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An experimental study on the water-purification properties of porous concrete

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Abstract

The results of an experiment on the compressive strength and water purification properties of porous concrete are reported in this paper. Two sizes of coarse aggregate were used, namely 5 to 10 mm, and 10 to 20 mm. Three absolute volume ratios of paste–aggregate were used, namely 30%, 40% and 50% for a given size of aggregate. The compressive strength is found to be higher when the size of the aggregate is smaller, and when the paste–aggregate ratio (P/G, vol.%) is smaller. In the water purification experiment, the amount of organisms attached on the porous concrete surface is indirectly examined by the consumption of the dissolved oxygen (DO, mg/l). Water purification of the porous concrete is evaluated by the removal amount of the total phosphorus (T-P, mg/l) and total nitrogen (T-N, mg/l). A porous concrete with a smaller size of aggregate and a higher void content was found to have superior ability of the removal of the T-N and T-P in the test water. This is due to the large specific surface area of the porous concrete. Results from this study show that porous concrete using industrial by-products is able to purify water efficiently.

Keywords: Fly ash; Silica fume; Granulated blast-furnace slag; Permeability; Mechanical properties

1. Introduction

Recently, various artificial structures and an increasing amount of pollutants brought about by industrial development have severely degraded the global environment, which in turn reminds us of the importance of material circulation, the food chain and water supply. Currently, concrete is heavily used as one of the major construction materials in modern industrial society. However, the construction of concrete structures has resulted in the alteration of natural ecosystems and less natural habitats, which has reduced the self-purifying capacity of the natural inhabitants of those ecosystems. This factor in conjunction with an increasing environmental load has led to a disruption in the environmental balance and is the cause of severe water pollution. In particular, common concrete used along the waterside pollutes water and soil through the alkaline substances that are contained in it, which in turn adversely affects the ecosystem [1–3]. Until now, development of water area environments has placed an emphasis on flood control and irrigation. However, in the future, consideration of the natural ecosystem through technological advances in the rehabilitation of water area environments will become an important task. One solution for the task comes from environment-friendly concrete, so-called eco-concrete, which can reduce the environmental load and contribute to the harmonious coexistence of humankind and nature [4]. Eco-concretes can be classified based on their usage as environmental load reducing types and bio-responsive types, which are subdivided into concrete for microbial attachment and concrete for water purification [5].

In this study, silica fume and fly ash, both industrial by-products, were added to the manufacture of environmental load reducing porous concrete, a bio-responsive eco-concrete, to which terrestrial as well as aquatic microbes can attach themselves. The porous concretes were then submerged under river water in order for bio-film to develop over the broad specific surface and internal continuous pores. Subsequently, the strength property of the porous concrete was evaluated according to the particle size of the aggregate and the paste–aggregate ratio (P/G). In addition,

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Table 1
Tests and variables used in the experiment

W/B (mass, %)		25
P/G (vol.%)		30, 40, 50
Admixture		Silica fume 10%, Fly ash 20%
The size of aggregate		5 ~ 10 mm, 10 ~ 20 mm
Test items	Cement paste	Flow test
	Hardened concrete	Compressive strength (Age 7, 14, 28, 90 days)
	Water purification	pH
		DO (mg/l)
		T-P (mg/l)
		T-N (mg/l)

its water purifying capacity was also evaluated with the use of the natural contact oxidation method.

2. Scope

The tests and variables used in the experiment are shown in Table 1. The water–cement ratio of the porous concrete was fixed at 25%. The amount of silica fume and fly ash to be added were 10% and 20%, respectively. In addition, an adequate mixing ratio of cement dispersing admixture for optimum flow value of the cement paste was determined. Two different aggregate particle sizes (5 to 10 mm and 10 to 20 mm) and three different P/Gs (30%, 40% and 50%) were incorporated in the experiment.

3. Materials

To increase the long-term strength and to decrease the elution of the alkaline component, blast furnace cement containing 30% blast furnace slag provided by domestic company "S" was used. Table 2 displays its physical properties. Coarse aggregate made of crushed stones with 5 to 10 mm and 10 to 20 mm singular particle sizes supplied by company "H" in Geumsan, Chungnam was used. Table 3 displays the bulk density, water absorption ratio and bulk unit weight of the coarse aggregate used. Fly ash from the bituminous coal-fired Boryung Thermal Power Plant was used. Table 4 displays its chemical compositions and physical properties. Silica fume provided by an Australian company "E" that is expected to have a strength enhancing effect was used. Table 5 displays its chemical compositions and physical properties. A high-range water-reducing admixture that improves the concrete property through a cement dispersing activity, a polynaphthalene sulphonate "Mighty-150", supplied by a Japanese company "K" was used. Table 6 displays its chemical compositions and physical properties.

