Geomechanics and Engineering, *Vol. 33, No. 2 (2023) 211-219*
https://doi.org/10.12989/gae.2023.33.2.211

Ultrasonically enhancing flowability of cement grout for reinforcing rock joint in deep underground

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(*Received October 13, 2022, Revised April 3, 2023, Accepted April 10, 2023*)

Abstract. This study analyzes the changes in the physical properties of grout by irradiating it with ultrasonic energy and assesses the injectability of the grout into deep rock fractures. The materials used in the research are OPC (Ordinary Portland Cement) and MC (Micro Cement), and are irradiated depending on the water/cement ratio. After irradiating the grout with ultrasonic energy, viscosity, compressive strength, and particle size are analyzed, and the results of the particle size analysis were applied to Nick Barton's theory to evaluate the injectability of the grout into deep rock fractures under those conditions. It was found that the viscosity of the grout decreased after ultrasonic wave irradiation, and the rate of viscosity reduction tended to decrease as the water/cement ratio increased. Additionally, an increase in compressive strength and a decrease in particle size were observed, indicating that the grout irradiated with ultrasonic energy was more effective for injection into rock fractures.

Keywords: cavitation; deep underground; grout; rock fissures; ultrasonic wave

1. Introduction

Major cities around the world are conducting various attempts and research on underground section development to resolve urban overcrowding issues. However, determining the space development is challenging due to the various ground conditions and laws with countries, especially in deep sections. Here after, the underground space that can be developed is determined to be areas below 40 meters in depth (South Korean standard). This is defined as a deep underground.

Major cities around the world are often located near rivers for reasons such as water supply and aesthetics, making it essential to consider the effects of groundwater. From this perspective, blocking groundwater inflow and securing space is the most crucial element in underground space development (Fei *et al.* 2021). Deep underground strata often consist of bedrock layers due to the relatively high pressure they receive compared to the ground surface (Mazaira and Konicek 2015). When excavating deep underground bedrock layers, groundwater inflow occurs due to stress release, which can be prevented by performing grouting, injecting appropriate slurry into the bedrock. Grouting is utilized to enhance the mechanical properties of the rock, prevent cracks, and serve the purpose of a cut-off wall (Jalaleddin 2013). However, effectively performing rock grouting is not easy due to various influencing factors and the uncertainty of discontinuity (Gunnar and Hakan 1996). For effective rock grouting, it is essential to identify the engineering characteristics of discontinuity through ground investigation and consider appropriate grouting materials, mix ratios, and particle size distribution of grouting materials (injection material).

A simple method to consider the particle size distribution of grouting materials is to utilize materials with small particle sizes, such as micro-cement (MC). Materials based on Ordinary Portland Cement (OPC) are inexpensive and have characteristics such as relatively low strength, long gel time, and imbalance of particle size. In contrast, MC has opposite properties and has advantages in bleeding and rheological properties (Warner 2003, Mollamahmutoglu and Yilmaz 2011). MC is a high-performance cement material made by appropriately grinding ordinary particle size cement and has similar penetrability to chemical grouts due to its small particles (Jianwu *et al*. 2022). The chemical method uses a admixtures in the grout to increase strength and stiffness or to facilitate fluidity, but it has environmental disadvantages compared to the physical grout method because it uses a admixtures. Physical grout methods include using a colloidal mixer, utilizing vibration, and the ultrasonic method proposed in this paper. The colloidal mixer improves the uniformity and viscosity of the slurry through high-speed and low-speed mixing. The high-speed mixing ensures that cement and water are sufficiently mixed, while the low-speed mixing evenly disperses additives and other components maintaining the stability of the slurry (Nonveiller 1996, ASTM C476-18 2018).

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ISSN: 2005-307X (Print), 2092-6219 (Online)

Table 1 Type of ultrasonic wave

	Single Frequency (28 kHz)	Single Frequency (40 kHz)	High Frequency (100~500 kHz)	Mega sonic (1 MHz)
Theory	Cavitation	Cavitation	Molecular Acceleration	Molecular Acceleration
Particle Acceleration	1500G	2500G	5000G	100000G
Impulsive Force	Hundreds of atmospheric Pressure	Dozens of atmospheric Pressure	Several of atmospheric Pressure	
Standing Wave	Very Powerful	Powerful	Weak	
Wave Characteristic	Diffusiveness	Diffusiveness	Straightness	Straightness
Usage	Normal	Normal	Precise	Super Precise

