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Study on the characteristics of grout material using ground granulated blast furnace slag and carbon fiber

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Abstract. This study aims to evaluate the applicability of a grout material that is mixed with carbon fiber, biogrout, ground granulated blast furnace slag (GGBS) powder and cement. Uniaxial compressive strength tests were performed on homo-gel samples at days of 1, 3, 7, 14 and 28. In addition, the variation of permeability with the mixing ratios was measured. Based on the uniaxial compressive strength test, it was confirmed that the uniaxial compressive strength increased by 1.2times when carbon fiber increased by 1%. In addition, as a result of the permeability test, it was found that when the GGBS increased by 20%, the permeability coefficient decreased by about 1.5times. Therefore, the developed grout material can be used as a cutoff grouting material in the field due to its strength and cut-off effect.

Keywords: cutoff grout; carbon fiber; biogrout; ground granulated blast furnace slag; homo-gels

1. Introduction

1.1 Background and objective

In general, grouting techniques used in Korean construction sites focus on improving ground strength. The cement and chemical liquid as main materials for the grouting techniques involves environmental issues, for example, carbon dioxide (CO_2) emissions and groundwater pollution. Moreover, Korea is a party for CO_2 emission limitation targets since 2015 according to the Kyoto Protocol, and should pay penalties for non-compliance of CO_2 emission limitation targets where CO_2 more than the targets is emitted. Therefore, it is necessary to develop environment-friendly materials to replace cement and reduce the use of it in the on-site ground improvement. Development of environment-friendly materials requires complying with the green growth policy for avoiding low-carbon global warming, and address issues of increasing raw material costs and lack of construction materials by developing new materials.

Recently, there is an increasing interest in the ground granulated blast furnace slag as a cement replacement material, which is a byproduct in the steel manufacturing process. Therefore, using the slag will reduce the volume of industrial wastes and air pollution, and it can be an economical material while conserving soil and water quality.

For this reason, the method for using ground granulated blast furnace slag as a cement replacement material has been studied for a long time (Yadu and Tripathi 2013, Pradhan and Mohanty 2017). However, the studies (for alkali activated slag paste) have focused mainly on replacing cement in the cement concrete field. Although it has many advantages including enhanced long-term strength, low hydration heat, and chemical durability, it has obvious disadvantages including early strength deterioration by retarded setting, many fine cracks, and early quick-setting, leading to limited applications. However, the properties of ground granulated blast furnace slag as a cement replacement material including quickly slowing flowability and early quick setting (Gelling) can rather be an advantage in the field of water cutoff for ground improvement, and the required early strength of 1-3MPa for grout materials is not as high as that of at least 20MPa for the cement concrete.

Biogrouting technique has been recently used by some researchers in place of a typical grouting. It uses microorganism minerals to fill the voids between the soil particles instead of cement and inhibits fine cracks smaller than 0.6mm (Kim and Park 2017, Sidik *et al.* 2014). Biogrouting can be applied in combination with recycled resources including GGBS (Ground Granulated Blast Furnace Slag) powder to increase the shear strength of soil.

Therefore, this study aims to develop a grout material by mixing calcite which is a microorganism mineral material, carbon fiber from crushed fiber which is a recycled resource and GGBS powder with cement (Ordinary Portland Cement).

The homo-gel uniaxial compressive strength tests at days of 3, 7, 21 and 28 were conducted to examine their strength. The permeability test was also conducted by changing the mixing ratios. The SEM analysis of mixed materials was conducted to find the best mixing ratio for field applicability of the grout material.

1.2 Literature review

The grouting technique is mainly used for preventing

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leakage of water from embankments and for reinforcing soft ground (Cheon 1998). Grout was first used by George Sample in the UK in 1776, and Barlow of the UK created the word grouting in 1864 (Glossop 1960). The Grouting Committee of American Society of Civil Engineers (ASCE) uses grout in the same meaning as grouting, but grout generally refers to the grouting material, and grouting is used for describing the process of using the grouting material.

The first case of technique for injecting chemical liquid to reinforce soft ground is the repair project for filling the lower part of damaged floodgate and reinforcing the alluvium with grouting material made by mixing clay with lime. Kutzner (1996) established the concept of chemical liquid injection for the technical procedure of grouting.