Table 2
Physical properties of Portland blast-furnace slag cement (data from manufactured company)

Specific gravity	Blaine (cm^2/g)	Stability (%)	Setting time (min)		Compressive strength (N/mm^2)		
			Ini.	Fin.	3 days	7 days	28 days
3.03	4.900	0.01	300	460	17.3	27.5	42.8

Table 3
Physical properties of aggregate

Grading (mm)	Specific gravity	Absorption (%)	Unit weight (kg/m^3)
5 ~ 10	2.69	0.6557	1504
10 ~ 20	2.69	0.6557	1488

4. Mixture proportions

Table 7 shows the mixture proportion of the porous concrete used in this study. Two types of concrete were made with a water–binder ratio of 0.25 and P/G of 30%, 40% or 50%, 10% silica fume and 20% fly ash. Whereas Type I used an aggregate with a single particle size of 5 to 10 mm, Type II used an aggregate with a single particle size of 10 to 20 mm. Porous concrete was mixed using a forced two-shaft circulating mixer. The above ingredients were mixed in accordance with the following separate charging method (Fig. 1): coarse aggregate and cement were added first and mixed in a dry state for 1 min followed by the addition of water containing a high-range water-reducing admixture and a subsequent mixing for 3 min.

5. Specimen and method of evaluation

Cylinder specimens (Φ100×200 mm) were made by rodding 25 times in three layers, and then applying a vibration for 10 s. The concrete panels for the water-purifying tests (400×400×100 mm) were made by rodding in two layers, and then applying a vibration for 10 s. The test specimens were removed from their forms after 48 h and cured under water at 20±3 °C according to the test procedure.

5.1. Flow test

To secure the required workability of the concrete, to prevent the separation of ingredients during the forming

Table 4
Chemical composition and physical properties of fly ash

Chemical composition

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	Ig.loss
65.3	25.5	4.25	1.20	0.98	0.21	1.03	3.63

Physical properties

Specific gravity	Blaine (cm^2/g)	Particle size (mm)
2.10	3124	0.02

Table 5
Chemical composition and physical properties of silica fume

Chemical compositions			
SiO_2	H_2O	CaO	Ig.loss
91.1	0.8	1.3	2.0

Physical properties		
Specific gravity	Blaine (cm^2/g)	Particle size (μm)
2.21	263,000	0.5

process, and to form continuous pores after the hardening process, the mixing ratio of the high-range water-reducing admixture that satisfied a target flow value was determined in accordance with KS L 5111.

5.2. Total void ratio measurement

The total void ratio was obtained by dividing the difference between the weight (W_1) of the cylinder specimen ($\Phi 100\times 200$ mm) in the water and that (W_2) measured following air drying for 24 h by the specimen volume. The equation used to obtain this value is as follows:

$$A = 1 - \left(\frac{(W_2 - W_1)/\rho_w}{V_1}\right) \times 100(\%)$$

Where: A=Total void ratio of the porous concrete, %; W_1=underwater weight of cylinder specimen, kg; W_2=weight of cylinder specimen dried in air for 24 h, kg; V_1=Specimen volume, mm^3; ρ_w=density of water, (kg/mm^3).

5.3. pH measurement

The pH of the cylinder specimen ($\Phi 100\times 200$ mm) was measured using a pH meter made by "O" company in Singapore after immersing it in river water for the predetermined periods of time and then in a particular amount of city water for 24 h [6].

5.4. Indoor water purification test

The indoor water purification test was performed using an indoor water purifying channel (Fig. 2) and the panel type specimen (400×400×100 mm) previously submerged under river water for 3 months in order for microorganisms to attach to it while circulating the water in the channel at a rate of 2 l/min. To simulate sunlight, artificial illumination of 2000 lx was applied at 12-h intervals. The river water under which the specimens were immersed was used as the standard water, whose properties are displayed in Table 8. The water level was maintained by replenishing the lost water with the standard water. The water temperature was maintained at 25±2 °C to minimize the influence of temperature change.

Table 6
Properties of admixture

Type	Color	Main ingredient	Solid (%)	Specific gravity	pH
High-range water-reducing admixture	Dark brown	Napthalene sulphonate	41 ~ 45	1.15±0.05	7 ~ 9

Table 7
Mix proportions of porous concrete

Series	W/B (mass, %)	P/G (vol.%)	Unit weight (kg/m^3)					AD (C×%)
			W	C	G	SF	FA	
CB30-I	25	30	68	272	1458	–	–	0.4
SF30-I			68	245	1458	27	–	1.3
FA30-I			68	217	1458	–	54	0.6
CB40-I		40	89	358	1458	–	–	0.4
SF40-I			89	322	1458	35	–	1.3
FA40-I			89	286	1458	–	71	0.6
CB50-I		50	111	445	1458	–	–	0.4
SF50-I			111	400	1458	44	–	1.3
FA50-I			111	356	1458	–	89	0.6
CB30-II	25	30	70	281	1444	–	–	0.4
SF30-II			70	253	1444	28	–	1.3
FA30-II			70	225	1444	–	56	0.6
CB40-II		40	92	368	1444	–	–	0.4
SF40-II			92	331	1444	36	–	1.3
FA40-II			92	294	1444	–	73	0.6
CB50-II		50	113	454	1444	–	–	0.5
SF50-II			113	408	1444	45	–	1.4
FA50-II			113	363	1444	–	90	0.7

CB=Portland blast-furnace slag cement; SF=Silica fume 10%; FA=Fly ash 20%; AD=high-range water-reducing admixture; I=5 to10 mm; II=10 to 20 mm; G=Coarse aggregate.

