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Ultrasonically Enhanced Liquid Flow through Porous Media and Variance of Influencing Factors

초음파 투사에 따른 흙시료 내 투수속도의 증가와 그 영향인자의 변화

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요 지

초음파 투사에 의한 흙시료 내 투수속도 증가에 관한 연구를 특별히 제작되어 준비된 실내실험 기구를 이용하여 수행하였다. 이 현상의 정확한 메커니즘을 이해하려는 노력의 일환으로 본 연구에서는, 초음파 투사시 투수속도 변화를 지배하는 영향인자를 도출하였다. 그리고, 다양한 실험 조건 하(시료의 종류, 초음파 조사의 유무, 그리고 온도 등)에 초음파에 의한 투수속도의 증가와 함께 이에 대한 메커니즘을 영향인자의 변화를 통해 살펴보았다. 연구결과에 의하면 초음파에 의해 시료내의 간극수 흐름이 크게 빨라졌으나 시험조건에 따라 그 값의 변화 폭이 크게 나타났다.

Abstract

This paper presented results of the laboratory tests conducted to investigate ultrasonically enhanced flow rate using specially designed and fabricated equipment. Influencing factor, α_i was verified to investigate the effect of ultrasound on soil matrix and flowing liquid. The test conditions involve soil types, temperature and ultrasonic energy. The test results indicate that ultrasound enhances the flow rate significantly. The degree of enhancement and the values of influencing factors, however, vary with test conditions.

Keywords : Flow rate, Hydraulic conductivity, Sandy soils, Stress waves, Ultrasound

1. Introduction

The behavior of the flow of fluids through porous media has been well known since Darcy (1856) formulated an empirical equation for the flow of water through sand. Among various investigators for the flow phenomena, Parker and Stringfield early in 1950 observed a sharp change of water level in a 50-m deep well in Florida due to a nearby passing train and a remote earthquake. They reported that the phenomenon could be attributed to the effect of stress wave on fluid flow through porous media. Later, Voytov et al. (1972) reported a large change in oil production, and a renewed production of abandoned wells due to a 6.5 magnitude earthquake occurred in Daghestan Republic (the former USSR) on May 14, 1970. Since then, stress waves

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have been utilized to enhance oil recovery by the petroleum industry both in the US and USSR.

It is known that ultrasound can markedly influence the behaviors of the flow of fluids through porous structures. However, studies of ultrasonic applications in soil science are scarce and are only in the conceptual stage. Berliner et al. (1984, 1987) showed that high intensity ultrasonic probe can disperse particulate suspensions resulting in an enhancement of the contaminant extraction. He hypothesized that a sound wave generates positive and negative pressure alternatively and thus stimulates the flow of liquids resulting in a change of the behavior. Reddi and Challa (1994), and Reddi and Wu (1996) presented that ultrasonic waves can increase not only the mobility of liquid ganglia but the porosity of the soil as well, resulting in a decrease in viscosity and buoyant pressure. Aarts et al. (1998) studied the mechanism of net flow rate induced by ultrasound. Poesio et al. (2002) found that ultrasound produced a significant effect on the pressure gradient and temperature at constant liquid flow rate through the core samples.

The available information reviewed above shows that ultrasonic waves could influence the behavior of the flow through the pore. The degree of enhancement varies with many factors, such as soil type, soil density, flow rate, temperature, wave frequency, energy level, and others. Since nearly every available study focused only on limited specific conditions without a systematic investigation for a broad spectrum of the various influencing factors, a methodology is not yet available for evaluating the effectiveness of ultrasonic waves. Such a methodology is essential in the practical application of using stress waves to enhance the flow of the pore liquid. It is with this objective in mind that this study was undertaken. The study investigates the effect of ultrasound on flow rate through laboratory study within a various range of the test conditions.

2. Laboratory Experiments

2.1 Test Equipments

The laboratory testing involved one-dimensional constant head tests and soil characteristics determinations. The constant head tests were conducted using specially designed and fabricated test equipment which is shown schematically in Figure 1. As shown, the test setup was composed of two parts - an ultrasonic processor and a test chamber, which was connected to a pump and de-aired water reservoir.