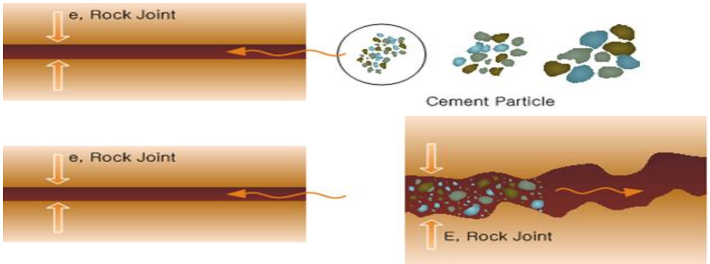


Fig. 1 e and E depending on the roughness of the joint (Barton 2004)

The vibration method involves using a vibrating injection device to change the injection pressure and vibration frequency to improve penetration injection range. Penetration injection is difficult in ground with small gaps, and as penetration injection progresses, particles are adsorbed, causing clogging. Vibrating grout improves the penetration injection range by changing the injection pressure and vibration frequency using a vibration device. There is research suggesting that using cement based on OPC for vibrating injection is more efficient than using micro cement (Kim *et al.* 2019). Lastly, there is the method utilizing ultrasonic waves proposed in this study. Ultrasonic wave is classified into Single Frequency (28 kHz, 40 kHz), High Frequency (100-500 kHz) and Mega sonic (1 MHz) depending on the frequency and is used in various fields such as medical care, communications equipment, appliances and construction.

The frequency characteristics are summarized in Table 1. In geotechnical engineering, various purposes are being researched depending on the usage and frequency, such as determining rock quality index (Jovicic *et al.* 1996), analyzing consolidation of soil and rock (Shen and Miura 1999), ground improvement (Kim *et al.* 2013), compaction enhancement (Park *et al.* 2014), sludge dewatering (Na *et al.* 2014), analysis of shear wave velocity in dry sand (Kim and Stokoe 2014), improving uniaxial compressive strength of cement (Kim *et al.* 2015), ground behavior monitoring (Park and Lee 2016), and evaluating the internal structure of ground improvement (Peng *et al.* 2019). In this study, physical force (cavitation principle) is used to disperse cement particles, thus creating the optimal injection state for the grout. By irradiating the grout with ultrasonic waves, the cavitation principle causes the dispersion of clustered particles, allowing for the adjustment of the particle size distribution of the injection material. The frequencies that cause cavitation are 28 kHz and 40 kHz in single frequency, and the 28 kHz single frequency, which can apply a relatively larger impact, is used. This frequency has strong standing waves and diffraction, and when ultrasonic waves are irradiated in the liquid, cavitation occur, resulting in hundreds of pressure shocks.

In this study, grout based on OPC and MC is prepared with various w/c ratios, and the physical property changes are observed after irradiating ultrasonic wave. Moreover, the applicability of injecting the ultrasonic wave-treated grout into rock joint is analyzed based upon Barton's joint-injection theory. This research aims to contribute to the improvement of crack and groundwater inflow problems that occur during the deep underground rock excavation process by enhancing the flowability of ultrasonically treated grout.

2. Grout injection and ultrasonic wave theory

2.1 Grout injection

In order to inject grout into rock joint surfaces, it is important to select materials with particle sizes that can pass through the rock joint spacing. If the particle size of the material is larger than the spacing of the rock joints, injection becomes difficult, and the effect of grouting is diminished. In this regard, Barton (2004) proposed a theory considering the correlation between penetrate real joints, theoretical hydraulic apertures, and roughness coefficients, as shown in Eq. (1). The joint aperture inequality $E \geq e$ was graphed by Barton (1972) based on thesis work by