5.5. DO (dissolved oxygen, mg/l) measurement

To measure the amount of microorganisms attached to the panel, the DO consumption (mg/l) was measured using the Winkler Titration Method [6].

5.6. T-P (mg/l) and T-N (mg/l) measurements

In the water purification test, the T-P (total phosphorus) and T-N (total nitrogen), which are the major elements causing eutrophication, were also measured. For T-P measurement, the Ascorbic Acid Method [6] was used. A standard PO_4 solution was prepared and a calibration curve was derived through measuring the absorbance of the solution at an 880-nm wavelength. The absorbance of the sampled test water according to dates was measured to

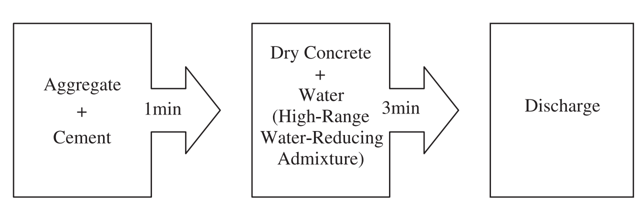

Fig. 1. Mixing method.

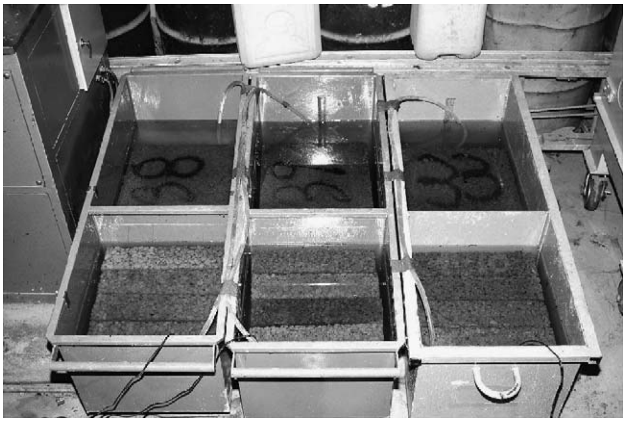

Fig. 2. The indoor equipment for water purification test.

determine the T-P (mg/l) from the calibration curve. For T-N measurement, the Persulfate Method [6] was used. A standard NO_2 solution was prepared and a calibration curve was derived measuring the absorbance of the solution at a 220-nm wavelength. The absorbance of sampled test water was measured to determine the T-N (mg/l) from the calibration curve.

6. Results and discussion

6.1. Total void ratio

The theoretical void ratios calculated based on the P/G and the absolute volume ratio of aggregate were 30%, 25% and 20% when the P/Gs were 30%, 40% and 50%, respectively. Fig. 3 displays the relationship between the theoretical and actual void ratio measured after the specimen was made. For the aggregate with particle size from 5 to 10 mm, the difference between the theoretical and actual void ratio was 0.5% to 1.2%, whereas it was 0.5% to 1.0% for the aggregate with particle size from 10 to 20 mm. Because there is little difference between the theoretical and actual void ratios, the theoretical void ratio obtained using P/G and absolute volume were used in this study. The error in void ratio was considered to have only a negligible influence on the compressive strength of the porous concrete and its surface area.

6.2. Compressive strength

As the porous concrete matured, its compressive strength increased as displayed in Fig. 4. At ages from 28 to 90 days, a relatively smaller increase in the compressive strength was noticed. The compressive strengths of the concretes with the same P/G according to the aggregate size are shown in Figs. 4 and 5. The concretes with 5 to 10 mm aggregate size exhibited 1.8 to 2.0 times greater strength than those with 10 to 20 mm aggregate size. This is considered to be related to the actual loading area. There was a larger load contact surface between the aggregate and the cement paste of the porous concretes containing 5 to 10 mm aggregate than that of the porous concrete containing 10 to 20 mm aggregate as displayed in Fig. 5. As for the effects of P/G on compressive, the porous concrete with a P/G of 50% exhibited 1.2 to 1.4 times greater strength than the porous concrete with a P/G of 30%. This indicates that as the P/G increases, the internal void ratio of the porous concrete decreases, resulting in enhanced strength. The compressive strength of the porous concrete with 5 to 10 mm aggregate size, 10% added silica fume, and P/Gs of 30%, 40% and 50%, exhibited an increase in strength by 15%, 10% and 9.5%, respectively, whereas that of the porous concretes with 10 to 20 mm aggregate size with identical amount of silica fume and P/Gs, increased by 10%, 15% and 13%, respectively. In addition, on the 28th day of concrete maturation, the porous concrete with the particle size of 5 to 10 mm and P/G of 50% produced a very high compressive strength of 23.7 N/mm^2. This may be due to the enhanced watertightness by the addition of ultrafine silica fume. However, when fly ash was added up to 20%, the porous concrete with 5 to 10 mm aggregate and with P/Gs of 30%, 40% and 50% exhibited 8%, 5.2% and 10% reduction in the compressive strength, respectively, whereas the porous concrete with 10 to 20 mm aggregate and with the same P/Gs, showed 5%, 3% and 12% reduction, respectively. This may be due to the reduced cement content replaced by the fly ash.

