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Reinforcing hydraulic structures with ZA-SOIL, produced from recycled resources, as a substitute for cement

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Abstract. Most of the hydraulic structures in Korea were built before 1970, with 69.4% of them having a service life exceeding 50 years. Ordinary Portland cement (OPC), which is currently in general use for the construction of these structures, is continuously facing price increases. In addition, considerable amounts of greenhouse gases generated during the manufacturing process cause environmental problems. Therefore, in this study, ZA-SOIL, a material developed by recycling inexpensive blast furnace slag powder and desulfurized gypsum, was mixed with sodium silicate and silica sol in a liquid state and evaluated as an alternative to OPC. The compressive strength and environmental characteristics of the ZA-SOIL product were experimentally compared with those of OPC to evaluate its applicability as a grout material. The results indicated that the compressive strength of the developed ZA-SOIL was 3.23, 2.88, and 1.25 times higher than that of OPC after 3, 7, and 28 d of curing, respectively. In addition, ZA-SOIL satisfied all prescribed criteria and was found to be environmentally stable. Further evaluation of the field applicability of ZA-SOIL revealed that the electrical resistivity increased after reinforcement, depending on the depth, and the permeability coefficient (k) sharply decreased. Therefore, ZA-SOIL, developed by recycling inexpensive circulated resources, shows potential as an OPC substitute.

Keywords: aging hydraulic structures; compressive strength; ordinary Portland cement; supplementary cementitious material; ZA-SOIL

1. Introduction

Hydraulic structures, including reservoirs or dams, are smart inventions (Li *et al.* 2022) for addressing certain issues related to human well-being (Renöfält *et al.* 2010) such as flood control, waterway dredging, and agricultural irrigation (Pan *et al.* 2016, Hudson *et al.* 2019). Moreover, they contribute to social sustainability via the generation of electricity (Chen *et al.* 2021). Many reservoirs are currently being built worldwide. Because of large regional differences in elevation in Korea, considerable amounts of agricultural water are required, Therefore, small-scale reservoirs, with heights of 10 m or less, have been constructed and managed in Korea (Cho *et al.* 2019, Lee *et al.* 2020). However, 69.4% of the approximately 17,500 agricultural reservoirs in Korea were built more than 50 years ago, with 51.7% built before 1945 (Lee and Oh 2018). The aging of these reservoirs is noticeable and those exceeding 50 years of age have challenges related to usability and stability owing to soil leakage, scour, and erosion (Song *et al.* 2022). Because the reservoirs require high maintenance costs, local governments in Korea cannot easily manage them, rendering systematic safety management challenging (Kim *et al.* 2022b).

In response to climate change and to prevent disasters, the improvement, repair, and reinforcement of aging reservoirs based on survey results is necessary (Lee *et al.* 2022). To this end, the reinforcement of reservoirs with cement has been widely applied owing to its easy constructability and low cost (Zhang and Sun 2019, Jang *et al.* 2020). However, the supply of bituminous coal in Korea has recently become unstable, resulting in a steady increase in the price of cement. In particular, the price of cement increased to \$56.3 in July 2021, \$65 in January 2022, and \$75 in September 2022. Moreover, further price increases are expected in 2023. Therefore, studies on supplementary cementitious materials (SCMs) that can replace cement are being actively conducted.

SCMs are used to partially or completely replace cement using materials such as blast furnace slag or coal-fired fly ash (Lothenbach *et al.* 2011). Scrivener and Nonat (2011) confirmed that the growth of calcium silicate hydrate (C-S-H), after reacting for 10 h, was achieved owing to the change in local concentration despite initially exhibiting a reaction slower than that of cement. Further, Serpell and Lopez (2013) achieved approximately 77.2% compressive strength after 28 d using SCMs from recycled hydrated waste with a water/binder ratio (W/B) of 70%. Yu and Shui (2014) demonstrated that a compressive strength of more than 60 MPa can be obtained when combining fly ash for the reuse of construction waste and that high-performance additives (approximately 5%) can significantly increase the

