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Basic Properties and Utilization of Steam-Cured Concrete Using Ground Granulated Blast-Furnace Slag

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Abstract

At the precast concrete factories, the ground granulated blast-furnace slag has been used concrete products for the purpose of the durability improvement on the resistance of the suppression of alkali silica reaction. The other purposes are the application to the high fluidity concrete and reduction of CO_2 emission, etc. This paper shows the effect of steam curing and the properties of the strength, the water tightness, the salt diffusivity and the examples of the utilization.

1. Introduction

Ground granulated blast furnace slag is an admixture that improves the durability and watertightness of concrete by increasing resistance to salt damage, restraining the alkali–silica reaction, and so on. Recently, attention is being paid to the fact that it also helps reduce CO_2 emission.[1)] On the other hand, when concrete is added to ground granulated blast furnace slag, it has a small initial strength and is susceptible environmental conditions; hence, it declines in strength development and durability when it is removed from the form early or cured insufficiently.[2)]

In the case of steam-cured concrete, the heated concrete is removed from the form early. Therefore, ground granulated blast furnace slag cannot be applied to steam-cured concrete. However, as higher durability has come to be expected of precast concrete products—mainly reinforced concrete segments and prestressed concrete products—the use of ground granulated blast furnace slag for steam-cured concrete is ernestly considered.

In this study, the author discusses the strength, watertightness, and salt resistance of steam-cured concrete added to ground granulated blast furnace slag, and the representative examples of application of steam-cured concrete.

2. Outline of Steam Curing

Steam curing is a method for accelerated curing whereby concrete is cured in hot steam to obtain the required strength early. Concrete that has been subjected to steam curing is called steam-cured concrete.

Figure 1 shows an example of temperature hysteresis of steam curing. The initial strength of concrete is significantly influenced by the maximum steam temperature and the temperature duration. The higher the maximum steam temperature, the earlier the concrete can be removed from the form and the larger the number of concrete production cycles (repetitions of forming and de-forming) per day. Generally, concrete plants produce ordinary-sized concrete products in 1.5 to 2 cycles/day and large-sized products in 1 cycle/day. The minimum strength required of concrete at the time of de-forming is 10–12 N/mm^2 and 15 N/mm^2 for ordinary- and large-sized products, respectively. In the case of a prestressed concrete product, the required strength is 35 N/mm^2 or more because a prestress is intro-

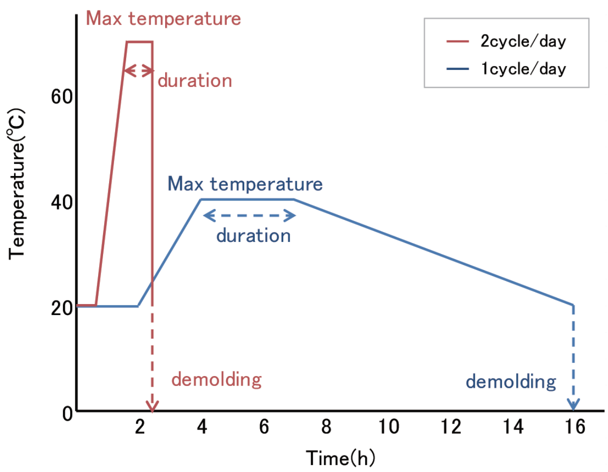

Fig. 1 Temperature history of steam curing

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duced to it during de-forming. Therefore, many prestressed concrete products are made in 1 cycle/day. There are cases in which concrete products are shipped early when the required strength is obtained. Usually, however, concrete products are not shipped till they reach the age of 14 days (28 days for certain types of concrete products).

3. Strength Characteristics

3.1 Effect of slag ratio

Figures 2 and **3** show the results of compressive strength tests of concretes added to ground granulated blast furnace slag 4000 and subjected to steam curing followed by air curing. Figure 2 shows the results obtained with concrete products produced in 1.5 to 2 cycles/day, and Fig. 3 with concrete products produced in 1 cycle/day. The compressive strength of concrete tends to decline with increase in the slag ratio. However, unlike the case of standard cured concrete, the steady increase in strength with the lapse of time cannot be expected. In particular, it should be noted that when ground granulated blast furnace slag is used under the maximum curing temperature of 70°C and de-forming for 2.5 h, the development of compressive strength of 14-day and 28-day concretes becomes less visible.

Regardless of the slag ratio, when the maximum curing temperature is raised to allow early de-forming, 14-day and 28-day concretes show a tendency to decrease in compressive strength. The difference in compressive strength in concretes constructed under steam curing conditions is about 10 N/mm^2 for each of the 14-day and 28-day concretes. Thus, to obtain the required strength, it is desirable to reduce the maximum steam curing temperature as far as possible.