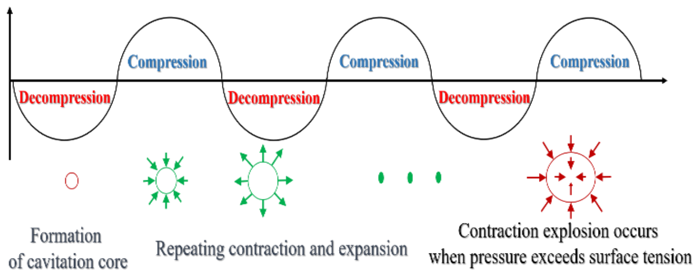


Fig. 2 Principle of cavitation

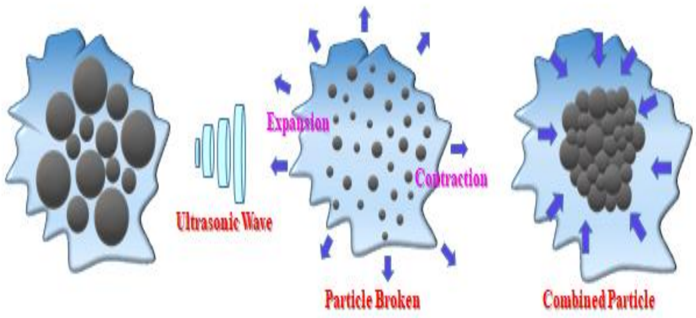


Fig. 3 Principle of ultrasonically irradiated grout

Danielsen (1971), and Sharp (1970) and later related to JRC by Barton (1982), based on in situ testing and further collection of data. The aperture inequality has been confirmed by numerous authors' water-flow experiments since those times. It is important because it allows grout particles to penetrate real joints (mean apertures: E) even when the theoretical hydraulic apertures (e) are apparently too small, as illustrated in the top diagram(Fig. 1).

$$\mathrm{E} \approx \sqrt{\mathrm{e} \times \mathrm{JRC}^{2.5}} \tag{1}$$

E: Penetrate real joints(Mean apertures)
e: Theoretical hydraulic apertures
JRC: Roughness coefficient

By using Eq. (1), the penetrate real joints can be calculated, and the passability of the grouting material for the penetrate real joints (E) can be determined using Eq. (2). D_{95} is the 95% passing particle size of the material, and it means that the penetrate real joints (E) must be large enough for the material to pass through.

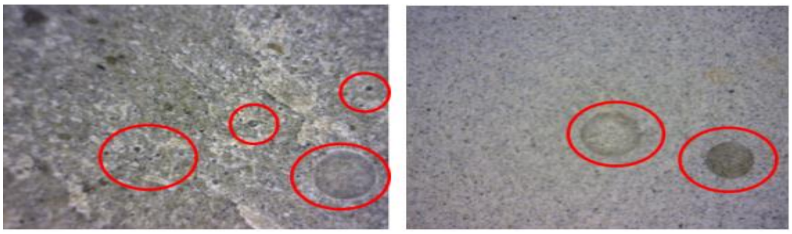
$$\mathrm{E} \geq 4D_{95} \tag{2}$$

2.2 Ultrasonic wave

Grout is a mixture of water and cement (cement paste) and can be combined with other materials to improve fluidity or strength. In rock grouting, it is common to use water, cement and admixtures to ensure fluidity due to the small gaps in the discontinuous surfaces. Cement does not dissolve in water, so it forms in a cohesive state. However, when ultrasonic wave is applied to the grout, a physical change occurs in which the particles disperse. This process is shown in Figs. 2 and 3. After determining the mix of cement and water, ultrasonic wave is applied during mixing. When the grout is irradiated with ultrasonic wave, tiny bubbles form, and these bubbles contract (compress) under pressure and expand when pressure is reduced. As the bubbles repeatedly contract and expand, their size increases, and when a certain pressure is reached, the bubbles explode, causing a massive shock wave (Almir *et al.* 2020). The following changes occur due to the explosion of the bubbles:

① Dispersion of flocculated cement particles
② Improved wetting ability of cement particles
③ Rearrangement of cement particles
④ Recombination of cement particles

The principle of cavitation due to ultrasonic irradiation has been proven in other research (Moon *et al.* 2017). Fig. 4 shows the cross-sections of the porous body taken using an electron microscope after ultrasonic treatment. In the case without ultrasonic waves (w/o uw), large voids were formed or numerous voids were observed (Fig. 4(a)), whereas with ultrasonic waves (w/ uw), small voids or no voids were formed (Fig. 4(b)). Bubbles can be formed during the grout mixing process due to incomplete mixing or during the hardening process, and these bubbles remain in the hardened body as voids. Such voids have a negative impact on the strength and durability of the grout. However, when ultrasonic waves are irradiated, the contraction and expansion of the bubbles cause them to burst, minimizing and removing the bubbles.