Germany started to produce Ground Granulated Blast furnace Slag (GGBS) powder which does not involve mixing and crushing granulated slag with clinkers in 1923. Thurament was produced by adding 3-4% of lime to crush the mixture coarsely to get 20% of particles of 0.09㎜. Although this admixture-type material put into the mixer to produce concrete was approved as a construction material in 1937, it was used for concrete of low strength because of limitations in use in consideration of reliable quality. The required 28th day strength of DIN mortar produced by mixing Portland cement with Thurament in the weight ratio of 1:1 was at least 70% of that of the Portland cement mortar. In Japan, producing GGBS powder described above aims at quality improvement of the GGBS cement, rather than using it as an admixed material.

Many researchers have studied GGBS in the past years to assess its properties and its behavior (Kim *et al.* 2014, Kim and Hahm 2015). Babu and Kumar (2000) measured the strength of GGBS at 28 days by replacing cement with 10-80% range. Gaurav *et al.* (2015) showed that the optimum ratio of GGBS was 40-50% considering the strength and economic efficiency. Sudarvizhi and Ilangovan (2011) observed that upto 80% replacement, GGBS can be effectively used as replacement for fine aggregate.

Khajuria and Siddique (2014) showed that GGBS added to the concrete had greater strength than the common concrete. Oner and Akyuz (2007) presented a laboratory investigation on optimum level of GGBS on the compressive strength of concrete. The test results proved that the compressive strength of concrete mixtures containing GGBS increases as the amount of GGBS increases. For more than 55% replacement, the addition of GGBS did not improve the compressive strength.

Rabbani *et al.* (2012) showed that GGBS and lime were added in percentages of 5, 10 and 15% and 1, 3 and 5% respectively, by dry weights of sand. The study results demonstrate significant improvements in uniaxial compressive strength. Moreover the swelling behavior of mixtures was decreased effectively.

In Korea, GGBS powder has been studied for using it as recycled fine aggregates. Most of the studies were done to analyze the properties of mortar not hardened by using recycled aggregate which is cheap recycled alkali resources, and basic properties such as enhanced strength of hardened concrete. For studying workability and engineering characteristics of concrete, researchers have studied the method for using the replacement ratio and fineness of GGBS powder. Furthermore, cemented sand by using GGBS and alkali activators has been studied.

Han *et al.* (2009) and Kim *et al.* (2014) used different cement and GGBS replacement ratios to examine the method for increasing flow performance and the minutely decreasing amount of air. Lee (2016) evaluated cement material performance by using GGBS and recycled coarse aggregate, and Kim *et al.* (2007) conducted an experimental study about engineering characteristics of concrete using a large amount of GGBS.

Min and Lee (2007) added the GGBS and an admixture (Alumina cement) to develop a highly acid-resistant material, and used the GGBS and a sodium-based activator to study the characteristics of non-cement slag.

As described above, in most studies on using GGBS, it was used as a resource replacing recycled aggregate in concrete.

Research on concrete using GGBS has been continuously developed, but research on grout materials has been limited.

Seo *et al.* (2019) developed a reinforcing grout material using GGBS and aramid fibers. The aramid fiber were dispersed to enhance the strength effect.

Sandrson *et al.* (2018) studied the effect of GGBS particle size on cement hydration and found that the fluidity and the heat of hydration decreased with decreasing GGBS content.

Shucai *et al.* (2017) developed a grout for long-term strength at relatively low cost using GGBS and fly ash instead of cement.

Zhang *et al.* (2019) developed a material that can control gel time and compressive strength using geopolymer, GGBS, and fly ash.

As described above, little research for developing a grout material using GGBS has recently been conducted. Therefore, this study aims to use GGBS as a grouting material and study it as a water cutoff.

2. Material used in the study

2.1 Overview of carbon fiber

Carbon fiber (Reinforcing fiber) used in this study as a material for repairing and reinforcing the grouting material is formed as grids by impregnating it with vinyl-ester matrix resin (see Fig. 1).