6.3. Immersion period and pH

The pH measurement for the evaluation of the adverse influence of free calcium carbonate on the environment is displayed in Fig. 6. Porous concretes containing an industrial by-product known as Pozzolan recorded pH of 10.2 to 11.17 from the 7th day after the specimen was immersed, which is lower than that of ordinary concrete. From the 5th week following dipping, the pH began going down and at the 90th day following immersion, the pH became less than 9, which is suitable for growth and inhabitation of organisms. The earlier pH drop in the porous concrete than in the ordinary concrete may be due to the larger specific surface and the added Pozzolan in the porous concrete.

6.4. Amount of attached microorganisms according to the P/G and aggregate sizes

Fig. 7 displays the measurement of dissolved oxygen consumption by microorganisms to indirectly evaluate the amount of microorganisms attached to the surface of porous concrete. The DO consumption is proportional to the number of the attached microorganisms. Fig. 8 shows the

Table 8
The quantity of standard water

Temperature	pH	DO (mg/l)	T-N (mg/l)	T-P (mg/l)
27 °C	7.8	7.9	2.058	0.053

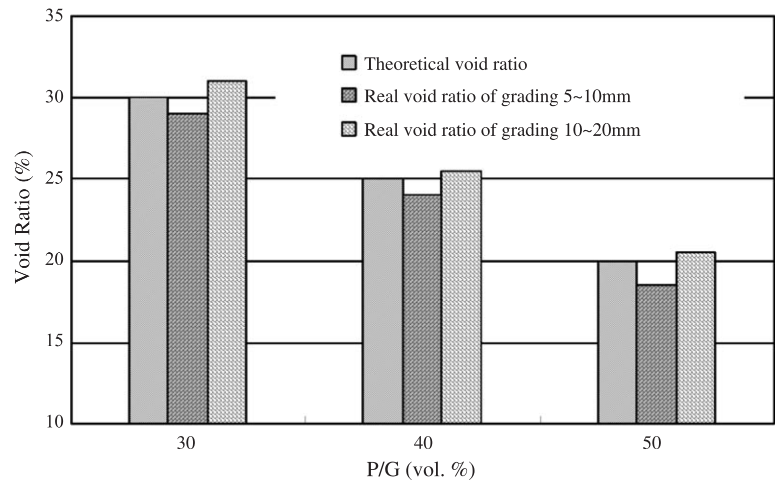

Fig. 3. Comparison of void in reality to that in theory.