(a)w/o uw grout specimen

(b)w/ uw grout specimen

Fig. 4 Comparison of grout specimen cross-sections based on ultrasonic wave treatment(Moon *et al.* 2017)

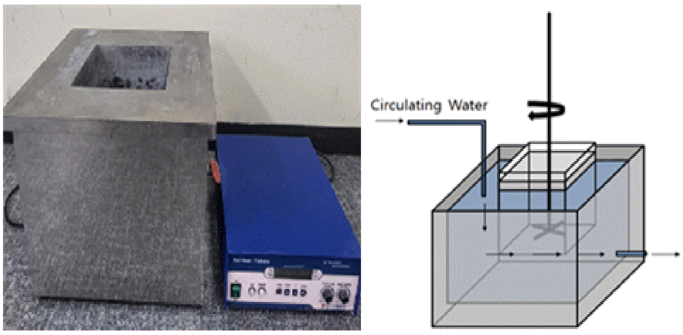


Fig. 5 Bath-type ultrasonic wave processor

Fig. 6 Viscosity measurement using rheometer SST

3. Experiments

The ultrasonic wave equipment was specially designed and manufactured for this study (Fig. 5). It was custom-made by Dong-shin Ultrasonic (South Korea). Inside the ultrasonic bath, there is a built-in vibrating socket capable of emitting a specific frequency, and the ultrasonic wave is generated by receiving frequency signals from a controller. The controller can fix the time and frequency of ultrasonic wave irradiation, and its time was set to 8 minutes based on the analysis of previous research results by our research team (Moon *et al*. 2017, Moon *et al.* 2019).

The compressive strength test was conducted to analyze the strength changes in samples treated with ultrasonic wave. For the compressive strength test, OPC is set to w/c = 0.5~1.0, while MC was set to w/c = 0.7~1.0 and 50(d) × 100(h) mm specimens were produced. The specimens were cured in water for 3, 7, 15 and 28 days, as shown in Fig. 7. Seven specimens were prepared for each case, and five intact specimens were selected for the compressive strength test. A Universal Testing Machine was utilized, applying a loading rate of 1min/mm. The Universal Testing Machine can perform tensile, compressive, and bending tests.

The particle size analysis was performed using a particle

Table 2 Experimental condition

- w/c : OPC = 0.5~1.0, MC = 0.7~1.0
- Curing Time(in water) : 3, 7, 15, 28day
- Ultrasonic Wave Output : 1,200Watt
- Ultrasonic Wave Irradiation : 8min
- Type of ultrasonic wave : Single Frequency(28 kHz)

Fig. 7 Water curing specimens(3, 7, 15, 28 days)

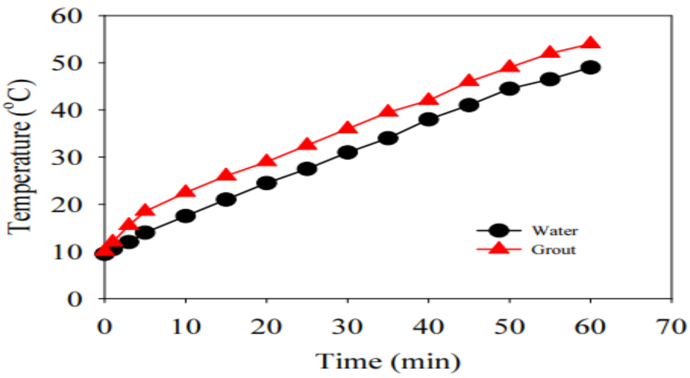


Fig. 8 Temperature change of water and grout depending on the duration of ultrasonic irradiation

size analyzer (Ls 230) from Beckman Coulter. The particle size analyzer is an instrument that uses a laser diffraction system, where scattered light is detected by a detector to measure the particle size. The measuring range of the wet analysis device is 0.04 μm~2000 μm, and all types of materials can be measured. The experimental conditions are summarized in Table 2.

When ultrasonic irradiation is applied to grout, cavitation causes bubbles to contract and expand, resulting in a very high temperature momentarily. However, in reality, the temperature increase is not significant and slowly increases linearly over time, as shown in Fig. 8. When ultrasonic is applied to both water and grout, the temperature increases linearly. In this study, the application time of ultrasonic wave was limited to 8 minutes, and the temperature increase at that time was confirmed to be about 4~5°C. When ultrasonic wave is applied to grout, the temperature of the grout increases and the intensity of cavitation weakens. In addition, the viscosity of the grout may appear to decrease due to the temperature increase. To prevent this, cooling water was circulated inside the ultrasonic equipment to maintain the grout temperature change within ±2°C and the laboratory temperature at 20°C.

