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Fast Consolidation of Soft Clay due to Ultrasonic Energy

압밀촉진을 위한 초음파의 활용

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요 지

준설매립 및 연약지반 처리에 있어 압밀촉진 공법들에 대한 연구가 활발하다. 본 연구에서는 초음파를 사용하여 압밀촉진을 유발하고자 하였고 그 영향 정도를 실내실험을 통하여 조사하였다. 실내시험은 특별히 제작된 압밀시험기를 사용하였으며 압밀시험 중 초음파를 시료에 직접 가할 수 있도록 고안되었다. 압밀시험 재료로는 원심력 시험기를 사용하여 원하는 조건에 맞는 동질의 시료를 제작하여 사용하였으며 초음파 강도, 처리 시간을 달리하여 시험을 실시하였다. 시험결과 초음파가 압밀에 미치는 영향은 큰 것으로 나타났으며 초음파 처리의 영향에 미치는 정도가 시험조건에 따라 다르게 나타났다. 본 연구의 결과를 이용하여 초음파에 의해 압밀촉진을 위한 공법개발의 가능성을 파악하였다.

Abstract

Various researches have been undertaken to develope a method of enhancing consolidation. This study investigated the effect of ultrasonic energy on consolidation through a series of laboratory experiments. The tests were conducted using a specially designed and fabricated equipment which can apply ultrasonic energy on a soil sample directly during a consolidometer test. Clay specimens were prepared from slurry using a centrifuge facility, and test conditions were varied depending on ultrasonic power and treatment time. The results of the study show that the effect of ultrasonic energy on consolidation is significant. The degree of significance varies with the test conditions. It could be concluded that the study showed potential application of ultrasound to reduce consolidation time.

Keywords : Consolidation, Consolidometer, Permeability, Soft clay, Ultrasonic energy, Ultrasound

1. Introduction

The growth of population and industry has resulted in increasing needs of the available areas for the industrial activities. Reclamation work using dredged clays is one of the methods to buildup the sites. Dredged clay transported to the reclaiming area by the pump is slurry with high water content. Before starting the engineering activities on the reclamation area, dredged clay should be consolidated or stabilized for certain time to acquire sufficient bearing capacity.

Consolidation or stabilization needs longer time to reach sufficient bearing capacity. Many techniques are used to reduce consolidation time and to improve the

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strength. The available techniques for soft clay improvement include the progressive trenching method, the vertical drain method, and the horizontal drain method to name a few. However, these techniques are not without drawbacks and a method that can be effective and also economical for a broad range of field conditions is not yet available. Therefore, much still remain to be done in order that a generally accepted methodology can be developed for a broad range of applications.

Kim et al. (2000) conducted a series of laboratory studies to investigate the effect of ultrasound on contaminant removal from soils. It was not with the objective of reducing consolidation time in mind that the study was undertaken. However, they showed the enhanced permeability of water and oil due to the acoustic waves. According to Frederic (1965), the mechanisms responsible for the observed increase in transport rates and unit-operation processes because ultrasonic energy can be divided into two categories: first-order effects on fluid particles involving displacement, velocity, and acceleration, and second-order phenomena including radiation pressure, cavitation, acoustic streaming, and interfacial instabilities. Usually one or more of the second-order effects are responsible for the enhancement in transport process.

A few studies are available on the effectiveness of using acoustic waves to enhance contaminant extraction from contaminated soils. Ellen et al. (1995) reported an increase in contaminant extraction due to acoustic excitation. They hypothesized that acoustic waves can overcome the capillary force on contaminants in a soil by alternating over- and under-pressures which produce pulling and pushing actions to contaminant droplets. Thus, large contaminant droplets can be broken into smaller droplets. These smaller droplets can be flushed out more easily. Another study by Iovenitti et al. (1995) reported an improvement in contaminant removal. Cleveland and Garg (1993) showed that ultrasonic excitation can remove suspending fine particles to which the contaminants are strongly sorbed. Also, Reddi and Challa (1994) presented that ultrasonic waves can increase not only the mobility of NAPL ganglia but the porosity of the soil as well, resulting in a decrease in viscosity and buoyant pressure.