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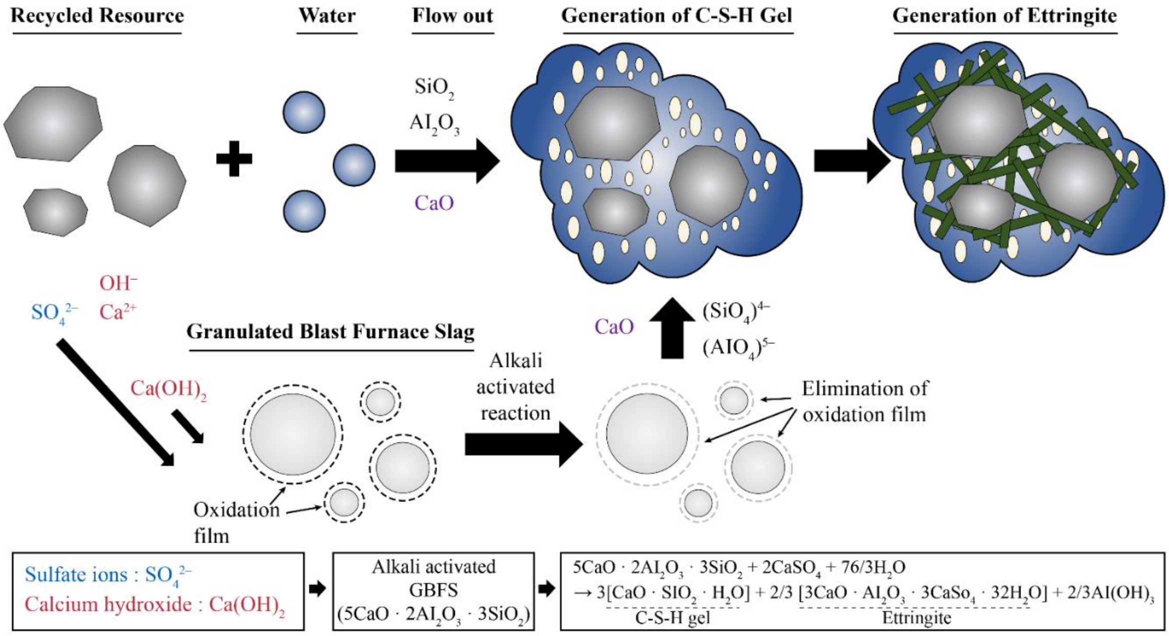


Fig. 1 Chemical reaction mechanism of ZA-SOIL

compressive strength of cement. Liu *et al*. (2016) investigated pozzolanic activity by recycling construction waste, increasing methane (CH) and ettringite contents based on the hydration time, and generating C-S-H and calcium aluminate hydrate (C-A-H), which can be used as SCMs. Zhang *et al*. (2019) demonstrated that mechanical properties can be significantly improved by accelerating early hardening processes and improving compact microstructures through SCMs recycled from construction waste. Wang *et al*. (2022) demonstrated that by incorporating calcium silicate aluminate hydrate (C-S-A-H) into mortar using granulated blast-furnace slag and stainless steel reducing slag, the compressive strength in the early stage of curing (within 3 d) can be increased. Further, they reported that the material can be used as a rapid grouting material.

As part of this research, this study produced SCMs for cement by recycling blast furnace slag powder (BFSP) and desulfurized gypsum, which are by-products of the steel manufacturing and power generation industries, respectively, and are circulated resources. BFSP is a typical SCM. Although the initial hardening rate of BFSP is low, it can increase long-term compressive strength, increase watertightness, and improve freezing resistance (Liu *et al.* 2019, Zhu *et al.* 2019, Wang *et al.* 2021). In addition, BFSP is 80% cheaper than cement and is therefore widely used (Guo *et al.* 2022, Xie *et al.* 2022). Meanwhile, desulfurized gypsum is a by-product of the desulfurization process of co-firing power generation. Notably, it can replace natural gypsum (Alemu *et al.* 2022, Zhou *et al.* 2022). Therefore, this study recycled the discarded by-products BFSP and desulfurized gypsum to form an SCMs, referred to as ZA-SOIL, and evaluated its use as a grouting material. To evaluate the proposed SCMs, we conducted a comprehensive review of the materials, performance, and prices through laboratory and on-site tests.

Table 1 Chemical constituents of ZA-SOIL

Material	Chemical constituents (%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss
ZA-SOIL	25.5	10.4	0.7	51.8	2.2	7.8	1.6
OPC	16.4	3.7	3.8	67.3	2.5	3.9	2.4

2. Materials and methods

2.1 Materials

2.1.1 ZA-SOIL

BFSP, a by-product generated in the iron-making process, is widely used owing to its cementitious behavior (potential hydraulic properties) (Tripathy *et al.* 2020). Desulfurized gypsum is a by-product generated in the co-firing power generation process, and 750,000 tons are generated annually. These byproducts are mostly landfilled and discharged owing to restrictions on industrial standards (Koralegedara 2019). The ZA-SOIL used in this study reacts with BFSP, desulfurized gypsum, and mixed materials, which are by-products, and generates hydrates such as C-S-H and ettringite, which is a ZA-SOIL that can induce a hardening reaction, through alkali activation, as shown in Fig. 1 (Kim *et al.* 2022a). In addition, compared with ordinary Portland cement (OPC), ZA-SOIL can achieve approximately 80–90% compressive strength and has excellent long-term strength, ensuring structural durability. Moreover, the chemical composition of ZA-SOIL (Table 1) is similar to that of OPC, except for the SO_3 component, and can therefore be used as an SCM.

