DURABILITY OF NEW ENVIRONMENT-FRIENDLY CONCRETE WITHOUT PORTLAND CEMENT

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Abstract

Processes such as burning fossil fuel and decarbonating limestone used in the manufacture of Portland cement account for 90% of CO2 emissions related to concrete production in Japan. The use of alkali activated slag in concrete has been studied as a way to reduce the proportion of Portland cement and thereby reduce CO2 emissions. Going further, the authors have been investigating an environment-friendly concrete that contains no Portland cement – a kind of slag concrete activated by calcium compounds and consists of ground granulated blast furnace slag, slaked lime, an expansive additive and limestone powder. This is a cast-in-place concrete and it does not require any secondary curing. Production of this environment-friendly concrete cuts CO2 emissions by 80% compared with concrete containing only ordinary Portland cement. In this study, the performance of the environment-friendly concrete is evaluated and compared with concrete containing blast furnace slag cement type-B (BB concrete). Resistance to alkali-silica reaction and chloride penetration is better than that of BB concrete. Resistance to freezing and thawing and carbonation is slightly lower than that of BB concrete. However, these characteristics can be adjusted by altering the water/powder ratio.

1. INTRODUCTION

There is a need to reduce society’s environmental impact. In the construction industry, there is a requirement to reduce CO2 emissions, such as by recycling construction materials and using by-products. The production of Portland cement (PC) accounts for 90% of CO2 emissions related to concrete manufacture, through such processes as burning fossil fuel and decarbonating limestone [1]. Since the energy efficiency of Japanese cement production is the best in the world [2], it is difficult to further reduce CO2 emissions related to the production of PC. However, the use of supplementary cementing materials is an effective way to reduce emissions. Japan’s Ministry of Land, Infrastructure, Transport and Tourism has recommended using ground granulated blast furnace slag (GGBFS) to reduce PC usage.

GGBFS is a by-product of steelmaking. In Japan, only the CO2 emissions related to crushing GGBFS are considered when processing it as a raw material for concrete. As a result, emissions are very low compared with the production of ordinary Portland cement (OPC). Consequently, replacing OPC with a large proportion of GGBFS can lead to a reduction in CO2 emissions by the construction industry.

In Japan, blast furnace slag cement Type-B (BB concrete) is specified in JIS R 5211. It consists of 30-60 mass% GGBFS and 40-70 mass% OPC. BB concrete is widely used instead
resistance to chloride penetration of BB concrete is better than that of OPCC. BB concrete results in about 50% lower CO₂ emissions compared with OPCC.

There is an expectation that CO₂ emissions can be cut further by developing concretes containing more GGBFS. In the 1990s, concretes containing many supplementary cementing materials were researched with the aim of reducing thermal stress. For example, low-heat concrete containing only 20-30% OPC came into practical use [3]. Slag gypsum cement composite containing 80-85% GGBFS, 12-18% desulfo gypsum, and 2-3% OPC has also been reported [4]. However, these concretes containing a high proportion of GGBFS often suffer surface deterioration and exhibit bad resistance to freezing and thawing [5]. Concretes with no PC have also been reported. For example, geopolymer compounds (which are a kind of inorganic binder) can be hardened without PC [6][7], although most existing geopolymer compounds require secondary curing such as with steam.

Recently, we have been researching a slag concrete activated calcium compounds without any PC [8][9]. It consists of GGBFS, slaked lime, an expansive additive and limestone powder. The GGBFS is chemically activated by reaction with the calcium compounds supplied as slaked lime and the expansive additive. The expansive additive forms calcium hydroxide and ettringite. This not only reduces shrinkage but also acts as a activator.

This environment-friendly concrete can be cast in place and reaches a nominal compressive strength of 24 N/mm² without secondary curing. As noted above, concrete containing a lot of GGBFS typically risks surface deterioration, but this concrete does not suffer surface deterioration. It also has drying shrinkage the same as that of BB concrete. Production of this environment-friendly concrete cuts CO₂ emissions by 50% compared with BB concrete.

The widespread adoption of this environment-friendly concrete in place of BB concrete will require a full evaluation of its performance. Basic quality requirements, such as manufacturability, workability and durability, are specified in the Standard Specification for Concrete Structures, which is the basic standard for practical applications in Japan [10]. This study was performed to evaluate various properties of the new PC-free concrete in accordance with this specification. It is first confirmed that the new concrete can be produced in a normal ready-mixed concrete plant. Then its resistance to alkali-silica reaction, chloride penetration, carbonation and freezing and thawing are evaluated and compared with the properties of BB concrete.

2. TEST METHOD

2.1 Preparation of materials

Table 1 shows the materials used in this study. All materials conformed to the Japan Industrial Standards (JIS). Table 2 shows the mix proportions of the environment-friendly concrete and BB concrete. Different aggregates were used in the test for alkali-silica reactivity. Test pieces of both concretes were produced in a ready-mixed concrete plant as well as in the laboratory. In this study, both cylindrical (φ10 x 20 cm) and cuboid (10 x 10 x 40 cm) specimens were used depending on the test, as described hereinafter.

