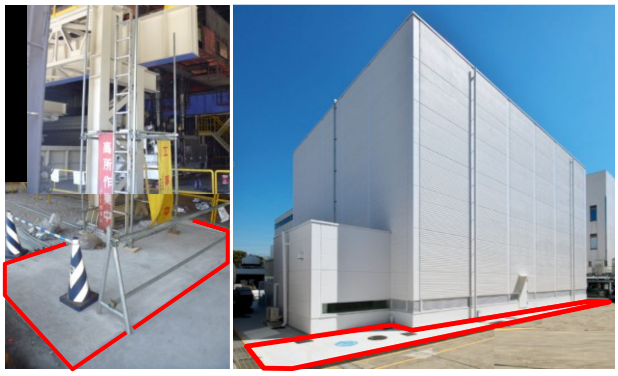
Study on A New Environment-friendly Concrete without Portland Cement

Taisei Corporation
Public Works Research Institute

1. Introduction

In the construction industry there is a demand for technologies to reduce the emissions of greenhouse gases, mainly CO_2. When 1 m^3 of the basic construction material concrete is produced, about 250 kg of CO_2 is emitted[1)], of which more than 90% results from the manufacture of Portland cement.

The recipients of the award have reduced the use of Portland cement to the limit and developed “environmentally-friendly concrete” with zero Portland cement content (Photograph 1)[2, 3)]. It is capable of reducing CO_2 emissions to about 1/4 that of normal concrete, and about 1/2 that of concrete using blast furnace cement type B, which is a designated procurement item of the Green Procurement Act. Also, the use of a large quantity of blast furnace slag which is a byproduct of the manufacture of steel contributes to promoting 3R (reduce, reuse, recycle).



a) Factory facility b) Research facility

Photograph 1 Structure to which environmentally-friendly concrete was applied
(area indicated by the red frame lines)

2. Characteristics of Environmentally-friendly Concrete

(1) Materials and proportions

The materials used and their proportions are shown in Table 1. Instead of Portland cement, blast furnace slag is used as the binder material to greatly reduce the CO_2 emissions. A special stimulus material is added to the blast furnace slag to exhibit latent hydraulicity. By the development of this stimulus material, the problems with using large quantities of blast furnace slag were overcome (Table 2).

Table 1 Example of materials used in environmentally-friendly concrete and their proportions

Name		Unit quantity (kg/m^3)						
		Water	Powder: P		Fine aggregate	Coarse aggregate	High performance AE water reducing agent	Water reducing agent
			Blast furnace slag	Stimulus material				
		W	BFS	St	S	G	Ad	Ad-R
Environment ally-friendly concrete	Basic※	155	333	99	714	958	3.5	
	Summer				732	959	6~7	
	Winter				715	944	4	
BB*		160	291#	—	791	1060	2.0	—

※: Water powder ratio (W/P) = 36%, fine aggregate percentage = 43%
*: Water powder ratio (W/P) = 55%, fine aggregate percentage = 43%
#: Blast furnace cement type B

(2) Environmental performance

The CO_2 emissions were calculated using the materials and proportions (Table 1), and the inventory data for each material[6-9)]. It is possible to reduce the emissions to about 1/4 the emissions of normal concrete using Portland cement with the same strength level, and about 1/2 the emissions of concrete using blast furnace cement type B (BB), which is a designated procurement item under the Green Procurement Act (Fig. 1). Also, because a large quantity of blast furnace slag, which is a byproduct of steel manufacturing, is used it is as effective also from the point of view of 3R.

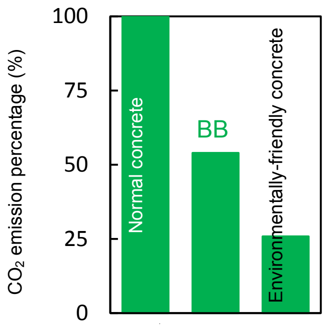


Fig. 1 CO_2 emissions of environmentally-friendly concrete

(3) Manufacturability

Commercial products are used as the powder (Table 1: P) and the chemical admixtures. The aggregates may be the normal aggregates used in a ready mixed concrete factory. Manufacture can be carried out using the normal equipment of the ready mixed concrete factory.

(4) Fresh properties and properties after hardening

Environmentally friendly concrete is a general-purpose concrete with a nominal strength of 24. Table 2 summarizes each of the properties, focusing on the expectation and concerns when a large quantity of slag is used, and compares the results with BB which is designated as a procurement item in the Green Procurement Act.

