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APPLICATION OF BLENDED CEMENT IN SHOTCRETE TO REDUCE THE ENVIRONMENTAL BURDEN

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ABSTRACT

The application of blended cements in shotcrete is investigated to reduce the environmental burden. Reduction of the environmental burden and meeting the required properties of quick setting and strength development are achieved using blended cements with blast furnace slag and a powder accelerator with a main component of calcium sulfo-aluminate. The powder accelerator is hydro-reactive and promotes quick setting and strength development in shotcrete. The reduced environmental burden of shotcrete with blended cement and powder accelerator are calculated.

INTRODUCTION

Blended cements, such as Portland cement mixed with blast furnace slag (BFS hereafter), are increasingly used in construction to reduce the environmental burden.

Although shotcrete with the use of blended cements has been tested and designed in the laboratory and applied to some tunneling projects (1, 2, 3), the application of the shotcrete with the use of blended cements in tunneling project is limited compared with the case for concrete in other construction fields. The major reason for small use of blended cements in shotcrete is that they detrimentally affect the important properties of quick setting and early strength development.

Powder accelerators with main components of calcium aluminate and calcium sulfo-aluminate are hydro-reactive and promote quick setting and early strength development in shotcrete. The quick setting property is highly advantageous in blended cement shotcrete containing less hydro-reactive Portland cement.

In the present study, we evaluated the quick-setting and strength development properties of shotcrete comprising blended cement and a powder accelerator, and quantitatively assessed the reduction of the environmental burden.

MATERIAL DESIGN AND COMPOSITION OF SHOTCRETE

Blended cement

The dominant materials used for blended cements are BFS, fly ash, and silica fume. BFS is the most widely used additive for concrete application, and it is standardized under JIS A 6206-1997. The standard gives amounts of magnesium, sulfur, and chloride components and ignition loss. Three types of BFS with different blaine specific surface areas, ranging from 3000 to 10,000 cm^2/g, are standardized for concrete application. For blended cement, BFS with a blaine specific surface area from 3000 to 5000 cm^2/g is used.

Fly ash is standardized under JIS A 6201-1999, and four types of fly ash with different blaine specific surface areas ranging from 1500 to over 5000 cm^2/g are standardized for concrete application. Type I with a blaine specific surface area exceeding 5000 cm^2/g is used for blended cement. Silica fume is standardized under JIS A 6207-1997.

In Japan, cements blended with BFS, fly ash, and pozzolan (silica fume) are standardized under Japanese Industrial Standards (JIS) R 5211-2003, R 5213-1997, and R 5212-1997.

Accelerator

Powder accelerator based on calcium aluminate promotes hydration of the cement, while the accelerator itself is hydro reactive to become solid (4, 5). Thus compared with other types of accelerators such as inorganic salt based chemicals and aluminum sulfate based liquid accelerator, cement mineral based accelerators have superior setting and early strength development properties. Accordingly, they have advantages in application to ground that has complicated geological formations and much spring water.

On the basis of cement chemistry, improvement of concrete performance is proposed by application of special cement additives and controlling the formation of ettringite ($3CaO\text{-}Al_2O_3\text{-}3CaSO_4\text{-}32H_2O$), a hydrate of calcium aluminate sulfate (6).

Quick setting, quick hardening, high strength, and expansion or shrinkage compensation is achieved by controlling the period of ettringite formation during the cement hydration. For example, the quick setting of cement or concrete is achieved by the formation of ettringite in the very first stage of cement hydration. Accelerators based on calcium aluminate or calcium sulfo-aluminate are used for the quick setting of cement and concrete (7).

Table 1 shows the properties of cement mineral based powder accelerators. An accelerator for normal shotcrete (Natmic Type 5; hereafter T5) is a powder based on calcium aluminate. A powder accelerator based on calcium sulfo-aluminate (Natmic Type 10, hereafter T10) is used for high-strength shotcrete with an additive content from 8 to 15% of the mass of the cement. T10 generates a large amount of ettringite at an early stage, which enhances the quick-setting performance.

Table 1. Properties of cement mineral based powder accelerators

Type	Main component	Chemical composition (mass%)			Additive content (%cement)
		CaO	Al2O3	SO3	
NATMIC Type 5 (T5)	Calcium aluminate	37.1	22.0	2.8	5 to 10
NATMIC Type 10 (T10)	Calcium sulfo-aluminate	42.6	22.3	28.6	8 to 15

Shotcrete composition

Table 2 lists the materials used in the shotcrete evaluation and Table 3 lists the composition of the evaluated shotcretes.