4. Results

In the grout mixing process, a notable difference was the change in the grout surface depending on the w/o uw or w/ uw. Fig. 9(a) shows the process of mixing water and cement without ultrasonic irradiation, and there was no change in the grout surface. However, Fig. 9(b) shows the process of mixing water and cement with ultrasonic irradiation, and changes appeared due to ultrasonic energy. This was because the internal pressure of the grout decreases, causing the flocculated particles to be dispersed, which led to a decrease in viscosity and an increase in the mixing speed, resulting in the formation of vortices.

Table 3 compares the viscosity of the OPC and MC. Both OPC and MC showed a decrease in viscosity as w/c increased. With ultrasonic irradiation, OPC showed a 66% reduction at w/c=0.5 and a 14% reduction at w/c=1.0, indicating that the efficiency of ultrasonic wave decreases as w/c increases. MC showed a 19% reduction at w/c=0.7 and a 7% reduction at w/c=1.0, similar to OPC, with the efficiency of ultrasonic wave decreasing as w/c increased. The most significant change was observed in the OPC case with w/c=0.5, and it was analyzed that the ultrasonic wave

(a) w/o uw grout (b) w/ uw grout

Fig. 9 Surface changes of grout depending on w/o uw or w/ uw

Table 3 Viscosity of grout by w/o uw or w/ uw

	OPC			MC		
w/c	w/o uw (Pa.s)	w/ uw (Pa.s)	Reduction of Viscosity (%)	w/o uw (Pa.s)	w/ uw (Pa.s)	Reduction of Viscosity (%)
0.5	1.76	0.60	66	-	-	-
0.6	0.81	0.54	33	-	-	-
0.7	0.47	0.39	17	1.76	1.42	19
0.8	0.40	0.33	18	0.86	0.70	19
0.9	0.31	0.25	19	0.56	0.50	11
1.0	0.26	0.21	19	0.54	0.48	11

Table 4 Compressive strength of specimens by curing time & w/o uw or w/ uw

		OPC			MC		
w/c	Curing Time (Day)	w/o uw (MPa)	w/ uw (MPa)	Increase of Compressive Strength (%)	w/o uw (MPa)	w/ uw (MPa)	Increase of Compressive Strength (%)
0.7	3	5.7	7.0	23	17.0	18.0	6
	7	7.5	8.5	13	17.3	18.5	7
	15	9.5	10.7	13	17.8	20.5	15
	28	11.8	13.1	11	20.2	22.2	10
0.8	3	2.4	3.0	25	10.3	11.1	8
	7	3.7	4.2	14	11.2	12.2	9
	15	4.9	5.3	8	13.6	14.9	10
	28	6.1	6.6	8	16.1	17.0	6
1.0	3	1.2	1.5	25	6.9	7.4	7
	7	1.4	1.8	29	7.1	8.5	20
	15	2.1	2.5	19	8.3	9.8	18
	28	3.5	4.0	14	9.9	10.7	8

irradiation efficiency is higher when the w/c is lower due to a greater number of flocculated particles. In general, when ultrasonic irradiation is applied, the viscosity tends to decrease, which can improve the flowability of the grout and increase injection efficiency. These results will be helpful in adjusting grout viscosity using ultrasonic wave.

Table 4 shows the changes in compressive strength according to OPC w/c, MC w/c, w/o uw, w/ uw and time.

When ultrasonic irradiation was applied, the compressive strength increased in all cases, and the rate of compressive strength increase varied depending on w/c and curing time. OPC specimens tended to have a higher rate of compressive strength increase, but the actual strength was not high, while MC specimens had a lower rate of compressive strength increase compared to OPC but exhibited higher strength.