The test chamber was made of a Plexiglas cylinder having an inside diameter of 5.0 cm with a height of 20 cm. In the upper part of the cylinder are installed an inlet and an outlet tubes. The inlet tube is connected to a reservoir of de-aired water with a pump, which is connected to the water tap; and the outlet tube is used to maintain constant heads by allowing overflow of excess water. At the lower part of the cylinder, there is another outlet tube which is connected to a graduate cylinder for measuring the flow rate. A sensor and piezometer are mounted at the bottom part of the cylinder to measure temperature and hydraulic head during the tests.

The ultrasonic processor device was a 500W-Ultrasonic Processor manufactured by Cole-Parmer International. The Processor was calibrated by the manufacturer. The entire apparatus was composed of a generator, a converter, an acoustic horn, and a flat tip as shown in Figure 1. The generator (or power supply) converted the conventional 60 Hz AC at 220 V to a 20 kHz electrical energy at approximately 1,000 V. The high-frequency electrical energy was fed to the converter to transform the energy to mechanical vibration. The vibrator was

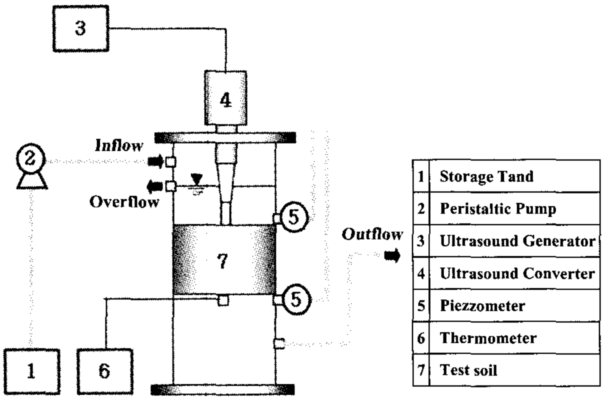

Fig. 1. Test setup

tuned to vibrate at 20 kHz. The acoustic horn and flat tip amplified the longitudinal vibration of the converter.

2.2 Test Soils

The test soils were commercially available Joomoonjin sand, a granite residual soil A, and a granite residual soil B which are very common in the Korean peninsular. Table 1 represents the physical properties of the test soils. Figure 2 shows the particle size distribution.

2.3 Test Procedure

Tests were started with carefully placing a pre-weighed soil sample in the test chamber. The soil specimen is then sandwiched between two #200 mesh screens to retain soil particles while allowing water to flow through the soil specimen. The soil specimen was saturated with water and maintains the water level at 1.5 cm above the top of the soil specimen. The permeability tests were conducted for two conditions - without and with sonication at 20 kHz frequency, high and low temperature of flow water, head differences of 2cm and 3 cm, and power of 120W, 240W, and 360W. The measurement was taken for the flow rate and the tests were started after obtaining the steady state of the outflow which takes about 3 days. After each test, particle size analysis was conducted to investigate the effect of ultrasound on soil particles.

3. Results and Discussion

3.1 Enhancement of Flow Rate

The test results of the flow rate are presented in Figures 3, 4, and 5 for Joomoonjin sand, a granite residual soil A, and a granite residual soil B, respectively. The figures show the variation of flow rate with time. In each figure, every five minutes, the power of ultrasound increases from 0 to 360W as shown. The vertical axes represent the variation of the flow rate during the tests in terms of times.