Table 2 Characteristics of environmentally-friendly concrete

Characteristics of environmentally-friendly concrete	Comparison with or correspondence to BB
Desirable properties	
• Low CO_2	→ About 1/2 that of BB
• Low heat generation	→ About 1/2 that of BB
• High resistance to chloride ingress	→ Better than BB
• High alkali silica resistance	→ Better than BB
Properties for which concerns have been resolved	
• Occurrence of the "sanding" phenomenon	→ Did not occur
• Generation of strength is slow	→ Same as BB, etc.
• Shrinkage is large	→ Same as BB, etc.
• Setting is slow	→ No problem at present. If necessary it can be dealt with using chemical admixtures
Can be dealt with if necessary	
• Low resistance to carbonation	→ It may be necessary to deal with this by design, etc.
• Low freeze thaw resistance	→ It may be necessary to deal with this by raising the strength level (lowering the water powder ratio), etc.

a) Fresh properties

Taking transport into consideration, the slump was adjusted to be 15±2.5 cm 60 minutes after mixing, and the air content was adjusted to 6±1.5%. These were satisfied even when the manufacturing plant, temperature, or source of the aggregates were different.

It can be delivered using a normal concrete pump, and this property classifies it as a high fluidity concrete[5, 10)].

b) Properties during hardening

Setting is slower compared with BB[4)], so the time for starting surface finishing work, etc., is delayed, but there have been no problems in construction.

The insulated temperature rise was obtained by a simple insulated test. When the concrete temperature at the time of pouring is between 11 and 32°C, the temperature rise was between 20 and 25°C. The performance was even better in terms of low heat generation[4)] compared with BB which is considered to be low heat generation and which when poured at 20°C the temperature rose to about 40°C.

Because a large quantity of blast furnace slag was used, there was concern over increased autogenous shrinkage. However, the autogenous shrinkage measured at 20°C was about the same as that for BB, so good properties were exhibited[4)].

c) Properties after hardening

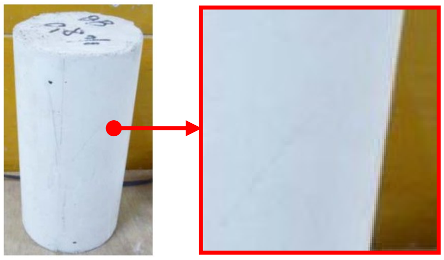
When a large quantity of blast furnace slag is used, there is a danger of occurrence of the “sanding phenomenon” in which the surface is fragile and peels[11]. This phenomenon was avoided by using a suitable powder composition.

There was a concern that strength evolution would be delayed in the same way as for setting. Compared with BB there was no delay in strength evolution in the initial period up to an age of 28 days, as in the examples described in Section 3 (Fig. 3).

There was also a concern that the drying shrinkage will be excessive, in the same way as for autogenous shrinkage. When measured in accordance with JIS A 1129, the shrinkage was smaller than that of BB, so the performance was good[4].

Photograph 2 Example of sanding phenomenon

Surface roughness and peeling



Photograph 3 Environmentally-friendly concrete

Smooth and robust surface

d) Durability

The resistance to carbonation was confirmed using an accelerated test (JIS A 1152). The carbonation that was about double that of BB. If carbonation resistance is required, it is necessary that the cover be checked. Note that by reducing the water powder ratio from 36% to 31%, it was possible to reduce the carbonation depth to about 1.5 times that of BB[4].

The resistance to chloride ingress was investigated by immersing in 3% NaCl solution, with reference to the Japan Society of Civil Engineers Standard JSCE G 572. There was no ingress of chlorides after immersion for 3 months or more, so it was concluded that the resistance to ingress was excellent. If it is assumed that ingress continued up to 3 months, then the diffusion coefficient is 0.56 cm^2/y, which is smaller than that of BB at 0.89 cm^2/y[4].

Regarding alkali silica reaction (ASR), the ASR mitigation effect was checked in accordance with ASTM C 1260 using mortar excluding coarse aggregates from Table 1, and using fine aggregate that was judged to be nonreactive in accordance with JIS A 1145 and A 1146 (Fig. 2). The percentage change in length of environmentally-friendly concrete very much less than that of BB. In JIS A 5308, BB is mentioned as a countermeasure against ASR, but environmentally-friendly concrete is even better, so it is expected to be effectively used with low-quality aggregates.

The freeze thaw resistance was evaluated in accordance with JIS A 1148. With the composition of Table 1 the resistance was insufficient, but when the water powder ratio was reduced from 36% to 31%, the prescribed standard was satisfied. When necessary it is possible to ensure the required performance by adjusting the composition[4)].