Typical fiber types include carbon fiber, glass fiber and aramid fiber, and the applicable carbon fiber is classified into high-strength carbon fiber and high-elastic carbon fiber. In terms of strength, the high-strength carbon fiber is about 1.5 times as strong as the glass fiber or aramid fiber. Moreover, because the high-elastic carbon fiber has an elasticity coefficient about 2 to 3 times as elastic as other two types of carbon fiber. Although the glass fiber is not much different from aramid fiber in terms of rigidity, they are very different in terms of toughness.

Typical fiber reinforcements include glass fiber, aramid fiber and carbon fiber, among which the glass fiber is

(a) Carbon fiber sheet (b) Crushed carbon fiber

Fig. 1 Used carbon fibers

Table 1 Properties of carbon fiber used in this study

Category	Properties
Fiber	High-strength carbon fiber
Fiber weight (g/m2)	200
Sheet size (W (m) × L (m))	0.5 × 50
Specific gravity of fiber	1.80
(g/cm3)	0.11
Design thickness (mm)	0.45
Standard installation thickness	390
Tensile strength (kg/cm in width)	1.5
Strain in rupture (%)	Properties

Table 2 illustrates physical and chemical properties of GGBS, cement and microorganism mineral

Classification	Specific gravity (g/cm^3)	Specific Surface area (g/cm^2)	Chemical composition
GGBS	2.94	8,000	SiO_2, Al_2O_3, Fe_2O_3
Cement	3.15	2,800	SiO_2, Al_2O_3, Fe_2O_3
Mircoorganism mineral	-	70,000	$Cacl_3$

weakened by the alkali component in concrete, and the aramid fiber is deteriorated by moisture. Therefore, the carbon fiber is used in this study.

If the ratio of the carbon fibers reinforcement exceeds 1.0%, the fluidity is drastically reduced due to the characteristics of the hydrophilic carbon fibers, which makes the quality control difficult due to flocculation.

The carbon fiber used in this study is produced by H Company, and crushed to be mixed with GGBS and cement. The crushed carbon fiber is about 0.5-1.0 cm in length and has the following specifications to implement better mixing performance and enhance field application to conduct the test. Table 1 illustrates properties of the carbon fiber used in this study.

2.2 Properties of grout materials

Table 2 shows the physical and chemical properties of GGBS, Cement and microorganism minerals.

The specific surface area of the microorganism mineral is 70,000 g/cm^2, which is approximately 10 times larger than 8,000 g/cm^2 of the specific surface area of GGBS. The chemical composition of GGBS is the same as that of cement, and microorganism mineral are composed of calcium carbonate.

3. Method of laboratory tests

3.1 Experiment for uniaxial compressive strength with different mixing ratios

3.1.1 Mixing ratio for measuring homo-gel uniaxial compressive strength

The homo-gel test is an experiment to measure the uniaxial compressive strength caused by the combination of grout materials with different mixing ratios of cement, GGBS, carbon fiber and microorganism mineral.

The homo-gel-type specimens produced with cylinder molds in 5cm (D) × 10cm (H) were manufactured to evaluate specimen strengths. They were removed 3 hours later to conduct water curing and then examine uniaxial compressive strength at days of 3, 7, 21 and 28.

Table 3 illustrated grout mixing ratios to measure the compressive strength. For producing grout, the contents of sodium silicate No.3 in solution A (350$m\ell$) were changed to be 175$m\ell$ (50%), 122.5$m\ell$ (35%) and 70$m\ell$ (20%) relative to water, and GGBS used for solution B was added by 0g(0%), 20g(20%) and 40g(40%) relative to cement. Furthermore, 0, 1% of carbon fiber was added in respective mixing ratios, and the 1% standard was based on the Guideline for Using Recycled Resources. W/C was fixed to 200% relative to the weight of cement + GGBS. Because the microorganism mineral is added in pre-processing by 10% relative to cement in field test, the fixed amount of 10g was added. Where the grout material contains the microorganism mineral, it can fill fine pores to implement a desired density.

For more reliable experiment, two cases for each mixing ratio were produced to use the average of uniaxial compressive strengths, and uniaxial compressive strength was measured by means of a universal loading tester. The compression speed was 1mm/min to measure uniaxial compressive strength.