2.1.2 Sodium silicate and silica-sol

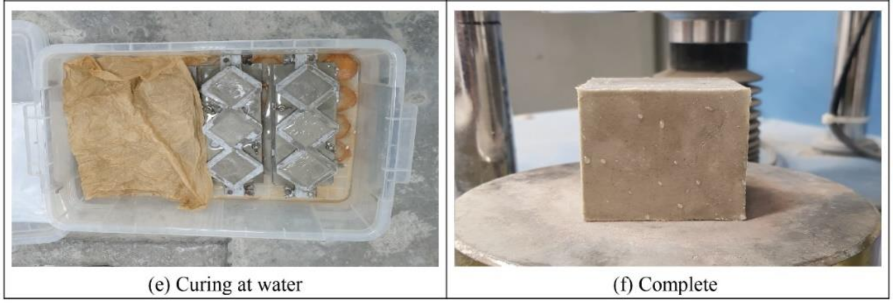
Sodium silicate is an alkali silicate in which SiO_2 is combined with a metal oxide (Xu *et al.* 2020b). It is produced through the dissolution of raw materials in a

(a) Preparing of liquid A and liquid B

(b) Mixing of materials

(c) Injecting homo-gel into the mold

(d) Surface arrangement



(e) Curing at water

(f) Complete

Fig. 2 Manufacturing process of the specimens

(a) Compressive test machine

(b) Test view

Fig. 3 Compressive test machine and test-view

Table 2 Modified sodium silicate used in this study

Content	Modified sodium silicate	Korean standards (KS M 1415)			
		Grade 1	Grade 2	Grade 3	Grade 4
Gravity specific (at 20°C)	1,300–1,400	Over 1,690	Over 1,590	Over 1,380	Over 1,260
Insolubility in water (%)	Under 0.2	Under 0.2	Under 0.2	Under 0.2	Under 0.2
Na_2O (%)	6.5–7.5	17–18	14–15	9–10	6–7
SiO_2 (%)	24.5–27.5	36–38	34–36	28–30	23–25
Fe_2O_3 (%)	Under 0.03	Under 0.05	Under 0.05	Under 0.05	Under 0.05

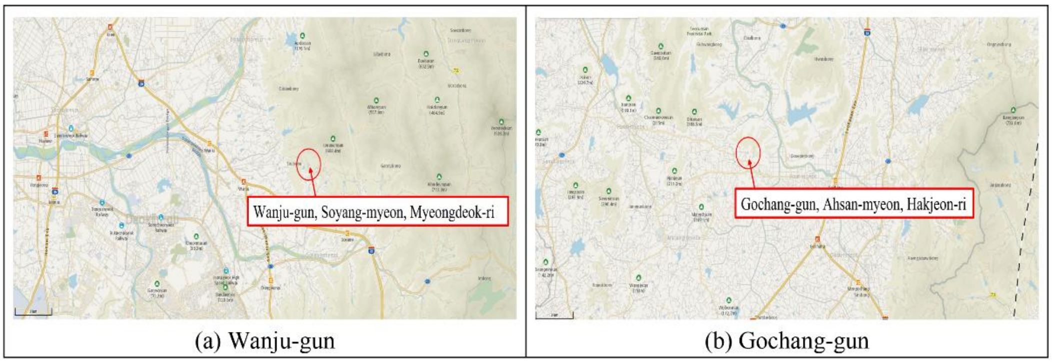
highly alkaline solution and the polymerization of ions (Ouyang *et al.* 2020). Notably, sodium silicate is used for various purposes towing to its quality because its reactivity, hygroscopicity, and adhesiveness vary depending on the type of alkali metal oxide, molar ratio, and moisture content. Moreover, silica-sol is used as a grouting material

Table 3 Properties of silica-sol

Material	Specific gravity	Na_2O (%)	SiO_2 (%)	Insolubility in water (%)	pH (at 20 °C)	Viscosity (at 20 °C, cP)
Silica-sol	1.220	0.7	31.5	1.5	9.8	14

Table 4 Mixing ratio of materials

Liquid A			Liquid B	
Sodium silicate	Silica-sol	Water	ZA-SOIL (or OPC)	Water
2.74×10^{-4} m^3	0.137×10^{-4} m^3	2.94×10^{-4} m^3	1.02×10^{-8} m^3 (1.08×10^{-8} m^3)	4.06×10^{-4} m^3



(a) Wanju-gun (b) Gochang-gun

Fig. 4 Locations of construction tests in Jeollabuk-do

because it gels in a stable state of colloidal SiO_2 particles in the range of 5–100 nm with a negative (–) charge (Xiang *et al.* 2022). In this study, sodium silicate was modified by changing the molar ratio from 3.3 to 4.4 and adjusting the levels of Na^+ and Si^+ ions to easily adjust the gel time. Table 2 presents a comparison of the sodium silicate used in this study with the Korean standard, KS M 1415 (2017). Table 3 presents the characteristics of the general silica sol (Song *et al.* 2019).