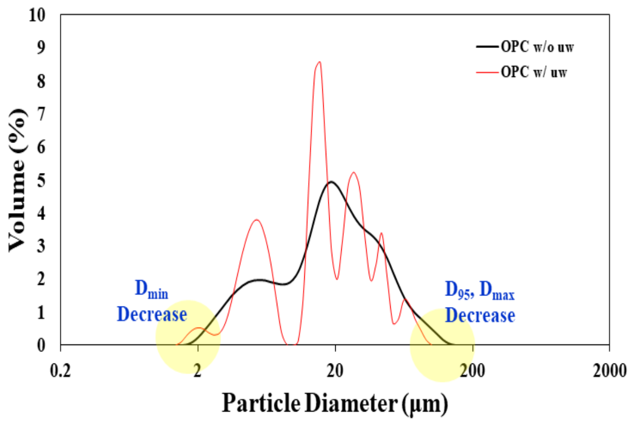


Fig. 10 Particle size distribution of OPC

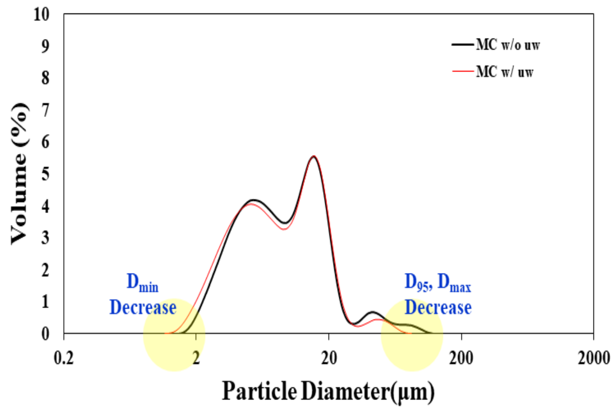


Fig. 11 Particle size distribution of MC

Table 5 Particle size analysis of grout by w/o uw or w/ uw

	OPC		MC	
	w/o uw (μm)	w/ uw (μm)	w/o uw (μm)	w/ uw (μm)
D_{50}	19.49	16.73	9.319	8.675
D_{90}	52.94	44.94	21.76	20.45
D_{95}	63.41	52.62	33.01	22.5
D_{min}	1.384	1.184	1.384	1.149
D_{max}	161.2	101.1	133.7	83.39
D_{avg}	25.19	21.56	12.78	11.19

Furthermore, both OPC and MC showed a tendency for strength to decrease as w/c increased. In summary, it was revealed that the compressive strength of OPC and MC mixtures generally increased when ultrasonic irradiation was applied. This suggests that ultrasonic waves can have a positive impact on the improvement of grout compressive strength.

Particle size analysis was conducted for w/c=0.7, which was selected as it was relatively easy to compare among the OPC and MC mix ratio cases and was expected to have the most particle flocculation. The experiment results showed that particle decomposition occurred well due to the effect of ultrasonic wave, and the particle size distribution was adjusted. In OPC, particles distributed between 111-161 μm were decomposed after ultrasonic irradiation and became smaller particles (below 101 μm), and the distribution of particles in the 17-25 μm range significantly increased in the 12-15 μm range after decomposition (Fig. 10). In MC, particles distributed between 85-134 μm were decomposed after ultrasonic irradiation and formed particles below 84 μm (Fig. 11). Overall, the particle size distribution uniformly decreased, with D_{avg}, D_{95} and D_{max} decreasing by 14%, 17% and 37% in OPC, and by 14%, 32% and 38% in MC (Table 5).

The size of rock joints is the most critical factor in grout injection (Huang *et al.* 2020). In this regard, Mitchel (1970) stated that penetration injection is possible if the particle size of the injection material is less than 1/3 of the apertures, and Barton (2004) proposed Eq. (2). The deep underground was set as depths below 40 meters underground, and by referring to Barton's (2004) paper, penetrate real joints were determined to be 138 μm.

Applying Eq. (2) to analyze the injectability of grout into deep underground rock joints, in OPC w/o uw, $4D_{95}$=253.64 μm, and in w/ uw, $4D_{95}$=210.48 μm. Although the particle size decreased due to ultrasonic irradiation, it exceeded the threshold of 138 μm, indicating that injection is impossible.

In the case of MC, w/o uw had $4D_{95}$=132.04 μm, slightly higher than the threshold, suggesting the possibility of clogging during injection. Meanwhile, w/ uw had $4D_{95}$=90 μm, which is below the 138 μm threshold, indicating a higher injectability.

5. Conclusions

In this study, grout based on OPC and MC was prepared at various w/c ratios and analyzed for changes in physical properties upon ultrasonic irradiation. The injectability of the grout into rock joints was assessed using Barton's theory after analyzing the physical property changes resulting from the ultrasonic irradiation.

The compressive strength was found to increase in all cases after ultrasonic irradiation. However, since the primary purpose of rock grouting is to resist the infiltration of groundwater, the influence of compressive strength is not considered a crucial factor (Yuhao *et al*. 2018). Nevertheless, this study demonstrated a significant result, as the compressive strength increased due to ultrasonic irradiation. This increase is believed to be a result of particle breakdown and rearrangement caused by ultrasonic wave, which enhances the wettability of cement particles, and is deemed a valuable outcome that can be utilized in various fields.