3.1.2 Producing homo-gel specimen

The recommended specimen mold size for uniaxial compressive strength experiment is 7cm (D) x 14cm (H) in 1:2 and it is required to comply with the ratio regulation of the sample size or diameter to height. However, it is hard to comply with the sample size or fit it into the mold used in experiment. Therefore, the mold used in this study was a cylinder mold of 5cm (D) x 10cm (H) in size having the ratio 1:2 of diameter to height. The experiment mold was made of cast iron, and a lubricant was thinly applied to the inner side of the mold to minimize specimen damage in the removal process. The mold sample was designed so that the specimen could be separated for easy mold removal after manufacturing the specimen.

Fig. 2 shows the container used in the experiment.

Table 3 Grout-mixing ratios

Solution A				Solution B		
Sodium silicate No.3 (mℓ)	Water (mℓ)	Cement (g)	GGBS (g)	Carbon fiber (%)	Water (mℓ)	Microorganism mineral (g)
175 (50%)	175 (50%)	100 (100%)	0 (0%)	0, 1	200	10
122.5 (35%)	227.5 (65%)	80 (80%)	20 (20%)			
70 (20%)	280 (80%)	60 (60%)	40 (40%)			


(a) Specimen mold (b) Lubricant application

Fig. 2 Uniaxial compression experiment mold used in producing homo-gel


(a) Specimen mold (b) Lubricant application

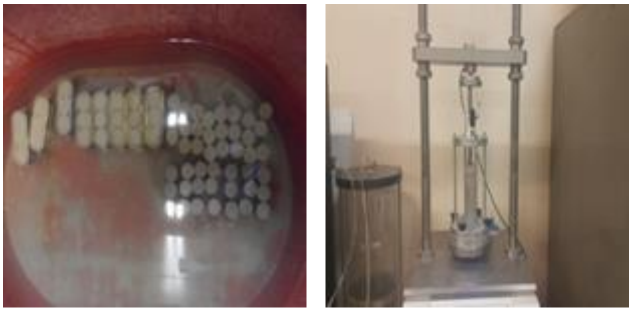

(c) Curing specimens (d) Test system

Fig. 3 Uniaxial compressive strength test system

After applying the lubricant to the specimen mold 1/2 of which is separated, the grout was mixed and formed in the mixing ratio. The grout was put in the produced mold, and the specimen was removed after 24 hours had elapsed to conduct water curing and age the specimen. The completed specimen size was 5cm (D) × 10cm (H) and was aged for days 3, 7, 21 and 28 to analyze uniaxial compressive strength of the grout, and Fig. 3 shows the uniaxial compressive strength test.

In this study, the uniaxial compressive strength test was measured to confirm the properties of the grout material.

Table 4 Sample mixing ratios for the permeability test

Solution A				Solution B		
Sodium silicate No.3 (mℓ)	Water (mℓ)	Cement (g)	GGBS (g)	Carbon fiber (%)	Water (mℓ)	Microorganism mineral (g)
105 (30%)	245 (70%)	100 (100%)	0 (0%)	0, 1	200	10

For stiff materials such as concrete, tensile strength can be measured, but it is difficult to measure tensile strength for grout. In addition, since the tensile strength increases with increasing compressive strength, only the characteristics of compressive strength are considered in this study.

3.2 Permeability test with mixing ratios

In this study, the saturated permeability test was conducted. The permeability test is widely used for all types of soil, and the amount of water is measured about Q and measurement time t to find water permeability.

Permeability test is an experiment to measure permeability coefficient of the mixing grout materials and soil. Therefore, the purpose of this experiment was to determine the cut-off effect of grout materials with different mixing ratios of cement, GGBS, carbon fiber and microorganism mineral.

Table 4 illustrates sample mixing ratios for the permeability test. For producing the grout, the content of sodium silicate No.3 in solution A (350mℓ) was 105mℓ (30%) relative to water, and the microorganism mineral in solution C was 10% of the amount of cement + GGBS. The amount of added GGBS used in solution B was 0g (0%), 20g (20%) and 40g (40%) relative to cement, and used carbon fiber was 0, 1%. The materials in each mixing ratio were mixed with 900g of standard sand to conduct experiment in the container of 100mm (D) x 120mm (H).