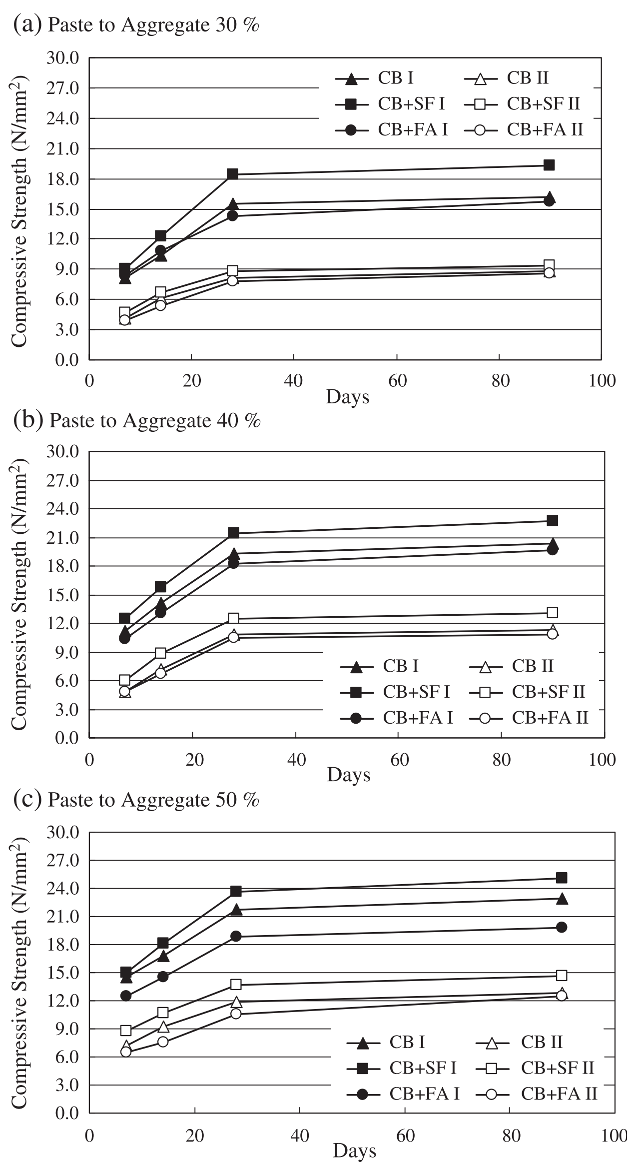

Fig. 4. The compressive strength by ages and grading.

results of DO consumption according to the aggregate size, P/G and the type of the admixture on the 14th day. The DO consumption is different between the DO concentration of the standard water channel with an initial DO concentration of 7.9 mg/l and that of the tested water channel after the porous concrete test panel (400×400×100 mm) was immersed in the river water for 3 months. The porous concrete with 5 to 10 mm aggregate size consumed twice as much DO as the one with 10 to 20 mm aggregate size. For the concretes with the same aggregate, the porous concrete with a lower P/G showed more DO consumption. Therefore, it can be said that the DO consumption by the attached microorganisms depends on the number of microorganisms and the specific surface of the porous concrete determined by aggregate size and P/G.

6.5. Amount of T-P (mg/l) removed according to P/G and aggregate size

The T-P (mg/l) measurements from the indoor water purification test according to aggregate size and the day when the measurements were taken are displayed in Fig. 9. Regardless of the aggregate size and P/G, the T-P began to

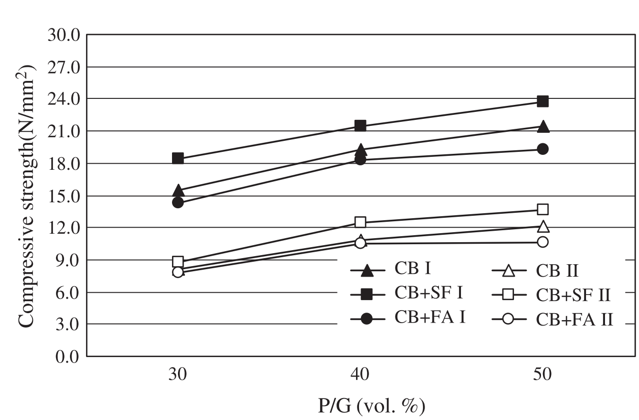

Fig. 5. The compressive strength by P/G and grading.

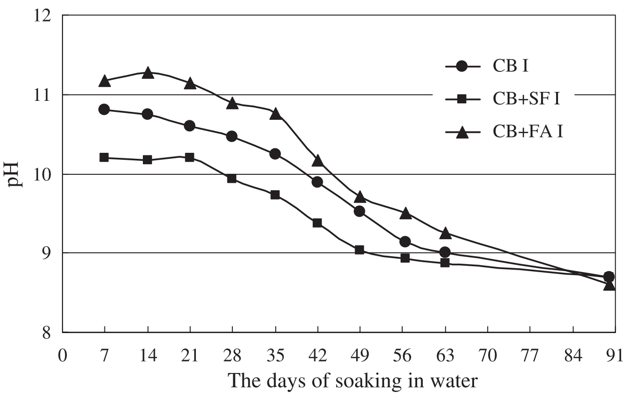

Fig. 6. The variation of pH by soaking days (5 to 10 mm).

decrease after the 3rd day of measurement. For the porous concretes with 5 to 10 mm aggregate size, T-P for the porous concrete with P/G of 30% decreased to 0.02 mg/l at the 7th day recording (96% reduction); T-P for the porous concrete with P/G of 40% dropped to 0.15 mg/l at the 11th day recording (72% reduction) and T-P for the porous concrete with P/G 50% went down to 0.178 mg/l at the 14th day recording (66% reduction). However, the T-P increased above the initial T-P of 0.53 mg/l starting at the 7th and 11th days of measurement. The reversion may be due to the fact that (1) the capacity of removing microorganisms attached to the porous concrete reached a limit within a short period of time because the water was circulated within the confined water purification channel or (2) the microorganisms could not be activated anymore due to the lack of dissolved oxygen depleted by fast growing bio-film facilitated by abundant phosphate, a nutrient for the aquatic microbes. The relationships among the P/G, aggregate size and the T-P are displayed in Fig. 10. In general, the porous concrete with 5 to 10 mm aggregate size showed 1.7 times higher removal capacity than the one with 10 to 20 mm aggregate size. As for the T-P removal capacity according to P/G, the amount of phosphate removed by the porous