It is seen that the flow rate increases when the

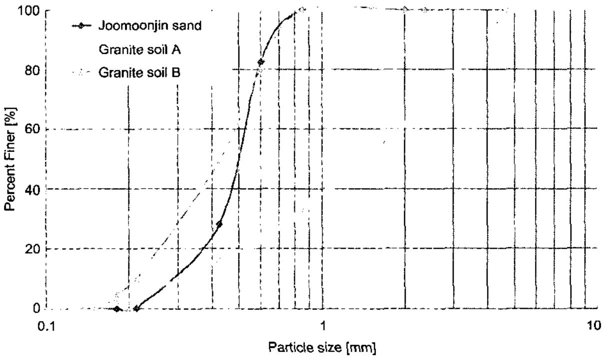

Fig. 2. Grain size distribution

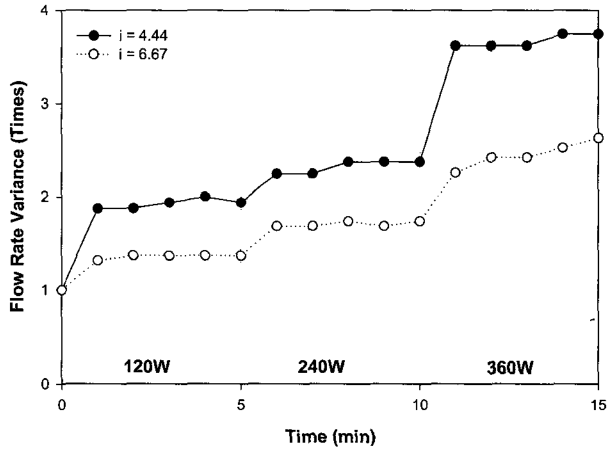

Fig. 3. Variation of flow rate with time (Joomoonjin sand)

Table 1. Physical properties of the test soils

	Joomoonjin Sand	Granite Residual A	Granite Residual B
Largest particle size	0.85 mm	4.75 mm	0.85 mm
Uniformity coefficient (C_U)	1.79	6.02	2.31
Effective grain size (D_{10})	0.29 mm	0.31 mm	0.21 mm
Median grain size (D_{50})	0.52 mm	1.29 mm	0.43 mm
Unified soil classifications	SP	SW	SP
Void ratio	0.6	0.6	0.6
Water contents	23%	23%	23%

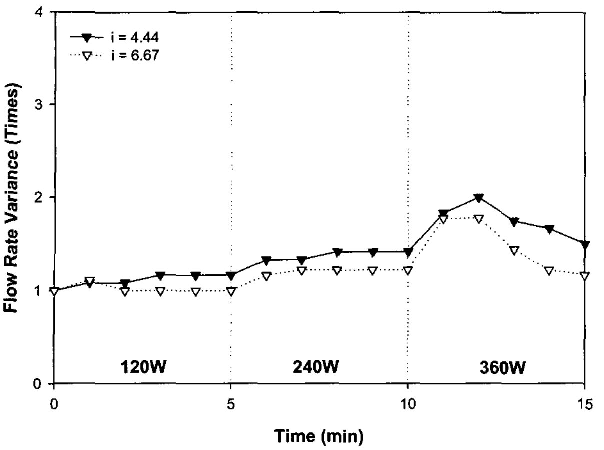

Fig. 4. Variation of Flow Rate with Time (Granite Residual Soil A)

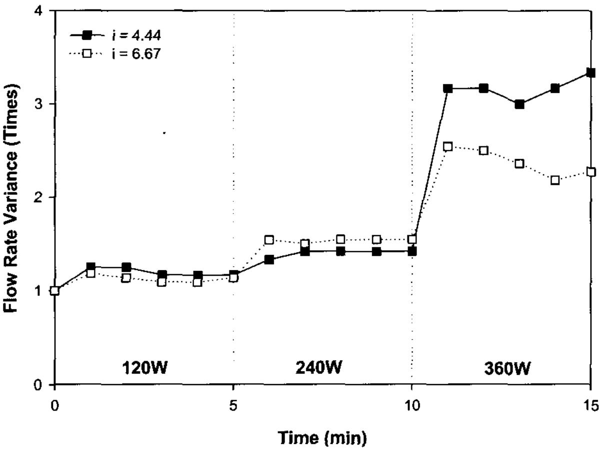

Fig. 5. Variation of Flow Rate with Time (Granite Residual Soil B)

ultrasonic source is turned on. As soon as sonication starts, the flow rate increases drastically. However, the degree of enhancement varies with the type of soil, head difference, and the levels of ultrasonic power. These are discussed in detail in the following section.