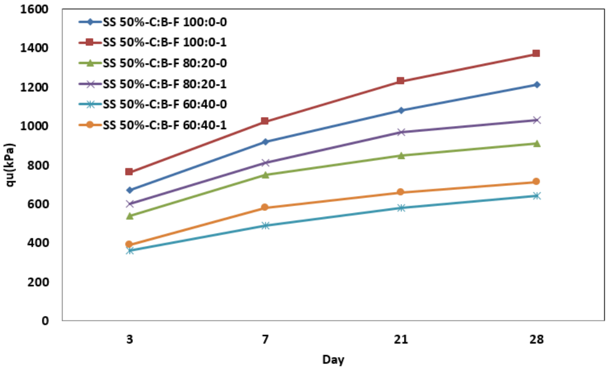
A wire net and a filter paper were installed in the lower part of the sample not to allow the sample to escape, and water curing after mixing was conducted at constant temperature 20±2˚C to conduct permeability test for curing for one day.

For more reliable experiment, two cases for each mixing ratio were prepared to obtain the average permeability.

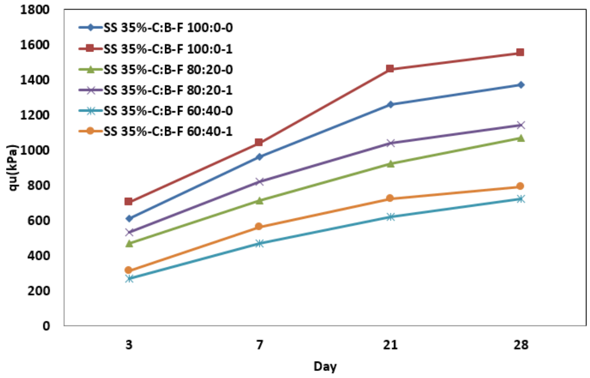
4. Results of laboratory experiment

4.1 Analysis of uniaxial compressive strength with different mixing ratios

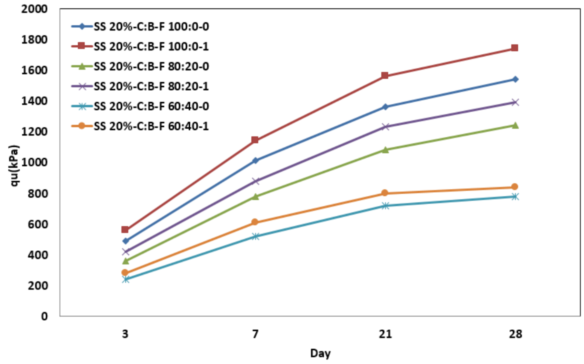
Fig. 4(a) presents the uniaxial compressive strength of



(a) Uniaxial compressive strength over time with sodium silicate 50%



(b) Uniaxial compressive strength over time with sodium silicate 35%



(c) Uniaxial compressive strength over time with sodium silicate 20%

Fig. 4 Uniaxial compressive strength depending on sodium silicate contents

the specimens with different mixing ratios for sodium silicate No.3 of 50%.

In comparison with the strength at day 28 for C:B-F 100:0-0, the strength of the specimen with 1% Carbon fiber for C:B-F 80:20-0 and for C:B-F 60:40-0 was about 75% and 52% lower, respectively.

Unlike the expectation, GGBS did not show hydration and pozzolanic reaction in the process of mixing with water as it showed reaction with cement, and the strength increase was not significant over time.

Since GGBS is composed of fine grains, it is very useful to water cutoff. However, as its initial strength was quite low it is necessary to mix it with admixtures, for example, lime, to enhance the strength for application.