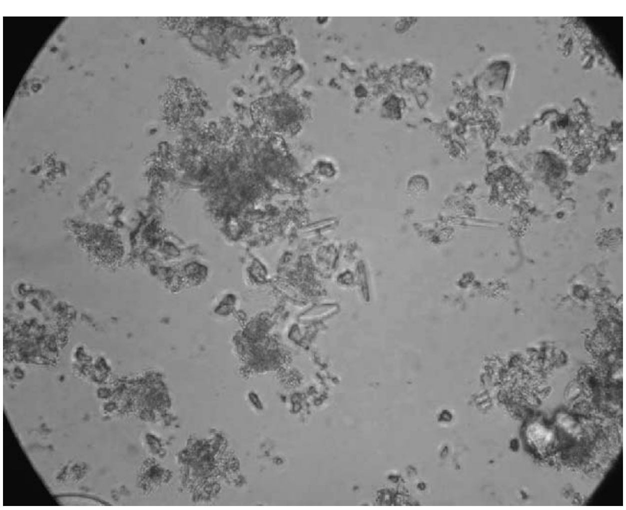

Fig. 7. Observed microorganism by microscope.

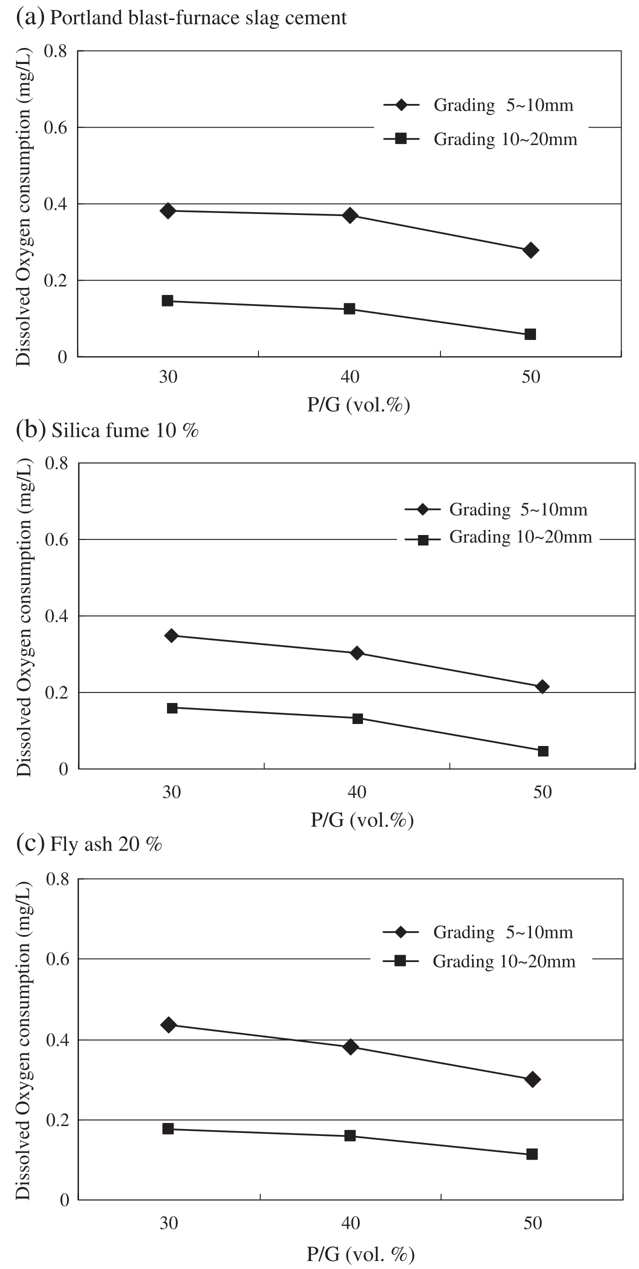

Fig. 8. The consumption of dissolved oxygen (mg/l) (at 14th days).

concrete with 10 to 20 mm aggregate size decreased as the P/G increased, while the porous concrete with 5 to 10 mm aggregate size showed no clear trend. However, like the DO consumption rate, the removal rate of T-P may be influenced primarily by the number of attached microbes. It can be said about this that the porous concrete with 5 to 10 mm aggregate size had more microbes attached thereto, thus having a higher T-P removal capacity.