2.2 Methods

2.2.1 Mixture process

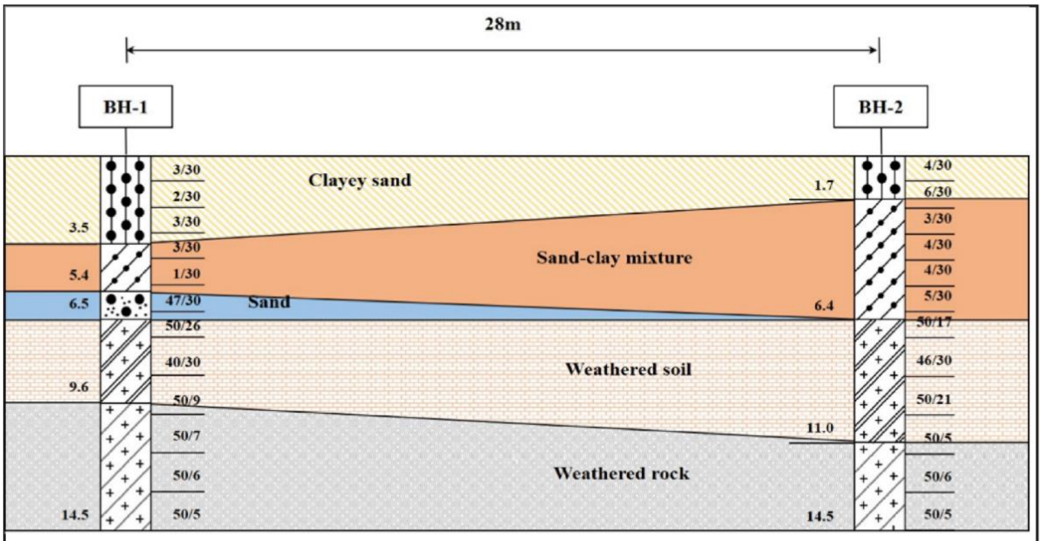
In this study, to recycle BFSP and desulfurized gypsum as grouting materials, sodium silicate and silica-sol were denoted as liquid A and ZA-SOIL as liquid B, as shown in Fig. 2(a). Specimens were manufactured according to the Korean test standard, KS F 2405 (2010). Table 4 presents the mixing ratio of the materials used to produce the specimens, and Fig. 2 shows the manufacturing process of the specimens. After mixing liquids A and B (Fig. 2(b)), the material formed, which was in a homo-gel state, was injected into prepared molds (Fig. 2(c)). Thereafter, the exposed surface of the material was leveled (Fig. 2(d)). After curing for 3, 7, and 28 d in water at 20 ± 3 °C (Fig. 2(e)), the specimens were ready for testing (Fig. 2(f)),

2.2.2 Laboratory test

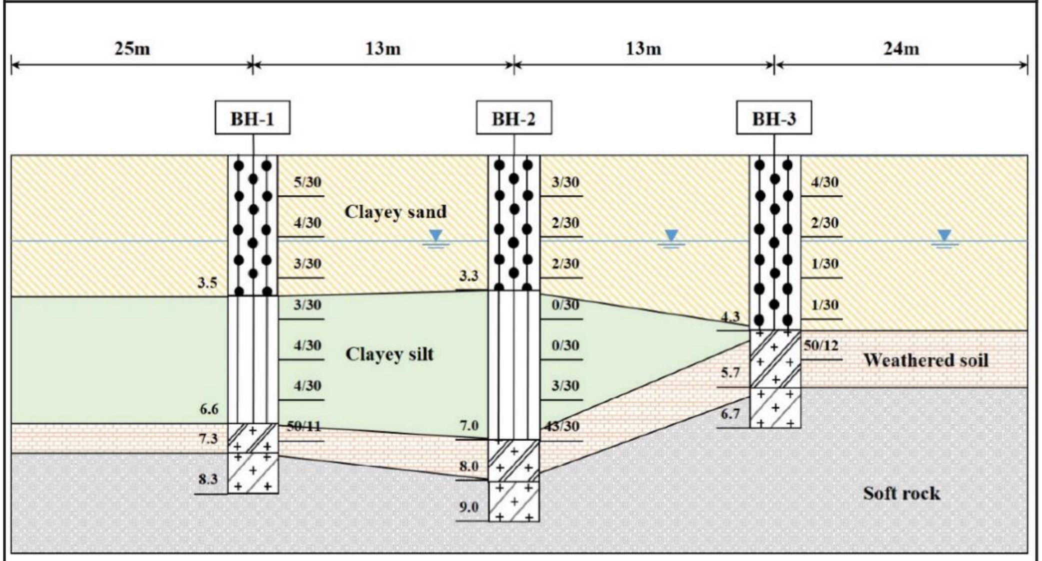
Laboratory tests were conducted to evaluate the compressive strength and environmental properties of ZA-SOIL. The compressive strength of ZA-SOIL was measured using a digital-type California bearing ratio tester (STM-501; Korea Ind. Co., Ltd.), which can measure compressive forces of up to 30 kN. The strain rate was set to 1 mm/min by applying the prescribed Korean test method, KS L 5105 (2022). Fig. 3 shows the test equipment and test view. For environmental evaluation, a soil contamination test was conducted to determine whether the soil was contaminated with heavy metals (MOE 2017). Further, a fish acute toxicity test was conducted to determine the effect of ZA-SOIL on aquatic ecology (OECD 2019).