In general, travelling acoustic waves attenuate in porous media which is caused by the friction between pore liquid and particles. In other words, ultrasonic energy produces a pressure gradient through the porous media resulting in transport of pore liquid. Attenuation in porous media can be presented as the following equation.

$$I = I_0 \varepsilon^{-\alpha x} \tag{1}$$

Equation (1) shows that intensity of ultrasonic energy (I) is proportional to the initial intensity of ultrasonic energy (I_0), and decreased rapidly with the distance (x). ε and α are constants. Darcy's law tells that flow rate is inversely proportional to viscosity (η).

$$Q \propto \frac{1}{\eta} \tag{2}$$

Viscosity of pore liquid can be related with frequency as following.

$$\eta w^{\alpha} = a \tag{3}$$

where w is frequency, and a and α are constants. Considering equations (2) and (3) simultaneously shows that ultrasound can increase flow rate which can be attributed to the decrease of viscosity.

This study investigated potential of applying aforementioned idea to stabilize soft clay within a less time. The investigation was conducted through laboratory experiments to study the effectiveness of ultrasound on consolidation and time to require for stabilization. Consistent clay specimens from slurry were prepared using a centrifuge facility.

2. Laboratory Experiments

2.1 Physical Properties of Test Material

The test soil was clay obtained from the coast of Pusan area. The physical properties of the test soil are summarized in Table 1, and the particle size distribution is shown in Figure 1.

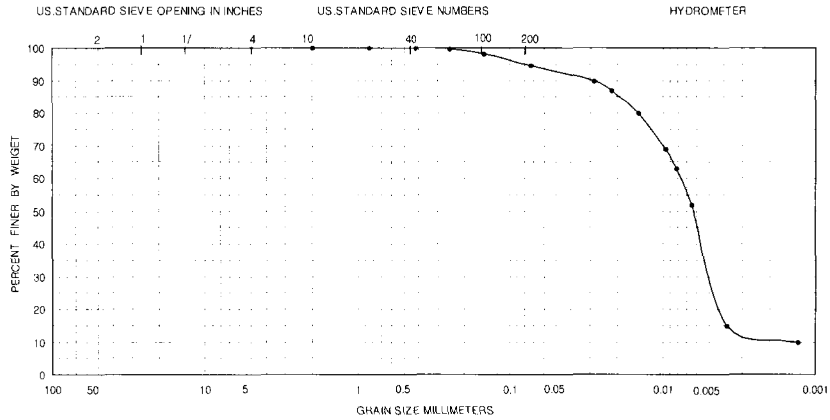


Fig. 1. Particle size distribution of test soil

Table 1. Physical properties of test soil

Mechanical Characteristics	Specific Gravity, G_s	Atterberg limit		USCS
		LL(%)	PI(%)	
clay	2.72	63.8	35	CH

2.2 Centrifuge Facility

Consolidated clay was prepared using a specially designed and fabricated centrifuge facility (Park et al., 2003). Figure 2 shows the facility, which has axisymmetrical 8 arms of 50 cm, 7.5 HP, and the maximum value of 1400 rpm. Eight cylinders with the radius of 20 cm and the height of 40 cm to contain specimens were connected to the arms. Slurry in the cylinders was consolidated to the desired degree by means of centrifuge forces. Thin films were located between the specimens and cylinders to reduce the frictional forces.

Consolidation test was then performed using a specially designed consolidometer which can apply ultrasound to clay specimen from the centrifuge facility. The