6.6. Amount of T-N removed according to the P/G and aggregate size

The T-N (mg/l) concentration measurements from the indoor water purification test according to aggregate size

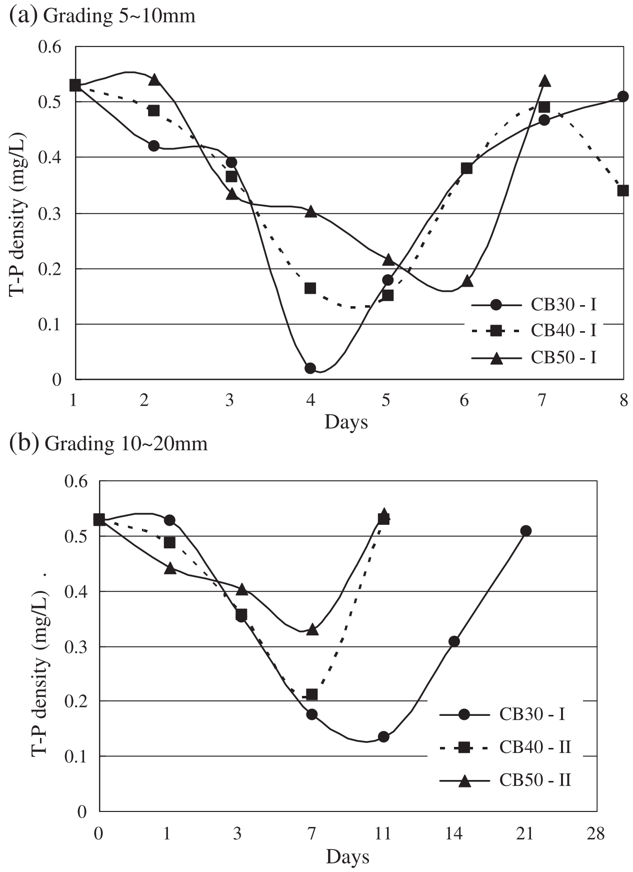

Fig. 9. Variation of T-P by days.

and the day when the measurements were taken are displayed in Fig. 11. Regardless of aggregate size and P/G, the T-N began to fall after the 3rd day of measurement. For the porous concrete with 5 to 10 mm aggregate size, the T-N for the porous concrete with P/G of 30% fell to 1.15 mg/l at the 7th day (with 44% reduction), the T-N for the porous concrete with P/G of 40% dropped to 1.1 mg/l at the 11th day (with 47% reduction), and the T-N for the porous concrete with P/G 50% went down to 1.3 mg/l at the 7th day (with 37% reduction). However, the T-P increased above the initial T-N of 2.058 mg/l starting on the 7th day of measurement. The reversion may be due to the fact that (1) the capacity of removing microorganisms attached to the porous concrete reached the limit within a short period of time because the water was circulated within a confined water purification channel or (2) the microorganisms could not be activated any more due to the lack of dissolved oxygen depleted by fast growing bio-film facilitated by abundant nitrogen, a nutrient for the aquatic microbes. The relationships among the P/G, aggregate size and the T-N are displayed in Fig. 12.

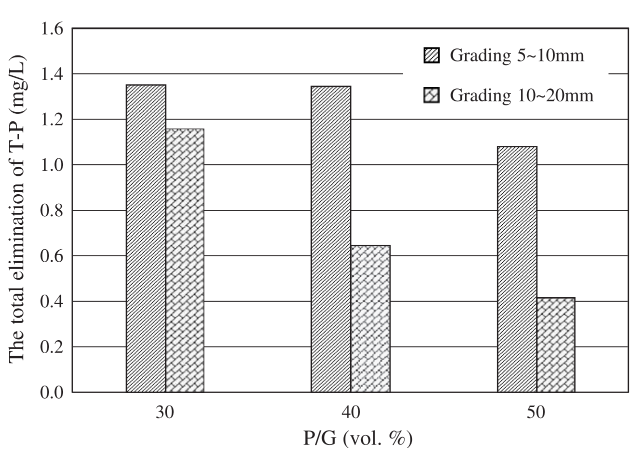

Fig. 10. The elimination of T-P (mg/l) in total.

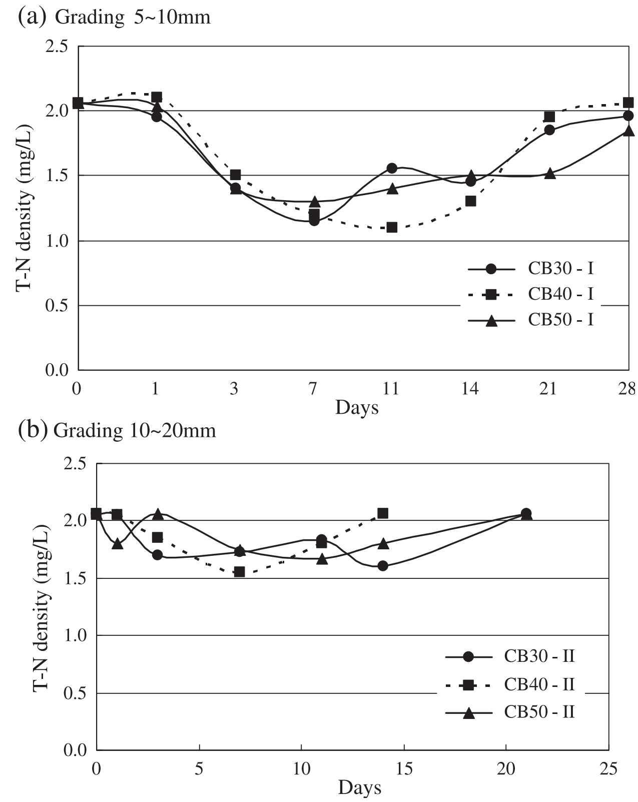

Fig. 11. Variation of T-N density by days.