Possible loss of fine particles due to the ultrasound was investigated through the particle size analyses, and summarized in Table 2. The results of the investigation show that the loss is not significant.

3.2 Influencing Factors and Variance Rates

Darcy's equation is shown in Equation (1). The coefficient of permeability can be related with the intrinsic permeability through the gravity acceleration and the kinematic viscosity of liquid. Amer and Awad(1974) suggested an equation representing the coefficient of permeability of sandy soils as Equation (2). In cooperating Equations (1) and (2), Equation (3) can be obtained regarding flow rate of soil matrix and liquid.

$$V = Ki = \frac{g}{\upsilon} ki \tag{1}$$

$$K = C_2 D_{10}^{2.32} C_u^{0.6} \frac{e^3}{1+e} \tag{2}$$

$$V = Ki = C\frac{1}{\upsilon} D_{10}^{2.32} C_u^{0.6} \frac{e^3}{1+e} i \tag{3}$$

where, V = flow rate
K = coefficient of permeability
g = gravity acceleration
i = hydraulic gradient
k = intrinsic permeability
ν = kinematic viscosity of liquid
C_2, C = constants
D_{10} = effective grain size
C_U = uniformity coefficient
e = void ratio

Equation (3) tells that enhanced flow rate due to ultrasound is a complex combination of changed values in viscosity, effective grain size, uniformity coefficient, void ratio, and hydraulic gradient. This paper named those factors as influencing factors, and investigated variation of influencing factors due to ultrasound.

Let α_i be the ratio of varied to original value and those should be obtained through algebraic manipulation. Table 3 shows the influencing factors and variance rates by ultrasound. We can develop a new equation for enhanced flow rate using Equations (1) and (2) as following:

Table 2. Loss of particles

	Joomoonjin Sand		Granite Residual A		Granite Residual B	
Hydraulic Gradient (i)	4.44	6.67	4.44	6.67	4.44	6.67
Loss (%)	0.057	0.068	0.141	0.176	0.093	0.144

$$\alpha_1 V = (\alpha_2 K)(\alpha_3 i) \tag{4}$$

$$(\alpha_2 K) = C\frac{1}{(\alpha_4 \upsilon)}(\alpha_5 D_{10})^{2.32}(\alpha_6 C_u)^{0.6}(\alpha_7 E) \tag{5}$$

where, $E = \frac{e^3}{1+e}$

If we take log at both sides of Equations (1) and (4), we can get the Equations (6), (7) and Equation (8). According to that manipulation, Equations (9) and (10) can be obtained.

$$\log(V) = \log(K) + \log(i) \tag{6}$$

$$(\log\alpha_1 + \log V) = (\log\alpha_2 + \log K) + (\log\alpha_3 + \log i) \tag{7}$$

$$\log(\alpha_1) = \log(\alpha_2) + \log(\alpha_3) \tag{8}$$

$$\log(\alpha_2) = -\log(\alpha_4) + 2.32\log(\alpha_5) + 0.6\log(\alpha_6) + \log(\alpha_7) \tag{9}$$

$$\alpha_7 E = \frac{(\alpha_8 e)^3}{1+\alpha_8 e} \tag{10}$$

Figures 3, 4 and 5 represent the flow rate variance of α_1.