Particle size analysis revealed that agglomerated particles were broken down, and the particle size distribution changed due to ultrasonic irradiation. While OPC decomposed a significant amount of particles after ultrasonic treatment, it was not suitable for injection into deep underground rock joints. After ultrasonic irradiation, OPC decomposed a large amount of particles, but it was found to be unsuitable for injection into deep underground. Before ultrasonic treatment, MC had the potential for clogging during injection, but after the treatment, stable injection seemed possible. However, further research on appropriate conditions is needed to enhance injectability.

In summary, it is significant that the properties of grout are improved by physical force (ultrasonic wave). This also has meaningful implications in terms of environmental friendliness. Typically, chemical methods are widely used for grouting reinforcement to obtain initial strength and fluidity. However, strength gained through chemical methods decreases over time and is environmentally harmful (Fei *et al*. 2020). In contrast, using ultrasonic wave does not involve chemical additives and breaks down particles with pure physical force, proving to be more environmentally friendly compared to chemical methods.

The application of ultrasonic energy can positively impact various aspects of grout, such as improving fluidity, adjusting particle size distribution, and enhancing compressive strength. It is expected that this will increase the stability and sustainability of grout injection in rock joints. Furthermore, utilizing ultrasonic energy for grout injection could contribute to effectively solving the issues of cracks and water ingress arising from rock excavation and tunneling processes.

Acknowledgments

This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (grant number 22UUTI-C157813-03) and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant number 2021R1I1A1A01049067).

References

ASTM International (2018), *Standard Specification for Grout for Masonry*, ASTM C476-18, American Society for Testing and Materials, Philadelphia, USA.

Barton, N. (1972). "A model study of air transport from underground openings situated below groundwater level", proceedings of the international society for rock mechanics (ISRM) symposium, Stuttgart.

Barton, N. (2004), "The Why's and how's of high pressure grouting-Part1", *Tunn. Tunnelling Int.*, **36**(9), 28-30. http://worldcat.org/issn/0041414X.

Barton, N., Bandis, S. and Bakhtar, K. (1985), "Strength, deformation and conductivity coupling of rock joints", *Int. J. Rock Mech. Min. Sci. Geomech. Abstracts*, **22**(3), 121-140. https://doi.org/10.1016/0148-9062(85)93227-9.

Danielsen, S.W. (1971), "Sprekkpermeabilitet(joint permeability)", Ph.D. Dissertation, Norwegian University of Science and Technology, Trondheim.

Draganovic, A., Karamanoukian, A., Ulriksen, P. and Larsson, S> (2020), "Dispersion of microfine cement grout with ultrasound and conventional laboratory dissolvers", *Constr. Build. Mater.*, **251**(10), 1-10. https://doi.org/10.1016/j.conbuildmat.2020.119068..

Gustafson, G. and Stille, H. (1996), "Prediction of groutability from grout properties and hydrogeological data", *Tunn. Undergr. Sp. Tech.*, **11**(3), 325-332. https://doi.org/10.1016/0886-7798(96)00027-2.

Huang, S., Pei, Q., Ding, X., Zhang, Y., Liu, D., He, J. and Bian, K. (2020), "Grouting diffusion mechanism in an oblique crack in rock masses considering temporal and spatial variation", *Geomech. Eng.*, **23**(2), 151-163. https://doi.org/10.12989/gae.2020.23.2.151.

Jovicic, V., Coop, M.R. and Simic, M. (1996), "Objective criteria for the determination of rock quality indices using ultrasonic pulse velocity", *Int. J. Rock Mech. Min. Sci. Geomech. Abstracts*, **33**(3), 319-324.

Jun, Y., Han, L., Meng, Q., Ma, D., Wen, S. and Wang, S. (2018), "Experimental investigation of the mechanical behaviors of grouted crushed coal rocks under uniaxial compression", *Geomech. Eng.*, **16**(3), 273-284. http://doi.org/10.12989/gae.2018.16.3.273.

Kim, B.K., Lee, I.M., Kim, T.H. and Jung, J.H. (2019), "Groutability enhancement by oscillatory grout injection:Verification by field tests", *Geomech. Eng.*, **18**(1), 59-69. https://doi.org/10.12989/gae.2019.18.1.059.

Kim, Y.U., Park, S.H., Moon, J.H. and Jang, S.M. (2013), "Ultrasonically enhanced effectiveness of various surfactants on disel removal from contaminated soil", *Jap. J. Appl. Phys.*, **52**(7), 227-228. https://doi.org/10.7567/jjap.52.07he09.