2.2.3 On-site application

To evaluate the applicability of ZA-SOIL in the field, test constructions were performed at two locations, namely, Wanju-gun and Gochang-gun in Jeollabuk-do. Only ZA-SOIL, and not OPC, was evaluated. The locations of the reservoirs are shown in Fig. 4, and the specifications of the reservoirs are presented in Table 5. As shown in Fig. 5, the ground investigation revealed that a mixed soil of clayey sand, clayey silt, and sand–clay with N values of four or less existed up to a depth of 7.0 m. The soils were in an extremely soft state. Fig. 6 shows that reinforcement was implemented using the grouting method. For reinforcement using ZA-SOIL, first, boring was performed (Fig. 6(a)), and then, a Manjet tube was installed (Fig. 6(b)). Thereafter, a mixing plant was installed (Fig. 6(c)), and liquids A and B were mixed to form a homo-gel material (Fig. 6(d)), which was injected (Fig. 6(e)) to complete the test construction (Fig. 6(f)). On completion of the test construction, a field test was conducted to determine the change in the permeability coefficient, and the applicability of the material was estimated by measuring the electrical resistivity with probes installed at 2-m intervals



(a) Wanju-gun



(b) Gochang-gun

Fig. 5 Geological column section on site

Table 5 Specifications of the test construction

Location	Material		Unit weight of binder (kN/m^3)	Depth (m)	C.T.C (m)	Diameter (m)	Row of hole
	Liquid A	Liquid B					
Wanju-gun	Sodium silicate and silica-sol	ZA-SOIL	7.43	6.5 (Mean)	2.0	2.0	2
Gochang-gun	Sodium silicate and silica-sol	ZA-SOIL	7.43	8.67 (Mean)	2.0	2.0	2

Table 6 Compressive strength of materials

Curing time	ZA-SOIL				OPC				Remark
	1	2	3	Mean	1	2	3	Mean	
3 d	0.67	0.65	0.65	0.66	0.19	0.21	0.21	0.20	Mixed with liquid A (sodium silicate and silica-sol)
7 d	3.63	3.49	2.88	3.33	1.25	1.10	1.13	1.16	
28 d	6.23	6.41	6.09	6.24	5.05	5.14	4.84	5.01	

(a) Boring in field (b) Installation of manjet tube

(c) Placement of mixing plant (d) Mixing with liquids A and B

(e) Injection of ZA SOIL (f) Construction completed

Fig. 6 On-site application of ZA-SOIL

Table 7 Comparison of soil contamination test results

Content (mg/kg)	Material		Domestic criteria			Remark
	ZA-SOIL	OPC	Area 1	Area 2	Area 3	
Cd	0.25	1.12	4	10	60	Mixed with liquid A (sodium silicate and silica-sol)
Cu	3.1	27.4	150	500	2,000	
As	Not dissolved	Not dissolved	25	50	200	
Hg	0.03	Not dissolved	4	10	20	
Pb	Not dissolved	17.6	200	400	700	
Cr^{6+}	Not dissolved	3.5	5	15	40	
Zn	6.2	277.8	300	600	2,000	
Ni	48.2	24.1	100	200	500	
F	299.0	1,076	400	400	800	

3. Results and discussion

3.1 Compressive strength

To examine the material performance of ZA-SOIL, a grouting material made from recycled BFSP and desulfurized gypsum, liquid A was mixed with sodium silicate and silica-sol was mixed with ZA-SOIL (or OPC).

