J. and Mydin, S. H. Mechanical properties of the unsaturated foam composite lightweight soil. Geotechnical Special Publication 2006; 147:1639-1650

[11] Ferahian RH. Vibrations caused by pile driving, National Research Council-Ottawa, March, 1968. p. 10

[12] Gamble DL, Jow Y-K, Simpson TA. Effects of blasting vibrations on uncured concrete foundations, Proceedings of the Conference on Explosives and Blasting Technique 11th, 1985. p. 124-136.

[13] Howes EV. Effects of blasting vibrations on curing concrete, Proceedings of the Symposium on Rock Mechanics 20th, 1979. p. 455-460.

[14] Lee J-E, Kwan Y-W. Mechanical characteristics of curing concrete affected by forced vibration Korea institute for Structural Maintenance Inspection 2000; 4(1): p. 243-248.

[15] Massarsch KR. Vibrations caused by pile driving, Magazine of the Deep Foundations Institute. Summer 2004 (Part 1) and Fall 2004 (Part 2), 2004. p. 39-42.

[16] Spears RE. Effect of blasting, jarring, and other transitory vibrations on fresh concrete, Comments on concrete no. 9, Portland Cement Association, 1981. p. 4

[17] Hulshizer AJ, Desai AJ. Shock vibration effects on freshly placed concrete, Journal of Construction Engineering and Management ASCE, 1984; 110(2): p. 266-285.

[18] Kim H-K. Study on evaluation method for construction vibrations. Master thesis, Chonnam National University, 2004.

[19] Song H-G. Study on the effect of vibrations on fresh concrete. Master thesis, Seoul National University, 1998.

[20] Dunham MR, Rush AS, Hanson JH. Effects of induced vibrations on early age concrete, J of Performance of Constructed Facilities, 2006; 21(3): 179-184

Dunham MR, Rush AS. Parametric analysis of the effects of induced vibrations on concrete at early ages. Rep. No. 04/A01,

[21] Engineering Forensics Research Institute EFRI, http://www.rose-hulman.edu/~hanson, 2004
Furr HL, Fouad FH. Bridge slab concrete placed adjacent to moving live loads, Texas Transportation Institute, 1981, p. 131
[22] Kwan AKH, Zheng W, Ng IYT. Effects of shock vibration on concrete, ACI Materials Journal; 2005 Nov.-Dec, p. 405-413.
[23] Manning DG. Effects of traffic-induced vibrations on bridge-deck repairs, NCHRP Synthesis no. 86, Transportation Research
[24] Board, Dec. 1981. p.40.
KATS. Standard test method for unconfined compression test of soils (KS F 2314), 2011
[25]