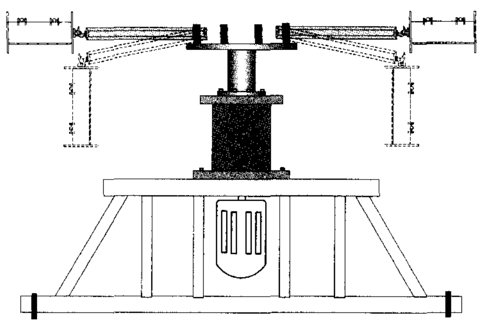


Fig. 2. Details of centrifuge configuration

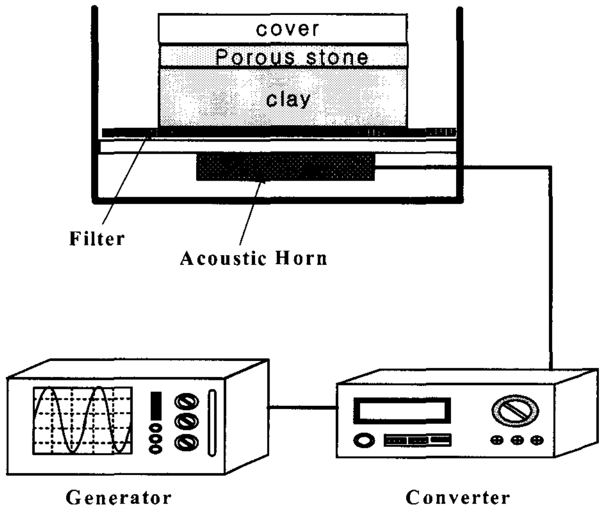


Fig. 3. Ultrasonic processor and consolidometer

schematic diagram of the consolidometer is shown in Figure 3.

2.3 Test Procedure

To investigate the effect of ultrasound on consolidation, this study was undertaken through ultrasound aided consolidation tests. The test conditions include various application time and power of ultrasound. These different levels were arbitrarily chosen to provide a range of test conditions. Just before the consolidation testing, clay slurry was treated using the centrifuge facility. Table 2 shows the variation of the preconsolidating pressure with the different rpm. r represents the distance between the center of the centrifuge facility and the middle of the specimen. W is the total weight of the specimen and a weight on the top

Table 2. Preconsolidation pressure

rpm	radius, r (cm)	Total weight (W, Kgf)	F(Kgf)	p'(kPa)
				Calculated
50	75	7.2	15.07	4.2
100	75	7.2	60.4	17
150	75	7.2	135.8	38.46
200	75	7.2	241.6	68.41
250	75	7.2	377.66	106.94
300	75	7.2	543.2	153.8

of the soil sample. The force acting on the soil sample can be obtained using equation (5). The preconsolidating pressure was then calculated by dividing total force by the area of the soil sample which is summarized in Table 2.

$$1\,rpm = \frac{rev.}{\min} \times \frac{2\pi \cdot rad}{1rev.} \times \frac{1\min}{60\sec} = \frac{\pi}{30}\,rad/\sec \quad (4)$$

$$F = ma = \frac{W}{g} \cdot \omega^2 \cdot r \quad (5)$$

The major steps involved in the experiments are as follows.

① Carefully place a sand mat at the bottom of the cylinder.

② Prepare clay slurry of water content over liquid limit and cure it for seven days.

③ Pour slurry into the cylinders and place a weight of 3.6 kg on the top of the soil sample.

④ Preconsolidate the prepared slurry in centrifuge at 50 rpm for 24 hours (Picture 1).

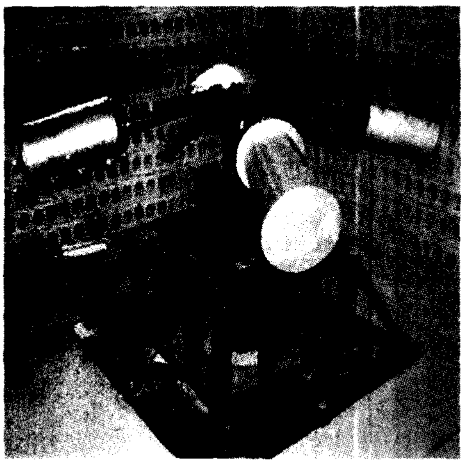
⑤ Centrifuge again the soil at 100, 150, 200, 250, and 300 rpm for 36 hours each.

⑥ Trim the preconsolidated soil, and conduct ultrasound aided consolidation test (Picture 2).