The compressive strength of the homo-gel state was measured. Table 6 presents the compressive strength test results for the homo-gel. The results show that the compressive strengths of ZA-SOIL are 0.66, 3.33, and 6.24 MPa, which are 3.23, 2.88, and 1.25 times higher than that of OPC after 3, 7, and 28 d, respectively. Kim *et al.* (2022a) observed that the intensity was 70–80% lower than that of OPC before 28 d. However, the ZA-SOIL in this study

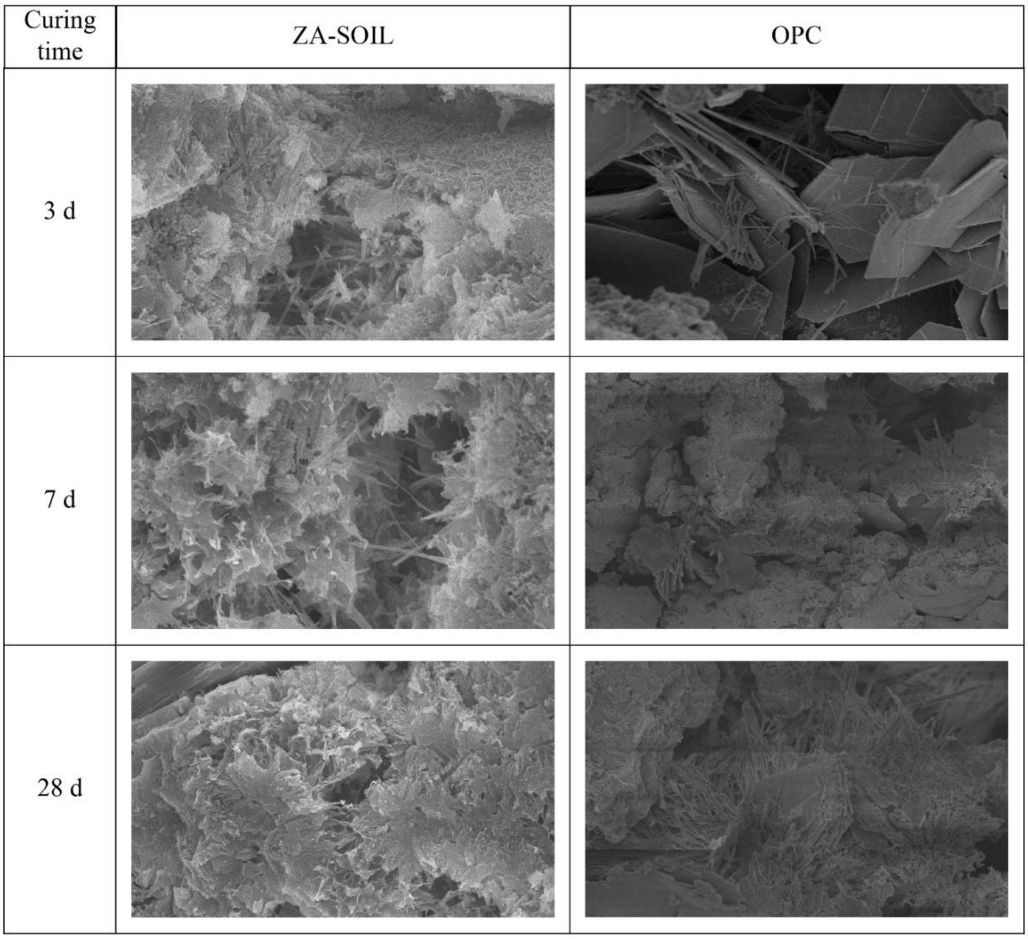


Fig. 7 Comparison of results based on SEM

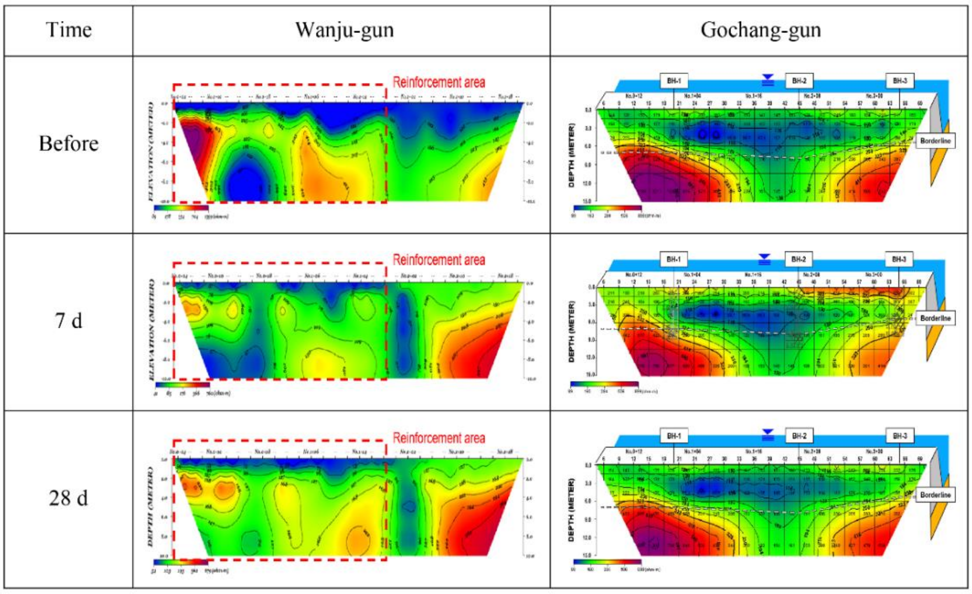
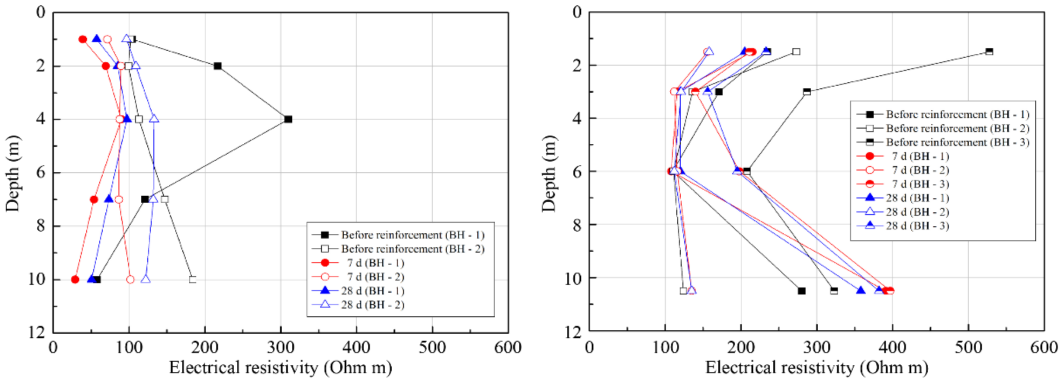


Fig. 8 Electrical resistivity survey results

exhibited fast curing owing to the reaction between sodium silicate and silica-sol. Fig. 7 shows scanning electron microscopy (SEM) imaging results for an accurate comparison. An analysis of the SEM images revealed that although the hydration rate and amount of hydrate could not easily be compared through quantitative analysis, a larger amount of C-S-A-H or ettringite was generated in ZA-SOIL than in OPC. In addition, the interparticle bonds between