Regarding durability, exposure tests were carried out in Okinawa, Tsukuba, and Niigata, which are continuously verified (Photograph 4).

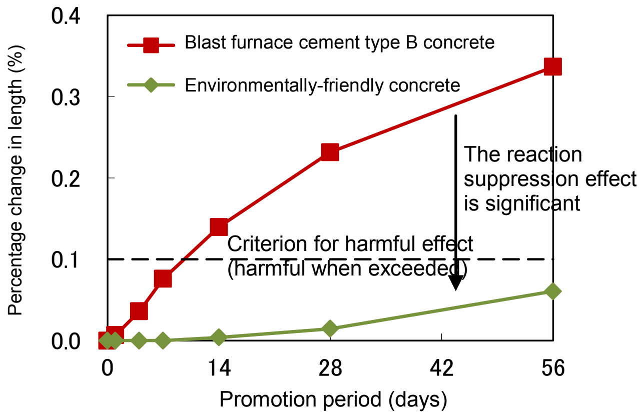


Fig. 2 Mitigation effect of environmentally-friendly concrete on alkaline aggregates

Photograph 4 exposure test (Okinawa)
Various performance verification in Okinawa, Tsukuba, and Niigata

3. Examples of Application

(1) Example of construction during summer[5)]

a) Outline of the construction

The concrete was applied to an RC structure floor member of of thickness about 20 cm, within the factory. The materials used and the composition were as shown in Table 1 (summer). As the construction was in the middle of summer, the temperature exceeded 30°C.

The concrete was produced in a standard ready mixed concrete factory, and transported in an agitator truck. As the temperature was high there were concerns that the loss of slump would increase, but the standard slump of 15±2.5 cm and the air content of 6.0± 1.5% were satisfied 30 to 60 minutes after mixing.

The concrete was transported within the factory using a wheelbarrow (single wheel vehicle) and placed, and compacted using a vibrator in the normal manner. In order to prevent evaporation of water a curing compound was applied, and the concrete was covered with a vinyl sheet until the following day, and from that following day until an age of 7 days was cured using a wet mat.

b) Properties after hardening

There were concerns over the effect on the finishing operation of the dissipation of water due to construction in the middle of summer and the occurrence of cracking, but no irregularity or plastic cracks were found on the surface.

The test specimens were subjected to standard curing (curing at 20°C in water) or sealed curing on site (sealed and placed outside), then compressive strength tests (JIS A 1108) were carried out. For each method of curing the strength at 28 days was about 35 N/mm^2, which satisfied the nominal strength of 24 (Fig. 3).

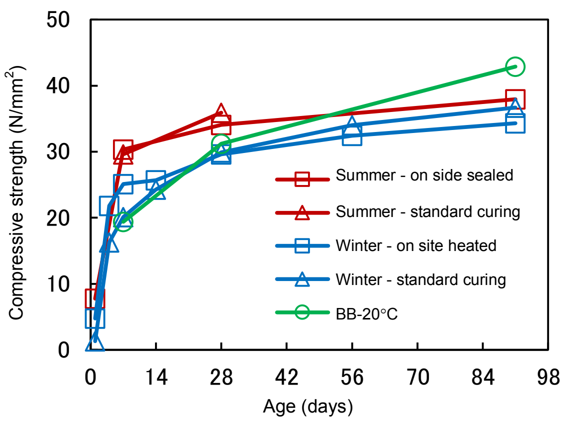


Fig. 3 Strength evolution of environmentally-friendly concrete

At 70 days the degree of rebound was measured using a test hammer and the Torrent air permeability test was carried out. The Torrent test measures the quality of the surface layer from the flow of air when a chamber is placed on the surface and the pressure is reduced[12)]. The degree of rebound of environmentally friendly-concrete with a nominal strength of 24 was 35 to 37, which is not inferior to the 39 obtained for normal concrete with a nominal strength of 30 constructed nearby, and in the Torrent test the result was “Very good: high durability” (Fig. 4). The sanding phenomenon which was a concern was not observed, and the concrete was robust.