3. Test Results

The test results for each test condition both with and without ultrasonic energy are presented graphically in terms of void ratio vs. pressure and settlement vs. time as shown in Figures 4 and 5, respectively. Frequency of ultrasound was 25 kHz, and power of ultrasonic energy was 50 W. The treatment time with ultrasound at each load step was 1 hour. It is seen from Figure 4 that sonication increases settlement at each load step. At the end of the loading step, it can be seen that the total settlements of both with and without sonication condition are equal. It can be explained as follows. Consolidation is induced by the excess porewater pressure caused by a load. Therefore, both conditions (with and without sonication) have the same excess porewater pressure, and should show the same final settlement at the end of the load steps. Ultrasound attributes only to the time required for dissipation of the porewater. At unloading condition, sonication reduces the expansion rate. It is also seen from Figure 5 that sonication decreases time to require the same settlement.

Log t vs. vertical strain (e_v) at each load step of consolidometer tests is illustrated in Figures 6 through



Picture 1. Centrifuge facility

Picture 2. Consolidometer

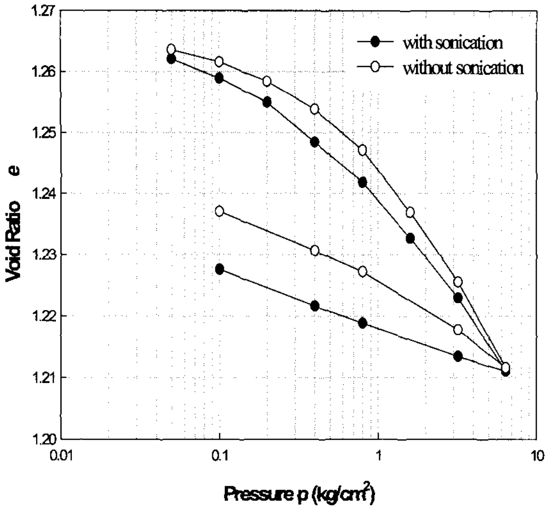


Fig. 4. $e-\log\ p$

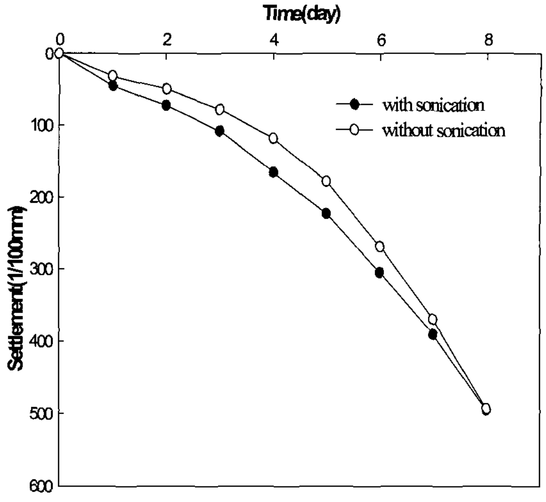


Fig. 5. Time vs. Settlement

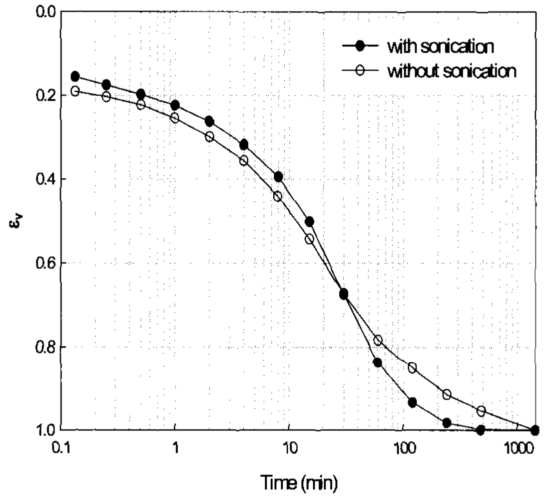


Fig. 6. Load step 0.05kg/cm^2

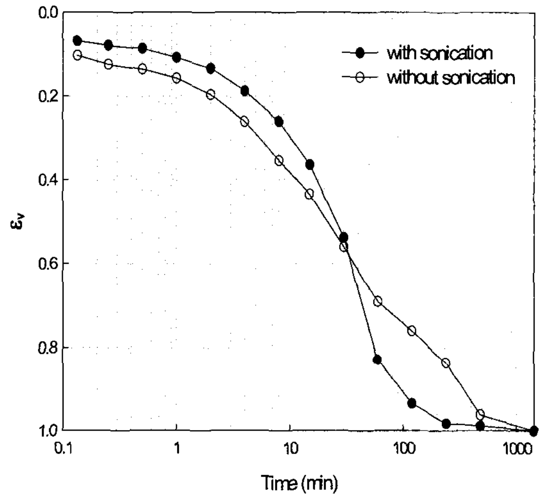


Fig. 7. Load step 0.1kg/cm^2

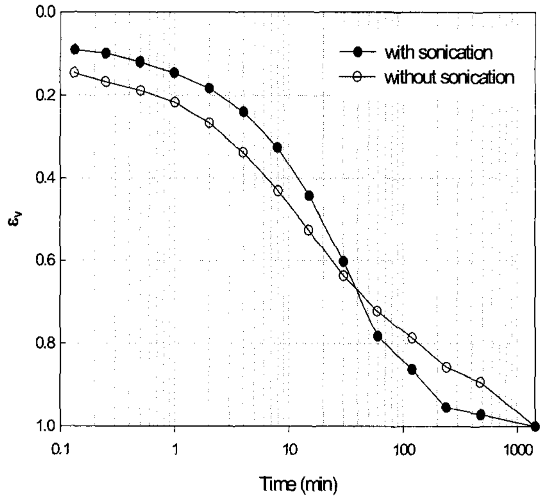


Fig. 8. Load step 0.2kg/cm^2

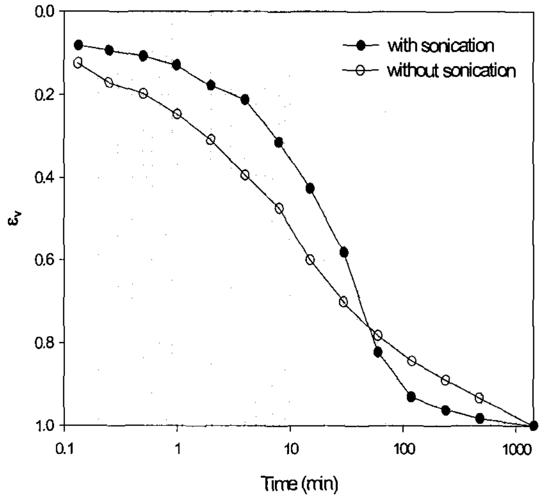


Fig. 9. Load step 0.4kg/cm^2

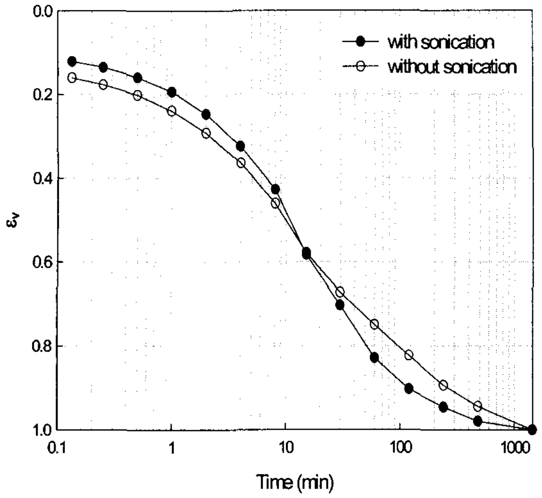


Fig. 10. Load step 0.8kg/cm^2

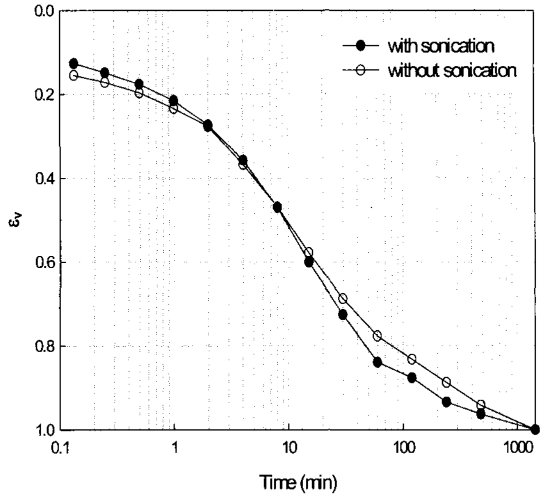


Fig. 11. Load step 1.6kg/cm^2

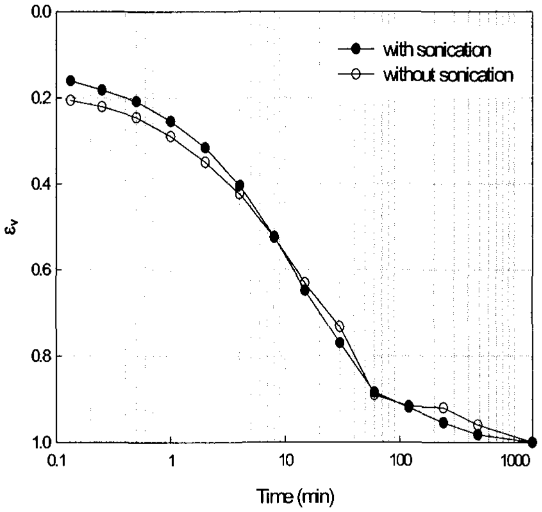


Fig. 12. Load step 3.2kg/cm^2

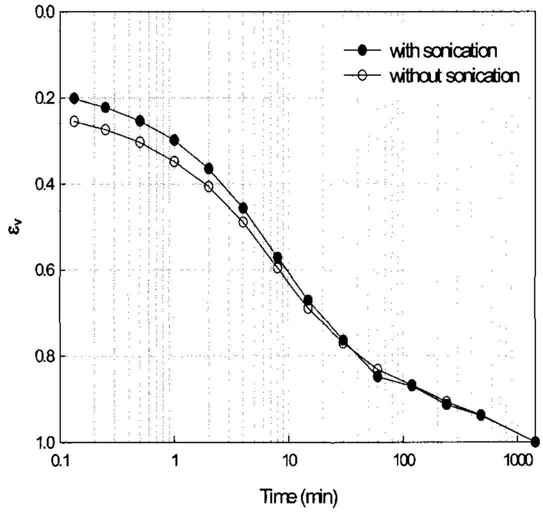


Fig. 13. Load step 6.4kg/cm^2

13. Figures show that there is a significant difference of time to reach the primary consolidation between with and without sonication conditions. The rate of the vertical strain shows similar trend at early stage of each load step, but as time goes by, ultrasonically treated specimen displays a great rate of vertical strain. It is also seen from the figures that the secondary consolidation or creep phenomena using the Casagrade method is not significant in the specimen treated by ultrasound. The end of the primary consolidation of ultrasonically treated specimen is far behind those of the non treated specimen. As the load increases, there is not significant difference of the vertical strain between with and without sonication conditions. It can be attributed to the reduced void ratio at later steps.

Figure 14 shows relations between the consolidation pressure and the coefficient of volume compressibility (m_v) with different sonication time. There is significant effect of ultrasound on volume reduction before the preconsolidation stress and the region of over consolidation. When the applied load passes the preconsolidation stress, ultrasound seems not affect volume reduction.

Treatment time can be another influencing factor to enhance consolidation time. Figure 15 shows variation of the normalized void ratio (e/e_0) with treatment time. It is seen that the normalized void ratio decreases as treatment time increases to a maximum around 1 hour then increases.