(a) Wanju-gun (b) Gochang-gun

Fig. 9 Comparison of electrical resistivity by depth

Table 8 Comparison of Asiatic ricefish populations

Content	Material	Time (h)					
		0	3	24	48	72	96
Number of Asiatic ricefish (pcs)	ZA-SOIL	10	10	10	10	10	10
	OPC	10	10	10	10	9	7

Table 9 Permeability coefficient result in the field

Time	Permeability coefficient (k, 10^{-5} m/s)							
	Wanju-gun		Gochang-gun					
	BH – 2		BH – 1		BH – 2		BH – 3	
	1–4 m	4–7 m	1–3 m	3–7 m	1–3 m	3–7 m	1–3 m	3–7 m
Before construction	27.97	6.33	1.69	0.39	0.68	0.27	1.09	0.56
28 d	1.71	0.05	0.26	0.07	0.19	0.12	0.17	0.05

the hydrates became dense. Hydrates such as C-S-H and ettringite were formed in materials mixed with BFSP and desulfurized gypsum (Xu *et al.* 2020a). Therefore, these materials can be applied to a reservoir using ZA-SOIL recycled from BFSP and desulfurized gypsum. In addition, we determined that ZA-SOIL can be used as controlled low-strength materials (CLSMs) for constructing underground structures if additional examinations are conducted to determine its fluidity and W/B.