Mazaira, A. and Konicek, P. (2015), "Intense rockburst impacts in deep underground construction and their prevention", *Can. Geotech. J.*, **52**(10), 1426-1439. https://doi.org/10.1139/cgj-2014-0359.

Mitchel, J.K. (1970), "In Place treatment of foundation soils, proceeding of soil mechanics and foundation engineering", *J. Soil Mech. Found. Division*, **96**(1). https://doi.org/10.1061/JSFEAQ.0001391.

Mollamahmutoglu, M. and Yilmaz, Y. (2011), "Engineering properties of medium-to-fine sands injected with microfine cement grout", *Mar. Georesour. Geotechno.*, **29**(2), 95-109. https://doi.org/10.1080/1064119X.2010.517715.

Moon, J.H., Xin, Z.H., Park, Y.B. and Kim, Y.U. (2019), "Ultrasonically enhanced physical properties of milky cement for ground improvement", *KSCE J. Civil Eng.*, **23**(10), 4525-4528. https://doi.org/10.1007/s12205-019-2357-3.

Moon, J.H., Zhenhua, X., Jeong, G.B. and Kim, Y.U. (2017), "Application of ultrasonic energy to enhance capability of soil improving material", *J. Korean Tunn. Undergr. Sp. Association*, **19**(4), 567-576. https://doi.org/10.9711/KTAJ.2017.19.4.567.

Na, S.M., Kim, Y.U., Jang, M., Son, Y.G., Lim, M.H. and Khim, J.Y. (2014), "An economic assessment of the enhanced dewaterability of municipal wastewater sludge following ultrasonic treatment", *Jap. J. Appl. Phys.*, **53**(7). https://doi.org/10.7567/jjap.53.07ke11.

Nonveiller, E. (1989), *Grouting Theory and Practice*, Science, Amsterdam, Netherlands.

Park, J. and Lee, J.S. (2016), "Ultrasonic monitoring of unsaturated soil behavior under cyclic loading", *Geotech. Test. J.*, **39**(4), 579-592.

Park, J., Chun, Y.W., Trung, H.T. and Kim, Y.U. (2014), "Effect of ultrasonic energy on self-weight consolidation of clay minerals", *KSCE J. Civil Eng.*, **18**(4), 971-974. https://doi.org/10.1007/s12205-014-0375-8.

Peng, J., Hu, X., Chen, C. and Liu, S. (2019), "Application of ultrasonic and electrical resistivity methods for the evaluation of the internal structure of ground improvement by jet grouting", *Appl. Sci.*, **9**(6), 1236.

Sharp, JC. (1970), "Fluid flow through fissured media.", Ph.D. Dissertation, University of London, London.

Shen, S.L. and Miura, N. (1999), "Ultrasonic velocity testing of the cementation effect on soil and rock", *Geotech. Test. J.*, **22**(1), 83-90.

Shin, J.H., Moon, J.H., Song, Y.K. and Kim, Y.G. (2015), "Ultrasonically enhanced physical properties of cement grout", *KSCE J. Civil Eng.*, **19**(6), 1693-1696. https://doi.org/10.1007/s12205-015-1267-2.

Warner, J. (2003), "Soil Solidification with Ultrafine Cement Grout", *In Grouting and Ground Treatment*, 1360-1371. https://doi.org/10.1061/40663(2003)82.

Xiao, F., Liu, Q. and Zhao, Z. (2021), "Information and knowledge behind data from underground rock grouting", *J. Rock Mech. Geotech. Eng.*, **13**(6), 1326-1339. https://doi.org/10.1016/j.jrmge.2021.06.013.

Yaghoobi Rafi, J. (2013), "Design approaches for grouting of rock fractures; Theory and practice", Ph.D. Dissertation, KTH Royal Institute of Technology, Stockholm.

Zhang, J., Wang, X., Jin, B., Zhang, X., Li, Z. and Guan, X. (2022), "Effect and mechanism of superplasticizers on performance of ultrafine sulfoaluminate cement-based grouting materials", *Adv. Mater. Sci. Eng.*, **2022**(2), 1-11. https://doi.org/10.1155/2022/3836517.

Zhou, F., Sun, W., Shao, J., Kong, L. and Geng, X. (2020), "Experimental study on nano silica modified cement base grouting reinforcement materials", *Geomech. Eng.*, **20**(1), 67-73. https://doi.org/10.12989/gae.2020.20.1.067.