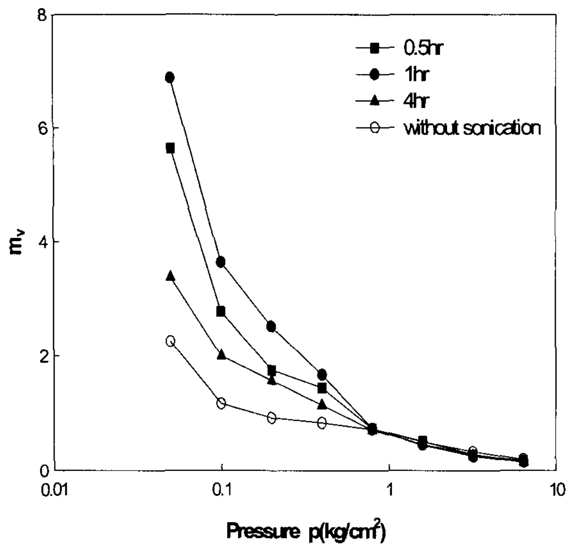


Fig. 14. Volume compressibility vs. Consolidation pressure

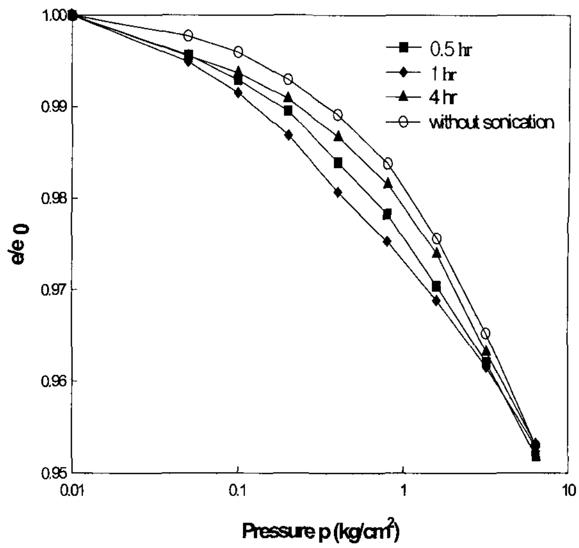


Fig. 15. Void ratio reduction with time

4. Summary and Conclusions

This study investigated the effect of ultrasound on consolidation time. The study involve laboratory experiments. Clay specimens were prepared from slurry using a centrifuge facility. The tests were conducted using a specially designed and fabricated equipments which can apply ultrasonic energy on a soil sample directly during a consolidometer test. From the results of the investigation, the following conclusions can be drawn.

(1) Ultrasound reduces consolidation time significantly. The degree of significance varies with test conditions.
(2) The effect of ultrasound on volume reduction is greater in the region of over-consolidation.
(3) The degree of enhanced consolidation time varies with treatment time with ultrasound. It is not proportional to treatment time.
(4) Application of ultrasound can reduce the secondary consolidation which can attributes rearrangement of soil particles due to ultrasonic energy.
(5) There is potential of a method development which can be applied widely to reduce consolidation time using ultrasound.

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References

1. Cleveland, T, G and Garg, Sanjay (1993), *Field demonstration of enhanced soil washing system for in-situ treatment of low-permeability soils*, Waste Management Proceedings of the Gulf Coast Hazardous Substance Research Centers Symposium on Emerging Technologies: Metals, Oxidation, and Separation, Vol.13, No.5-7, pp.519-520, Belmont, TX.
2. Frederick, J. R (1965), *Ultrasonic Engineering*, New York: John Wiley and Sons.
3. Iovenitti, J. L., Rynne, T. M., and Spencer, J. W., Jr. (1995), *Acoustically enhanced remediation of contaminated soil and ground water*, Proceeding of opportunity 95-environmental technology through small business, Morgantown, West Virginia, November.
4. Kim, Y., Khim,, J., and Lee, I. (2000), *Sonication Effect on NAPL Extraction from soils*, Journal of Korean Geotectechnical Society, Vol.16, No.3, pp.23-28.
5. Park, Yong-Won, Kim, Byoung-Il, Lee, Sang-Ik, and Park, Jong-Ho (2003), *Triaxial Test on Sand-Clay Composite Samples*, Proceedings of the 12 ARC Conference on Soil Mechanics and Geotechnical Engineering, Vol.1, pp.521-524, Singapore.
6. Reddi L.N. and Challa, S. (1994), *Vibratory mobilization of immiscible liquid ganglia in sands*, Journal of Environmental Engineering, Vol.120, No.5, pp.1170-1190.

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