Table 5 Results of uniaxial compressive strength test

SS:W (%)	C:B-F(%)	Uniaxial compressive strength(kPa)			
		3day	7day	21day	28day
50:50	100:0-0	670	920	1080	1210
	100:0-1	760	1020	1230	1370
	80:20-0	540	750	850	910
	80:20-1	600	810	970	1030
	60:40-0	360	490	580	640
	60:40-1	390	580	660	710
35:65	100:0-0	610	860	1260	1370
	100:0-1	700	1040	1460	1550
	80:20-0	470	710	920	1070
	80:20-1	530	820	1040	1140
	60:40-0	270	470	620	720
	60:40-1	310	530	680	790
20:80	100:0-0	490	1010	1360	1540
	100:0-1	560	1140	1560	1740
	80:20-0	360	780	1080	1240
	80:20-1	420	880	1230	1390
	60:40-0	240	520	720	780
	60:40-1	260	560	760	850

Fig. 4(b) exhibits the uniaxial compressive strength of the specimens with different mixing ratios for sodium silicate No.3 of 35%.

Compared with the strength at day 28 for C:B-F 100:0-0, the strength of the specimen with 1% Carbon fiber for C:B-F 80:20-0 and for C:B-F 60:40-0 was about 73-78% and 50-52% lower, respectively.

As shown in Fig. 4(a), it is considered necessary to increase the amount of an additional admixture or cement to enhance the effect for strength. However, because the strength of water cutoff grouting required in the field is generally at least 60kPa, alternative resources can be used from 20% to 40% for the optimum mixing ratio depending on circumstances, and using an additional admixtures is required in consideration of the mixing ratio for enhancing strength.

Fig. 4(c) shows the uniaxial compressive strength of the specimens with different mixing ratios for sodium silicate No.3 of 20%.

Compared with the strength at day 28 for C:B-F 100:0-0, the strength of the specimen with 1% Carbon fiber for C:B-F 80:20-0 and for C:B-F 60:40-0 was about 79-80% and 49-51% lower, respectively.

The analysis of uniaxial compressive strength depending on the contents of GGBS compared with cement shows that using alternative resources from 20% to 40% for the optimum mixing ratio is effective depending on circumstances because the strength of water cutoff grouting actually required is generally at least 60 kPa. In consideration of environment-friendliness and economy, application of strength of sodium silicate 20% for actual

Table 6 Results of permeability

Sample	Water flow (cm^3)	Sample length (cm)	Specimen area (cm^2)	Hydraulic head difference (cm)	Measurement time (sec)	Permeability (cm/sec)
C:B-F (100:0-0)	12.42	15	176.6	17.75	600	9.9×10^{-5}
C:B-F (100:0-1)	12.01	15	176.6	17.75	600	9.6×10^{-5}
C:B-F (80:20-0)	5.56	15	176.6	17.75	600	4.4×10^{-5}
C:B-F (80:20-1)	5.31	15	176.6	17.75	600	4.2×10^{-5}
C:B-F (60:40-0)	3.2	15	176.6	17.75	600	2.6×10^{-5}
C:B-F (60:40-1)	3.0	15	176.6	17.75	600	2.4×10^{-5}

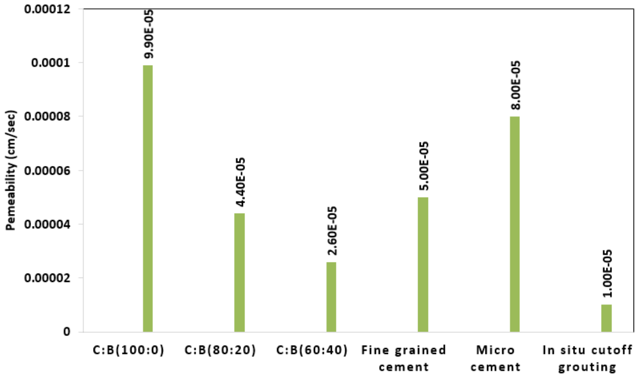


Fig. 5 Analysis of water cutoff effect depending on water cutoff grout material

(a) 500 magnifications

(b) 1000 magnifications

Fig. 6 SEM photos of general sample

installation will ensure enough water cutoff effect and enhanced strength.

Table 5 shows that the compressive strength at day 3 increased with an increase in sodium silicate. However, the compressive strength at day 28 decreased with an increase in sodium silicate. This is because excessive sodium silicate causes a number of small cracks in cement.

The compressive strength for the specimens with 1% carbon fiber was about 1.2 times larger than that for the specimens without carbon fiber. It appears that the carbon fiber reinforces the grouting specimen and prevents the development of cracks in the grouting specimen as the grouting specimen is being hardened.