Table 2. Materials used in shotcrete evaluation

Material	Specification	Density (g/cm^3)
Cement (C)	Normal Portland cement Blaine specific surface area: 3200 cm^2/g	3.15
Blast furnace slag (BFS)	Blast furnace slag Blaine specific surface area: 5000 cm^2/g	2.98
Sand (S)	River sand, crashed, F.M. 2.90	2.62
Gravel (G)	< 13 mm	2.64
Super plasticizer (SP)	Poly-carboxylic-acid-type (FTN-30)	
Accelerator (T5)	Calcium-aluminate-based powder	2.6
Accelerator (T10)	Calcium-sulfo-aluminate-based powder	2.8

Table 3. Composition of shotcrete

Grade	W/B (%)	s/a * (%)	(kg/m^3)						Acc. (kg/m^3)
			W	C	BFS	S	G	SP	
N; Normal	60	60	216	360	0	1006	676	-	25.6 (T5)
B; Blended Cement	50	60	200	220	180	1004	675	2.8	32 (T10)

* s/a is the sand content as a percentage of the total mass of sand and gravel

Equipment and system for shotcrete

Figure 1 is a schematic diagram of shotcrete system of wet process using powder accelerator. Powder accelerator is added to wet-mix shotcrete using an air conveyance system and a supply device similar to that used in rotary system equipment. The accelerator is conveyed with pressurized air and mixed with wet concrete at the Y-intersection with the mixing pipe, before sprayed from the nozzle.

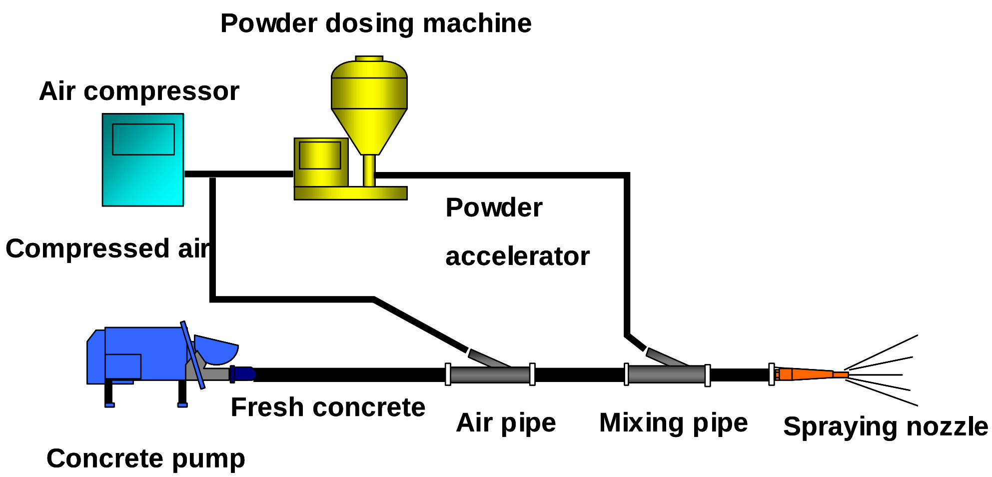

Figure 1. Schematic diagram of shotcrete system of wet process using powder accelerator

EVALUATION OF MORTAR – QUICK SETTING PROPERTY

Quick setting was evaluated using mortar with normal Portland cement and blended cement. Mortar was prepared with water to cement ratio of 60% and cement to sand ratio of 1/3. Powder accelerator was added to the fresh mortar and mixed for 15 seconds in the mixer, and then immediately molded in a specified case. The additive content was 7% for T5 and 10% for T10, which are the standard additive contents for the accelerators. Evaluation was carried out at 20°C. The quick setting of mortar was evaluated by measuring the Proctor penetration resistance in accordance with ASTM C-403. The times of initial setting (3.5 MPa resistance) and final setting (28 MPa resistance) were measured.

Figure 2 shows the setting conditions of quick-setting mortar. Mortar with blended cement and T10 (BB+T10) has higher penetration resistance than mortar with normal Portland cement and T5 (OPC+T5). As T10 has a larger amount of sulfur, the formation of ettringite may influence the quick setting property of cement blended with blast furnace slag.