The tests of the hydraulic gradient variance give us the increased head loss ($\triangle h_p$). Figure 6 shows the test results of the hydraulic gradient variance. Using Equations (11) and (12), α_3 can be extracted. And then, using Equation (8), α_2 can be obtained.

$$\bar{i} = \frac{\Delta h_0 + \Delta h_p}{\Delta l} \tag{11}$$

$$\alpha_3 = \frac{\bar{i}}{i} \tag{12}$$

where, i = hydraulic gradient before sonication

$\bar{i}$ = hydraulic gradient on sonication

Table 3. Influencing factors & variance rates by ultrasound

Influencing Factor	Variance Rate	Influencing Factor	Variance Rate
V	α_1	C_u	α_6
K	α_2	$E\left(=\frac{e^3}{1+e}\right)$	α_7
i	α_3		
ν	α_4	e	α_8
D_{10}	α_5	k	α_9

$\triangle h_0$ = head loss before sonication [cm]

$\triangle h_p$ = increasing pressure head on sonication [cm]

$\triangle l$ = height of soil matrix (=4.5cm)

α_3 = variance of hydraulic gradient

The kinematic viscosity of liquid is a function of temperature, and ultrasound may cause an increase of temperature of liquid. Figure 7 is the value of the increased water temperature by ultrasound. Temperature measurements can evaluate α_4. α_5 and α_6 can be obtained through particle size analyses and changes in D_{10} and C_U due to ultrasound. It is assumed that α_5 and α_6 remain constant during tests and are always final value of the test because it is impossible to measure the varied particle size during ultrasound excitation. Incorporating aforementioned values and Equation (9) and (10) gives α_7 and α_8. This paper omits the specific pro-

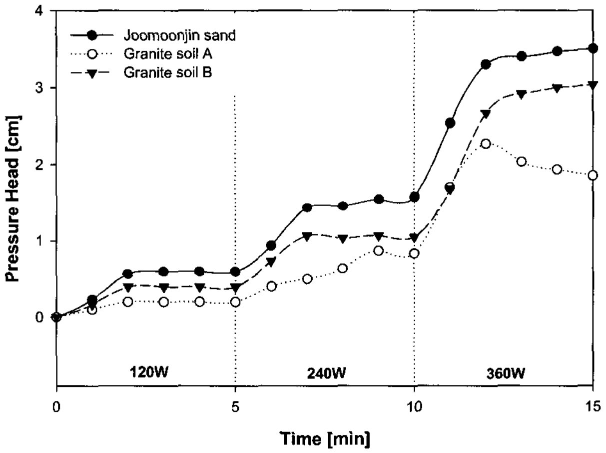

Fig. 6. Increased head loss by ultrasound

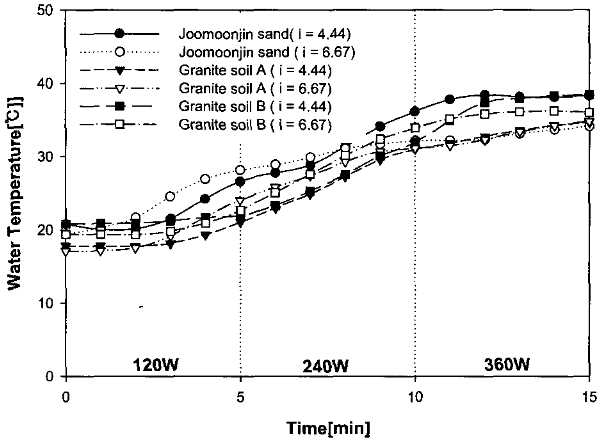

Fig. 7. Increased water temperature by ultrasound

cedures of obtaining α_i on account of limited space.

Figures 8 through 13 show the variation of α_i due to the application of ultrasound with different test conditions. Considering those Figures, Flow rate (α_1) increases at high ultrasonic power and low hydraulic gradient. α_3 is high at i = 4.44 and increases with time. As it would be expected, the viscosity factor (α_4) decreases with time. It can be attributed to its temperature increase due to ultrasound. Each different test condition, α_5 and α_6 shows similar trend. Void ratio factor α_8 shows not significant variation except granite residual soil A which lost more fine particles than other soils did (Table 1). It can infer that granite residual soil A is most fragile among the tested specimens resulting in clogging and reducing void (Figure 10 and 11). However, α_2 representing the coefficient of permeability shows different variation with soil type. The coefficient of permeability increases in most cases except the certain range in granite residual soil A. It can be attributed to its fine particles broken down due to ultrasound clog void resulting in a decrease of the permeability.