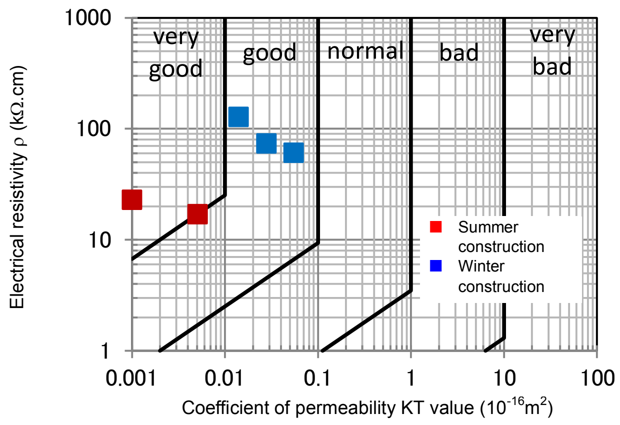


Fig. 4 Evaluation of the quality of the surface layer using a Torrent air permeability test

Photograph 5 Construction using a pump

(2) Examples of construction in winter[5)]

a) Outline of the construction

The concrete was applied to a part of slab on the ground (berm) of thickness about 20 to 40 cm within the research facility. The materials used and their composition were as shown in Table 1 (winter).

Unlike the example described previously, the concrete was produced in a ready mixed concrete factory and after transport in an agitator truck, it was delivered under pressure using a piston type pump for a horizontal distance of 103 m. The slump and the air content after pumping under pressure satisfied the target values of 15±2.5 cm and 6.0± 1.5% respectively. The properties were similar to high fluidity concrete[10)], so it could be delivered under pressure by normal methods.

Compaction and finishing were carried out using a vibrator and a trowel, using the normal procedures. After finishing the concrete was covered with a wet curing mat, a heating sheet (electrically heated), and a fire prevention sheet in that order. The heating sheet and the fire prevention sheet were removed at 7 days, and the wet curing mat was removed at 14 days. The minimum air temperature was less than 0°C, but during the heated curing period the temperature was maintained at a higher than 10°C from the surface into the interior.

b) Properties after hardening

Either the standard curing or curing using a heated sheet for seven days to simulate the construction environment was carried out, and thereafter sealed "heated curing" was carried out outdoors, following which the compressive strength was measured (JIS A 1108). In each case the strength at 28 days was about 30 N/mm^2, which satisfied the nominal strength of 24. The heating was carried out for 7 days, but the strength from 7 days onwards was the same as that for the standard curing (Fig. 3). The degree of rebound was measured at 265 days using a test hammer. The degree of rebound was 34 to 36, which was the same as the example of construction during the summer period, so a structure with the same strength can be obtained by construction in winter. There was a concern that if the air temperature is low the initial strength would be reduced, but as a result of appropriate curing sufficient strength evolution was exhibited.

The surface was smooth without irregularities or waviness. At 265 days the Torrent air permeability test gave a result that was "good" (Fig. 4). In addition, it was confirmed that the surface was sound as appropriate to the strength using a Japan Society of Finishings Technology type testing machine.

It was verified that environmentally-friendly concrete can exhibit good performance without the occurrence of the sanding phenomenon by using appropriate curing, regardless of the period in which the construction is carried out.

4. Conclusion

The development of concrete that does not use Portland cement but uses blast furnace slag as the binder is in progress, in order to reduce to the maximum extent possible CO^2 emissions associated with concrete. It is expected that the CO_2 emissions of concrete can be reduced to about 1/4 of the emissions of normal concrete.

The performance has been evaluated by comparison with BB, which is a designated procurement item in accordance with the Green Procurement Act, and the fundamental characteristics have been summarized (Table 2). Environmentally-friendly concrete has low heat generation properties, and excellent chloride ingress resistance and ASR resistance. In concrete using a large quantity of blast furnace slag, there are concerns regarding the occurrence of the sanding phenomenon, delay in strength evolution, and an increase in autogenous shrinkage and drying shrinkage, but in practice these were not a problem, and for a nominal strength of 24 it was confirmed that the performance was the same as that of BB. On the other hand, carbonation is rapid, and the freeze thaw resistance is difficult, so caution is necessary. Note that in order to resolve these issues, it is suggested that it is effective to reduce the water powder ratio.

This environmentally-friendly concrete has been applied to structures during the summer period and the winter period, which are considered to have a severe construction environment. The member on the ground to which this concrete was applied had a high specific surface area, so dissipation of moisture and heat were significant, and the construction environment was severe as a result of these aspects. For construction during the summer period, there were concerns over an increase in the loss of slump, difficulty with the finishing operation, the occurrence of plastic cracks, etc. Also, there was a concern that the initial strength would be reduced during winter. In addition, it was necessary to check the surface fragility known as the sanding phenomenon. By applying the concrete to actual structures, it was confirmed that these concerns were unfounded, and there were no latent problems.

It has been verified that environmentally-friendly concrete can exhibit the appropriate performance, regardless of the construction environment. With the encouragement of receiving this award, we wish to increase our efforts to maximize its use in order to reduce the environmental load.

Acknowledgments

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