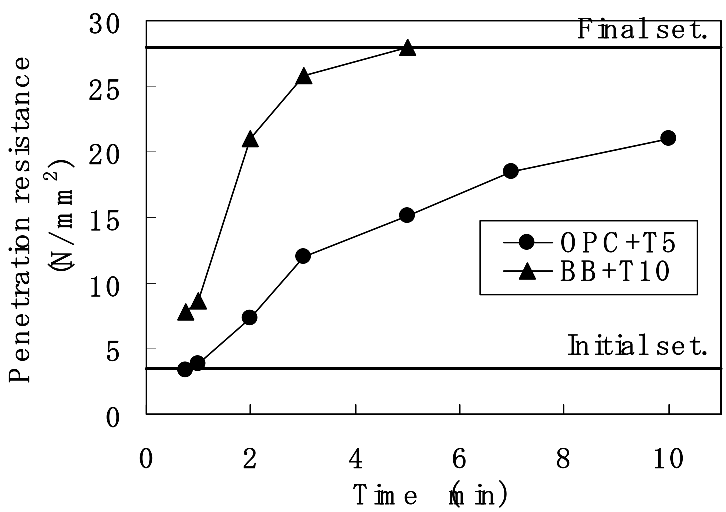

Figure 2. Quick setting property of mortar with blended cement and accelerator

EVALUATION OF SHOTCRETE – STRENGTH DEVELOPMENT

Shotcrete was evaluated in a model tunnel 4.5 m high, 5.5 m wide, and 20 m long. The wet process was applied, and a piston-type concrete pump with a maximum capacity of 25 m^3/hr was used in the experiments.

The pull-out strengths at shotcrete ages of 3 hours and one day were measured in accordance with JSCE-G562 (8). Shotcrete was applied to a frame with dimensions of 50 and 50 cm, and blocks were sampled. The test piece were cored (55 mm diameter and 110 mm long), and the core strengths at 7 and 28 days were measured in accordance with JIS A 1107 (9, 10).

Table 4 and Figure 2 present the results of strength development from an early shotcrete age of 3 hours to a late age of 28 days. The compressive strength of the base concrete was measured for test piece of 100 mm diameter and 200 mm long cylinders.

The compressive strength of blended cement shotcrete was higher than that of normal shotcrete from 1 day onwards, and it reached around 50 MPa after 28 days. The core strength of the blended cement shotcrete was higher than that of base concrete after both 7 days and 28 days, which contrasts with the case for normal shotcrete with T5. Shotcrete with blended cement of blast furnace slag and powder accelerator based on calcium sulfo-aluminate results in superior quick setting and strength development from an early age to long age in shotcrete.

Table 4. Strength development of shotcrete (MPa)

	Pull-out strength		Core strength		Base concrete	
	3 hrs	1 day	7 days	28 days	7 days	28 days
N	3	11	22	27	25	36
B	3	14	30	51	23	42

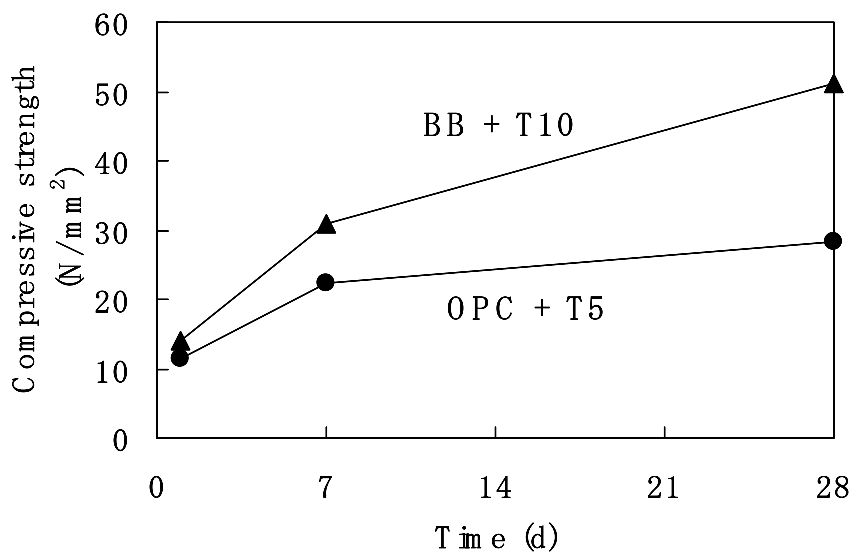

Figure 2. Compressed strength of shotcrete from 1 day to 28 days

ASSESSMENT OF THE ENVIRONMENTAL BURDEN OF SHOTCRETE

Table 5 gives the basic contents of CO_2 in the component materials of concrete given by Japan Society of Civil Engineers (11). The unit emissions of CO_2 here refer to the amount of CO_2 emission per unit during the manufacturing of the materials. The CO_2 emission of blast furnace slag is considered to be zero. The unit emissions of accelerators (T5 and T10) are the sums of the unit emissions for each component, calcium aluminate and calcium sulfo-aluminate for example, and electric power for mixing, crushing, and other processes. CO_2 emission of shotcrete was calculated by multiplying the unit emissions of CO_2 of the materials constituting shotcrete by the amounts used and summing.