From 120W to 240W of ultrasonic power, Joomoonjin sand has the highest flow rate. From 360W, Granite soil B shows the similar values to those of Joomoonjin sand which can be found at the values of α_2 and α_8. It can be known from those results that in relatively low ultrasound power enhancement of flow rate is governed mainly by soil type. In high ultrasound power, however, particle size distribution of soil controls to enhance flow rate. Comparing α_1, it can be induced that hydraulic

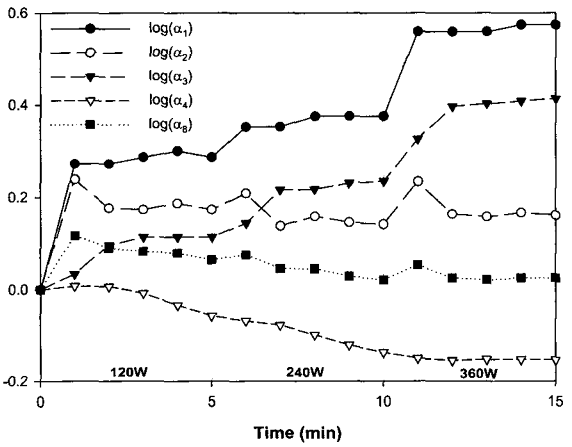

Fig. 8. Variation of influencing factor with time (Joomoonjin sand, i = 4.44)

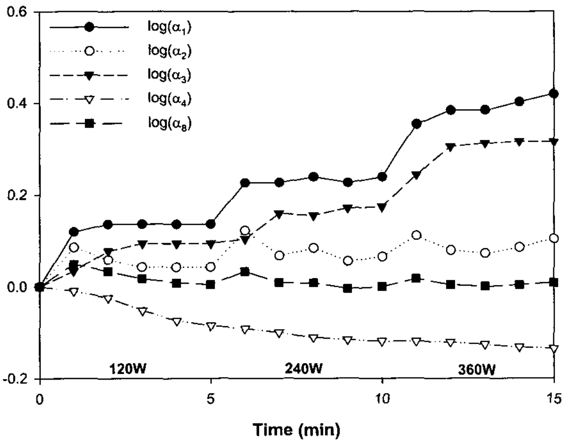

Fig. 9. Variation of influencing factor with time (Joomoonjin sand, i = 6.67)

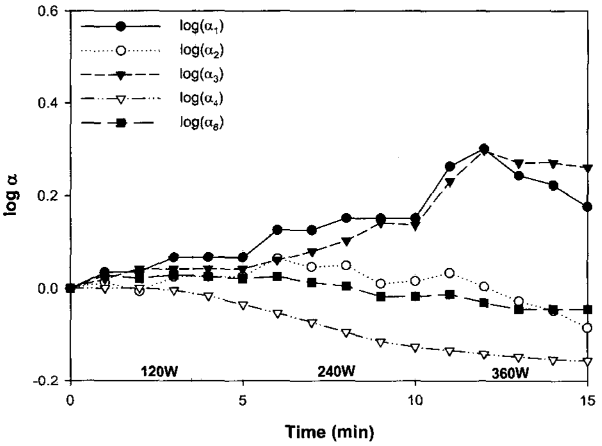

Fig. 10. Variation of influencing factor with time (Granite residual soil A, i = 4.44)

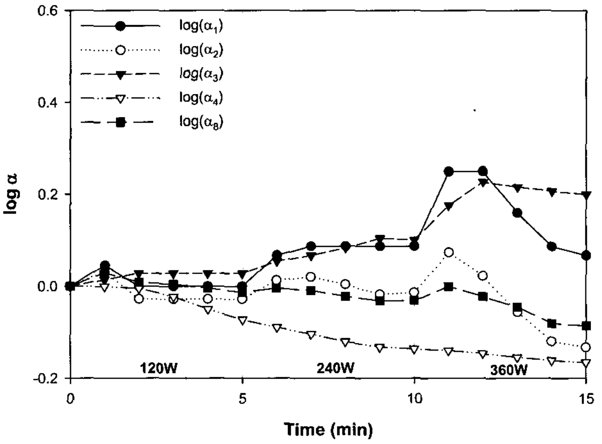

Fig. 11. Variation of influencing factor with time (Granite residual soil A, i = 6.67)