2.2 Test procedure

First, the slump and air content of fresh concrete were tested 0, 30, 60 and 90 minutes after mixing in accordance with JIS A 1101 and JIS A 1128. It should be noted that the initial 30
minutes after mixing corresponds to transportation time. The target values of slump and air content between 30 and 90 minutes after mixing were 15±2.5 cm and 6±1.5%, respectively. For the BB concrete, target slump was 15±2.5 cm and target air content was 4.5±1.5%. In order to increase resistance to freezing and thawing, the environment-friendly concrete contained more entrained air than the BB concrete.

Second, compressive strength was measured. Cylindrical specimens cured in water for 1, 4, 7, 14, 28, 56, 91 and 182 days were used for these tests. Test procedures were in accordance with JIS A 1108.

Third, the durability of the environment-friendly concrete was compared with that of BB concrete. Resistance to alkali-silica reaction was evaluated by reference to ASTM C 1260. Essentially, this test method is specified for evaluating the potential reactivity of aggregates. In this study, the test was performed to estimate the difference in resistance to alkali-silica reaction between the two mixtures. Aggregate with a potential reactivity at ASTM C 1260 was used in order to cause sufficient expansion for the experiment. Concrete was screened to produce mortar in the laboratory. Three test pieces (2.5 x 2.5 x 28.5 cm) were cured in water for 7 days at 20°C. Test pieces were attached the two metal gauge studs and stored in 1 mol/l NaOH solution for 56 days at 80°C and the expansion ratio of the concrete was measured at 1, 4, 7, 14, 28 and 56 days. If the expansion ratio of the mortar is less than 0.1% at 14 days, it is considered that the aggregate was non-reactive.

Rapid chloride penetration tests were conducted by reference to JSCE G 572. Test pieces (10 x 10 x 40 cm) were cured in water for 28 days. Each test piece was cut in half (10 x 10 x 20 cm) and after drying was coated with epoxide resin except on the cut surface. Once the resin hardened, the specimen was immersed in water again for a day, and then immersed in 3 mass% NaCl solution for 182 days. It was cut into five pieces 5 mm in thickness from the exposed surface. The chloride ion concentration of each piece was evaluated by potentiometric titration and the chloride penetration of the environment-friendly concrete and BB concrete was estimated.

Accelerated carbonation was measured in accordance with JIS A 1153. Three test pieces (10 x 10 x 40 cm) were cured in water for 28 days. Test pieces were coated with epoxide resin except on two opposite long sides and accelerated carbonation took place at 20°C, 60% relative humidity and 5% CO₂ gas concentration. Carbonation depth was measured at 7, 28, 56 and 91 days of accelerated carbonation.

Resistance to freezing and thawing was measured in accordance with JIS A1148. Three test pieces (10 x 10 x 40 cm) were cured in water for 28 days. Freezing and thawing cycle consisted of alternately lowering the temperature from 5°C to -18°C and raising it from -18°C to 5 °C. Freezing and thawing cycle was repeated six times a day for a total of 300 cycles. Resistance to freezing and thawing was evaluated by measuring the change in relative dynamic modulus of elasticity during the test period.
3. PERFORMANCE OF ENVIRONMENT-FRIENDLY CONCRETE

3.1. CO₂ emissions
Table 3 shows the CO₂ emissions generated in the process of manufacturing the concrete materials. Figure 1 shows the CO₂ emissions of OPCC, BB and environment-friendly concrete as calculated by multiplying the unit emissions of the raw materials (Table 3) by their usage per unit volume of concrete. The production of environment-friendly concrete results in roughly 80% lower emissions compared with that of OPCC. Emissions are also 50% lower than those of BB concrete. Moreover, the environment-friendly concrete uses over 300 kg of GGBFS per 1 m³ concrete, which will accelerate the recycling of by-products.

3.2. Properties of fresh and hardened concrete
Figures 2 and 3 show the properties of fresh environment-friendly concrete when mixed in a normal ready-mixed concrete plant. Slump loss was low during the 90 minutes after mixing
because of the retarding agent. Target slump (15±2.5cm) and target air content (6±1.5%) were satisfied.

Figure 4 shows the compressive strength of the environment-friendly concrete. The compressive strength at 1 day was 1.3 N/mm² under the influence of the retarding agent. Then at 28 and 91 days it was 29.9 and 40.7 N/mm², respectively. This confirms that the long-term compressive strength of the environment-friendly concrete is sufficiently greater than the target nominal strength of 24 N/mm² at 28 days.

Concretes containing a high proportion of GGBFS often suffer surface deterioration. Photograph 1 compares the surface appearance of (a) a concrete suffering surface deterioration and (b) environment-friendly concrete. The sound original surface remains intact in the case of environment-friendly concrete. This result demonstrates the superior effect of the calcium activator.