4.2 Permeability test analysis in different mixing ratio

Table 6 illustrates the result of permeability test analysis. When cement was just mixed, the amount of water flow for 600 seconds was 12.42 cm3, and the measured permeability was 9.9×10-5 cm/sec. When the amount of added carbon fiber was 1%, water flow was 12.01 cm3 and the measured permeability was 9.6×10-5 cm/sec. When the amount of added GGBS was 20%, permeability was 4.4×10-5 cm/sec, and when the amount of added carbon fiber was 1%, it was 4.2×10-5 cm/sec. Moreover, when the amount of added GGBS was 40%, permeability was 2.6×10-5 cm/sec, and it was 2.4×10-5 cm/sec when the amount of added carbon was 1%.

Fig. 5 shows comparison of the result of this study with the water cutoff effect for the conventional development technique.

Park *et al.* (2004) used powder and micro cement to conduct a permeability test. The experiment showed permeability of 5.0×10^{-5} *cm/sec* and 8.0×10^{-5} *cm/sec*, respectively, suggesting a similar tendency to the case of C:B 80:20%. Moreover, there is no specified standard for field grouting water cutoff evaluation, but it is determined water cutoff is achieved when permeability is about 1.0×10^{-5} *cm/sec*. Therefore, enough water cutoff by the grout used in this study is implemented where C:B is 60:40%.

(a) Sample reinforced with large volume of fiber (b) Sample reinforced with large volume of fiber

(c) Sample reinforced with small volume of fiber (d) Sample reinforced with small volume of fiber

Fig. 7 SEM photos of general sample reinforced with carbon fiber

It was observed that permeability decreased by about at least 1.5 times as GGBS increased by 20%. Therefore, where GGBS is used for grouting, it is required to use it as a water cutoff grouting material, and it is also necessary to raise the mixing ratio of an additional admixture and cement if enhanced strength is required.

4.3 SEM analysis result

The test for fiber reinforcement properties aims to examine the mechanism of bonding fiber to cement in the grouting material, and the material samples fractured in measuring uniaxial compressive strength were used. The samples of C:B-F 0% and C:B-F 1% were sent to the Research Facilities Center of Chosun University for the analysis.

Based on the SEM electron microscope, Fig. 6(a) shows the photo of a collected sample of C:B-F 0%, and Fig. 6(b) shows the outer surface of the collected sample by 500 and 1,000 magnifications. Multiple grains accumulated on the specimen surface are shown, and they are cement scraps, microorganism minerals and were dense between particles.

The photo of samples containing carbon fiber with C:B-F 1% was taken, and Fig. 7(b) shows the outer surface of the collected sample by 1,000 magnifications. Fig. 7(b) shows the carbon fiber combined with the grouting material, and the hardened specimen affects compressive strength because it behaves as one mass with the carbon fiber. Moreover, fiber reinforcement like the reinforced concrete will contribute to enhancing strength.

However, it is very difficult to mix carbon fiber very evenly in the grout. As clearly shown in Fig. 7(a) and 7(d) for the same specimen, Fig(a) has more carbon, but Fig(d) has less carbon fiber. In the case of 7(d), the strength increase can be very little. Therefore, the improvement of grouting mixing equipment is very necessary for even mixing of the grouting materials.

5. Conclusions

- Although the homo-gel uniaxial compressive strength at day 3 increased, the specimen had partial cracks. This caused the reduction in the strength at day 28 significantly as the content of sodium silicate No.3 increased. Furthermore, when 1% of carbon fiber was added, uniaxial compressive strength increased by about 1.2 times, and it is considered that the carbon fiber is effective as a reinforcement in the grouting material to enhance strength.
- The permeability test showed that permeability was about 1.0×10^{-5} cm/s for C:B 60:40%, implying that the developed grouting material is quite useful for water cutoff. It was observed that permeability decreased by at least about 1.5 times as GGBS increased by 20%, clearly indicating that the use of GGBS is considerably useful for grouting.
- The SEM analysis showed the carbon fiber reinforced the grouting material, leading to the improved strength of the grout.

Acknowledgments

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