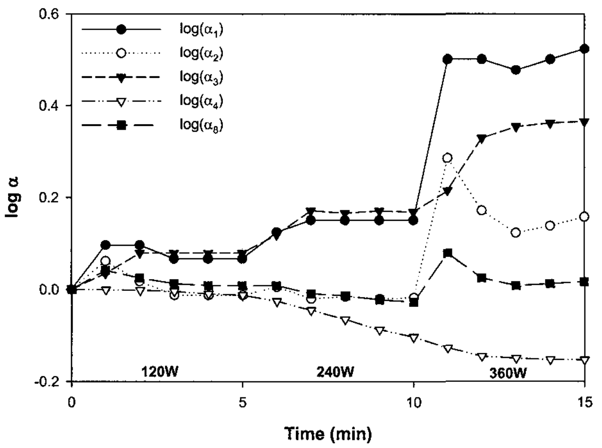

Fig. 12. Variation of influencing factor with time (Granite residual soil B, i = 4.44)

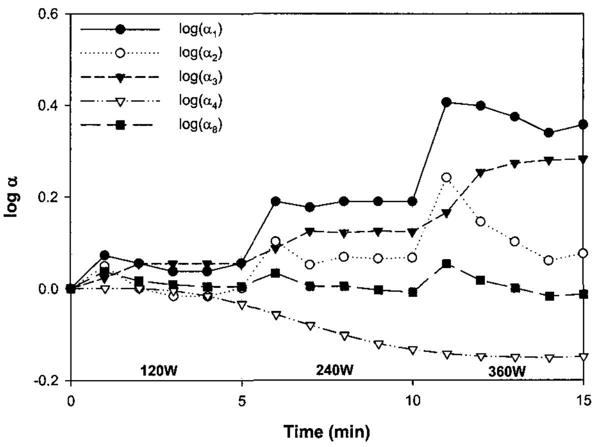

Fig. 13. Variation of influencing factor with time (Granite residual soil B, i = 6.67)

gradient is the major factor to increase flow rate due to ultrasound because hydraulic gradient has the biggest increasing value among all of the influencing factors.

The variation of α_i is proportional to the power of ultrasound and inverse-proportional to the head difference. Head difference is time dependent process and it can be immersed to the power factor. Low head difference means the slow movement of liquid resulting in enough time to acquire ultrasonic energy into the soil mass and liquid.

4. Summary and Conclusions

This paper presented results of the laboratory tests conducted to investigate ultrasonically enhanced flow rate and variation of influencing factors using specially designed and fabricated equipment. The test conditions involve soil type (Joomoonjin sand, a granite residual soil A, and a granite residual soil B), temperature, and ultrasonic power. From the results, the following conclusions can be drawn.

(1) Ultrasound enhances the flow rate of liquid through porous media significantly. The degree of enhancement varies with test conditions. Joomoonjin sand shows greatest increase of flow rate whereas a granite residual soil A does least.

(2) The influencing factor, α_i was verified using the equations for the permeability. Variation of α_i might indicate the portions of the effectiveness of ultrasound on soil mass and liquid. As results of investigation, viscosity was decreased. However, voids in Joomoonjin sand, a granite residual soil B increased whereas voids in a granite residual soil A decreased.

(3) In relatively low ultrasound power soil type controls the enhancement of flow rate due to ultrasound whereas the particle size distribution of soil does the enhancement of flow rate due to ultrasound in high ultrasound power.

(4) Applying ultrasound to enhancing flow rate of the pore liquid, hydraulic gradient could be the major factor to obtain a significant effectiveness.

Acknowledgements

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