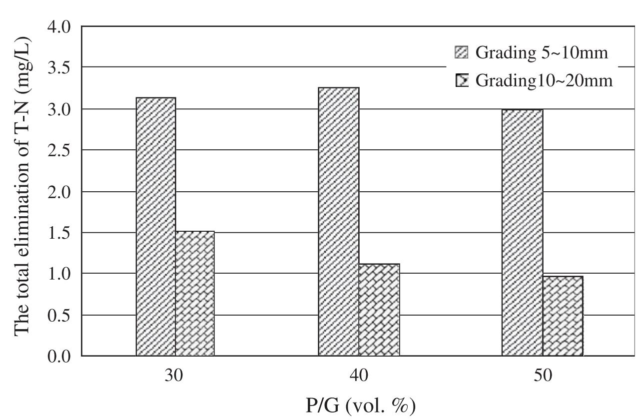

Fig. 12. The elimination of T-N (mg/l) in total.

Regardless of the P/G, the porous concrete with 5 to 10 mm aggregate removed 2.8 times as much T-N as the one with 10 to 20 mm aggregate. For both the porous concrete containing 5 to 10 mm aggregate and that containing 10 to 20 mm aggregate, the increase in P/G gave no influence on the removed amount of T-N. The removal of T-N was independent of P/G (vol.%) in both porous concretes with a different aggregate. The increase in P/G had no influence on the removed amount of T-N. From this, it can be said that the porous concrete may be influenced more by the specific surface area determined by the aggregate size than by the number of internal pores determined by P/G. The removal of T-N may be influenced primarily by the amount of attached microbes as mentioned in Section 6.4 regarding the consumption of dissolved oxygen. Therefore, the porous concrete containing 5 to 10 mm aggregate with a larger specific surface carries more microbes attached to it and has a higher T-N removal capacity.

7. Conclusions

The results of the evaluation of the physical characteristics and water-purifying capacity of the porous concrete and the effects of its aggregate size and P/G are presented. The main conclusions are summarized as follows:

1. When the P/G (vol.%) is identical, the porous concrete that contains silica fume and fly ash exhibited greater compressive strength with a smaller aggregate size. In the case that P/G is 50%, for example, the porous concrete with an aggregate size of 5 to 10 mm showed 1.8 to 2.0 times higher compressive strength than the one with a particle size of 10 to 20 mm. When the particle size is identical, as the P/G increases, the compressive strength of the porous concrete containing 5 to 10 mm aggregate increased by more than 1.1 to 1.2 times and that of the porous concrete containing 10 to 20 mm aggregate increased by more than 1.1 to 1.4 times. As for the compressive strength of the porous concrete mixed with admixture, when the silica fume mixing ratio was 10%, the compressive strength increased by 10% to 15% for both cases of porous concretes containing 5 to 10 mm and 10 to 20 mm aggregate, whereas, when the fly ash mixing ratio was 20%, it decreased by 5.2% to 10% and 3% to 12%, respectively.
2. The addition of Pozzolan, which reduces elution of the alkaline component that adversely influences the aquatic ecosystem, resulted in a lower pH (10.2 to 11.17) than that of an ordinary concrete after being immersed under water for 7 days. On the 90th day following immersion, regardless of the mixing ratio, the pH started to go down from the 5th day after immersion, and reached a value of PH 9, which provided suitable conditions for the growth and inhabitation of organisms.
3. The dissolved oxygen consumption by attached microorganisms was twice as high in the case of the porous concrete containing 5 to 10 mm aggregate than in the case of the porous concrete containing 10 to 20 mm aggregate. When aggregate size is identical, the dissolved oxygen consumption increased in inverse proportion to the P/G.
4. In the indoor water purification test, the concentration of T-P (mg/l) and T-N (mg/l) were reduced by the attached microorganisms after a certain period of time. In the case of the porous concrete containing 5 to 10 mm aggregate, 1.7 times more T-P (mg/l) and 2.8 times more T-N (mg/l) were removed than in the case of the porous concrete containing 10 to 20 mm aggregate.
5. The reduction of T-P (mg/l) and T-N (mg/l) by microorganisms on the 7th and 11th days of the water purification test may be due to the fact that the T-P and T-N removal capacity of the microbes has reached their limits in the confined space, or the fact that the activity of the bio-film attached to the porous concrete surface became less active after consuming the majority of the dissolved oxygen in the test water. If the porous concrete can maintain the DO (mg/l) concentration at a level equivalent to that of natural rivers, it can be effectively used for the continuous purification of water.

Acknowledgements

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