Table 3: CO₂ emissions of concrete materials

<table>
<thead>
<tr>
<th>Material</th>
<th>CO₂ emissions (g/kg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>764.3</td>
<td>11</td>
</tr>
<tr>
<td>BB</td>
<td>444.1</td>
<td>11</td>
</tr>
<tr>
<td>GGBFS</td>
<td>26.5</td>
<td>12</td>
</tr>
<tr>
<td>Expansive additive</td>
<td>764.3</td>
<td>*</td>
</tr>
<tr>
<td>Slaked lime</td>
<td>229</td>
<td>13</td>
</tr>
<tr>
<td>Lime stone powder</td>
<td>16.1</td>
<td>12</td>
</tr>
<tr>
<td>Sand</td>
<td>3.7</td>
<td>12</td>
</tr>
<tr>
<td>Gravel</td>
<td>2.9</td>
<td>12</td>
</tr>
<tr>
<td>Water</td>
<td>0.2</td>
<td>14</td>
</tr>
</tbody>
</table>

*: Expansive additive is assumed to have the same CO₂ emissions as OPC

![Figure 1: CO₂ emissions of various concretes](image1)

![Figure 2: Slump of fresh concrete](image2)

![Figure 3: Air content of fresh concrete](image3)
3.4. Durability

Figure 5 shows the expansion ratios of the environment-friendly concrete and BB concrete as determined in the alkali-silica reactivity test. According to ASTM C 1260, if the expansion ratio of the mortar is less than 0.1% at 14 days, it is considered that it was non-reactive. The expansion ratio of BB concrete was found to be over 0.1% after 14 days of accelerated testing and the eventual expansion ratio was more than 0.3%. Meanwhile, the expansion ratio of the environment-friendly concrete was close to 0% until 14 days and the eventual expansion ratio was less than 0.1%.

BB concrete is generally more resistant to the alkali-silica reaction than OPCC, and the environment-friendly concrete exhibited an even lower expansion ratio than BB concrete. The risk of the alkali-silica reaction occurring is considerably lower with the environment-friendly concrete.

Figure 6 shows the total content of chloride ions in environment-friendly concrete and BB concrete after 182 days of immersion. The penetration of chloride ions into the environment-friendly concrete is lower than that into the BB concrete. The apparent chloride diffusion coefficient calculated using Fick’s second law of diffusion is estimated to be 1.13 x 10^{-10} m^2/s in environment-friendly concrete and 2.05 x 10^{-10} m^2/s in BB concrete. In general, BB concrete has a high resistance to chloride penetration, and using environment-friendly concrete can reduce chloride migration further.

Figure 7 shows carbonation depth, as measured in the accelerated test, of environment-friendly concrete and BB concrete. After 26 weeks of accelerated testing, the carbonation depth of the environment-friendly concrete was about 10 mm more than that of BB concrete. The carbonation rate of environment-friendly concrete is roughly 1.5 times faster. However, when the water-powder ratio was reduced from 0.36 to 0.31, the carbonation rate of the environment-friendly concrete was equivalent to that of BB concrete.

Figure 8 shows the change in dynamic modulus of elasticity during the freezing and thawing test for environment-friendly concrete and BB concrete. The relative dynamic modulus of elasticity of the environment-friendly concrete after 300 cycles was less than 60%, which means that the concrete does not have good resistance to freezing and thawing.
On the other hand, the weight loss ratio was 1.0%, while that of BB concrete was 4.4%. It seems that the environment-friendly concrete is less resistant to freezing and thawing than BB concrete. However, resistance to freezing and thawing improved when the water-powder ratio was reduced to 0.31. Thus the mix proportion can be adjusted for cold climate.
4. CONCLUSION

We have developed an environment-friendly concrete that uses no Portland cement. The fresh and aged properties of the environment-friendly concrete were evaluated. The durability of the environment-friendly concrete was also evaluated and compared with that of BB concrete. The main conclusions of this work can be summarized as follows.

1) A normal ready-mixed concrete plant was able to produce environment-friendly concrete with satisfactory slump and air content. Compressive strength was approximately 30 N/mm² after the first 28 days.

2) The environment-friendly concrete was more resistant to the alkali-silica reaction than BB concrete and chloride penetration was lower than that in BB concrete. Resistance to carbonation and freezing and thawing of the environment-friendly concrete were slightly lower than for BB concrete. However, both properties could be improved adequately by reducing the water-powder ratio.

This work shows that the durability of environment-friendly concrete is almost the same as that of BB concrete and that it can be adjusted to suit ambient conditions. Regarding environmental impact, CO₂ emissions in the production of the environment-friendly concrete are reduced by 50% compared with BB concrete and by 80% compared with OPC.

REFERENCES

[1] Japan Concrete Institute, Report of committee on minimizing global warming substance and waste in the concrete sector, Japan Concrete Institute (2010).