3.2 Environmental review

To examine the environmental impact of ZA-SOIL recycled from BFSP and desulfurized gypsum, soil contamination and fish acute toxicity tests were conducted. Table 7 presents a comparison of the results of the soil contamination tests for ZA-SOIL and OPC. Soil contamination standards are divided into Areas 1 to 3: Area 1 represents a polluted area such as schools or children's facilities; Area 2 represents industrial sites area such as warehouses, sports facilities, and amusement parks; and Area 3 represents other areas such as roads or railways. Typically, these standards are applied in order of strictness: Area 3 > Area 2 > Area 1. The analysis indicates that the soil contamination test results for ZA-SOIL fell within the Area 1 standards for all items. Furthermore, the analysis revealed that ZA-SOIL showed lower values than the standard values of Area 1 for all items. In addition, all criteria, except for that for nickel, exhibited a lower level than for OPC. Therefore, ZA-SOIL can be applied in both schools and children's facilities. Table 8 presents a comparison of the results for the fish acute toxicity tests for ZA-SOIL and OPC. The results show no change in the fish population when exposed to ZA-SOIL, and the survival rate was 100%. However, OPC exposure resulted in the fish population reducing to 9 after 72 h and to 7 after 96 h, indicating a survival rate of 70%. Therefore, from an environmental perspective, ZA-SOIL from recycled BFSP and desulfurized gypsum is superior to OPC and can be safely utilized in various fields.

3.3 Reinforcement effect analysis

To evaluate the applicability of ZA-SOIL in the field, test constructions were conducted at two locations, namely, Wanju-gun and Gochang-gun. The electrical resistivity survey results are shown in Fig. 8. Based on the survey, in the case of Wanju-gun, the electrical resistivity decreased in the section saturated to a depth of approximately 3 m before introducing reinforcement. However, after reinforcement, the electrical resistivity increased within the range of 57–150 Ω·m after 28 d. Further, in the case of Gochang-gun, the electrical resistivity was within the range of 76–118 Ω·m before introducing reinforcement. However, after reinforcement, the electrical resistivity was within the range of 82–123 Ω·m after 28 d. Fig. 9 compares the electrical resistivity survey results for varying depths. Before construction, a difference in electrical resistivity with depth was observed. However, after reinforcement, the electrical resistivity was constant throughout the homogeneous construction of ZA-SOIL. Table 9 presents the permeability coefficient field measurements. The results show that the permeability coefficient ranged from 0.27×10^{-5} to 1.69×10^{-5} m/s in Wanju-gun and from 1.71×10^{-5} to 27.97×10^{-5} m/s in Gochang-gun. However, the permeability coefficient after reinforcement decreased significantly at most depths, ranging from 0.05×10^{-5} to 0.26×10^{-5} m/s in Wanju-gun and 0.05×10^{-5} to 6.33×10^{-5} m/s in Gochang-gun. Therefore, the results confirm that ZA-SOIL from recycled BFSP and desulfurized gypsum can replace OPC as reinforcement for reservoirs. However, in the case of OPC, the deterioration reaction caused by environmental factors such as chloride ions, freezing and thawing, and CO_2 must be considered; therefore, the long-term effects of ZA-SOIL must be considered through an additional review.

4. Conclusions

In this study, to recycle discarded BFSP and desulfurized gypsum, laboratory tests and test constructions were performed to investigate the use of ZA-SOIL as a substitute for OPC in grouting materials, and the results were analyzed. The main conclusions are as follows:

- The compressive strength of ZA-SOIL in the homo-gel state fabricated by mixing sodium silicate and silica sol was 0.66, 3.33, and 6.24 MPa at 3, 7, and 28 d, respectively. Compared with OPC, ZA-SOIL was 3.23, 2.88, and 1.25 times higher at 3,7, and 28 d, respectively. Notably, the expression of the initial compressive strength was excellent.
- The environmental impact evaluation of ZA-SOIL through the soil contamination test revealed the material to be within the domestic standards in Korea. Therefore, ZA-SOIL can be applied in environments such as schools and children's facilities. In addition, ZA-SOIL showed no toxicity in the fish acute toxicity test. Therefore, ZA-SOIL is environmentally friendly and can be used.
- In the applicability evaluation of ZA-SOIL, an electrical resistivity survey was conducted following the test constructions, and the permeability coefficients were measured in the field. The evaluation results showed that the electrical resistivity in the field increased over time, and the electrical resistivity increased with depth at each location. In addition, the permeability coefficient at the site ranged from 0.05×10^{-5} to 1.71×10^{-5} m/s in Wanju-gun and 0.05×10^{-5} to 0.26×10^{-5} m/s in Gochang-gun. Therefore, the electrical resistivity of ZA-SOIL is sufficient, and the permeability coefficient is reduced by more than 2.25 times, ensuring sufficient stability and certainty in the field.
- By using ZA-SOIL as a grouting material, resources such as BFSP and desulfurized gypsum can replace OPC in the construction field. Particularly, if follow-up research and analyses are performed, they can be used in various fields as SCMs, such as CLSMs and closed pipe-filling material, to replace OPC. However, the leaching problem resulting from changes in the molar ratio between sodium silicate and silica sol and changes in long-term environmental effects have not been sufficiently investigated, thus further studies are necessary.

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