Table 5. Unit CO_2 emissions

Item	CO_2 primary unit (kg-CO_2/ton)
Normal Portland cement	757.9
Blast furnace slag	0
Sand	3.5
Crushed stone	2.8
Accelerator (Natmic Type 5)	691.4
Accelerator (Natmic Type 10)	508.6

The following parameters were used to assess the environmental burden of shotcrete. The assumption was that 100 m^3 of concrete with a specified concrete strength of 18 N/mm^2. This assessment only covers CO_2 emission at the material level. CO_2 emissions during work execution, including those resulting from the operation of heavy-duty vehicles and transportation of materials, were not taken into account.

Figure 3 shows the CO_2 emission of each shotcrete operation. The use of shotcrete with blended cement (BB+T10) produces 31% less CO_2 emission than the use of normal Portland cement (OPC+T5) does for the same shotcrete amount. Moreover, as the compressive strength of BB+T10 is twice that of OPC+T5, the use of BB+T10 can reduce the shotcrete thickness required to achieve equal rigidity to $1/2^{(1/2)}$ (or 71%) of the OPC+T5 thickness. Thus accounting for the reduction in shotcrete thickness for BB+T10, the use of BB+T10 requires 51% less CO_2 emission than the use of OPC+T5 does.

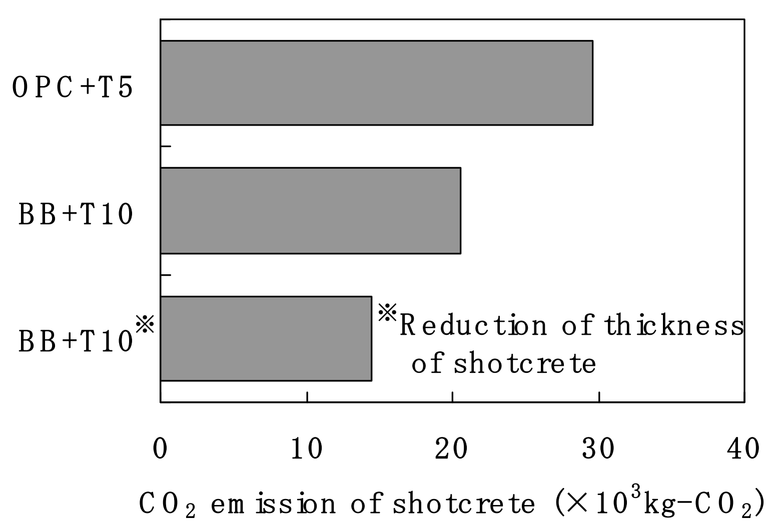

Figure 3. CO_2 emissions from operations involving shotcrete

These results indicate that shotcrete with cement blended with blast furnace slag and calcium-sulfo-aluminate based powder accelerator has superior setting and strength development characteristics, which combine to reduce the environmental burden.

SHOTCRETE WITH BLENDED CEMENT IN TUNNEL PROJECTS

Several tunnel projects in Japan have used shotcrete with blended cement. Shotcrete with blended cement using fly ash has been applied in many tunnel projects in Japan. In the Shin-Tamayama tunnel and Kamosaka tunnel projects, cement blended with 14 to 17% fly ash was applied with a powder accelerator based on calcium aluminate (3). In the Sakaigatani road tunnel, cement blended with 27% fly ash (JIS I type) was applied with a slurry-type accelerator based on calcium aluminate (12). In the Kusuda shinkansen railway tunnel, cement blended with 20% fly ash was applied with a powder accelerator based on calcium aluminate and a slurry-type accelerator (13).

Although shotcrete with blended cement using blast furnace slag has been applied in several tunnel projects in Japan, few applications are reported. As the concrete containing Portland cement blended with blast furnace slag shows high durability against acid and sea water, mountain tunnel in volcanic zone with acid or the liquid-natural-gas underground storage located in coast area are expected to be reported.

CONCLUSIONS

The application of blended cements in shotcrete was investigated to reduce the environmental burden. Reduction of the environmental burden and meeting shotcrete performances of quick setting and early strength development were achieved using cements blended with blast furnace slag and powder accelerator with a main component of calcium sulfo-aluminate.

The reduction in the environmental burden of the shotcrete containing blended cements and powder accelerator was calculated. Shotcrete with blended cement containing 45% blast furnace slag can reduce CO_2 emission by about 30% compared with the case for normal Portland cement.

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