When ground granulated blast furnace slag is used to improve the concrete durability, the slag ratio is generally set at 50%. With ground granulated blast furnace slag 4000, however, the compressive strength of the 14- or 28-day old concrete being de-formed hardly reaches that of normal Portland cement. Therefore, when using ground granulated blast furnace slag, it is necessary to take suitable measures such as setting the optimum slag ratio and decreasing the water–binder ratio. When the water–binder ratio is decreased (the proportion of binder is increased) to obtain the required compressive strength, the mix proportion nearly becomes that of Self-compacting High-performance Concrete because the ground granulated blast furnace slag has segregation resistance. When ground granulated blast furnace slag is used for steam-cured concrete, it is often intended to obtain a high-fluidity concrete to save labor in placement work and improve working environments as well as improve the concrete durability.

3.2 Effect of slag fineness

Figures 4 and **5** show the relationships between fineness of ground granulated blast furnace slag and compressive strength of concrete with a slag ratio of 50%. Figure 4 shows the results obtained when ordinary Portland cement was used as the base cement, and Fig. 5 shows the results obtained when high-early-strength Portland cement for prestressed concrete products was used. Regardless of the cement-type used, when the fineness of ground granulated blast furnace slag is high, the compressive strength of concrete of

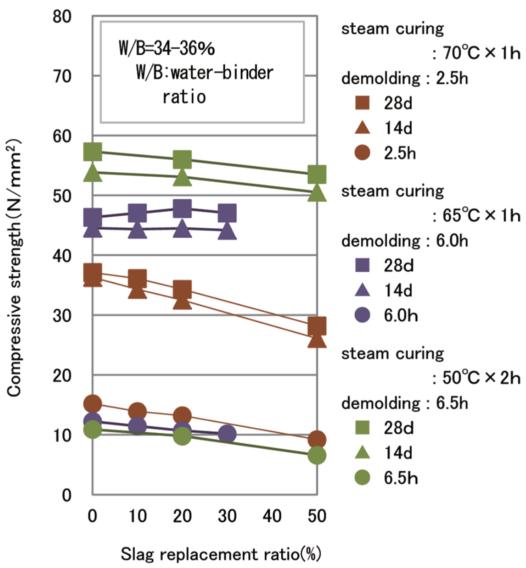

Fig. 2 Results of compressive strength test (1.5-2 cycle/day)

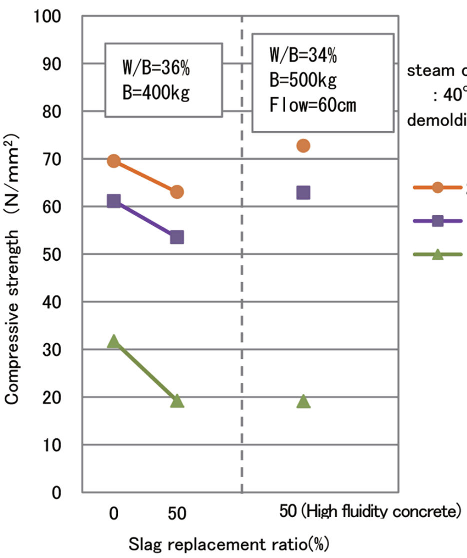

Fig. 3 Results of compressive strength test (1 cycle/day)

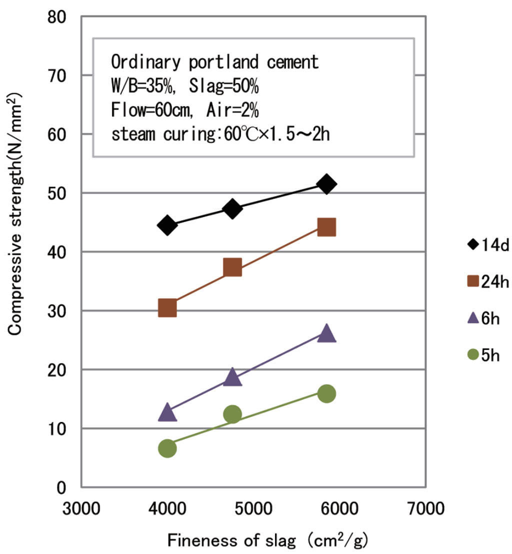

Fig. 4 Relationship between fineness of slag and compressive strength

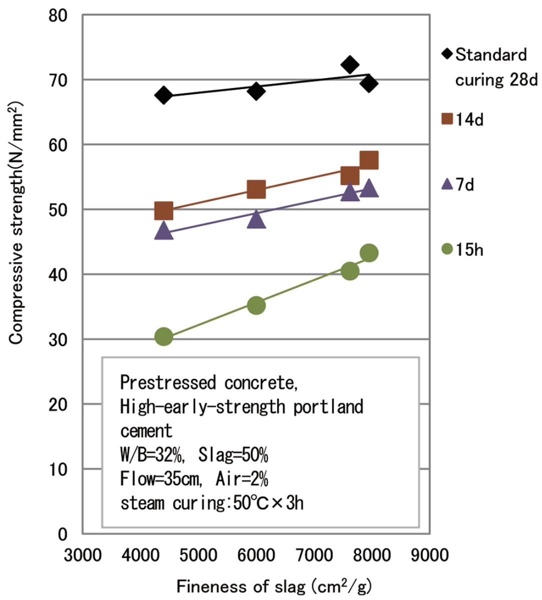

Fig. 5 Relationship between fineness of slag and compressive strength

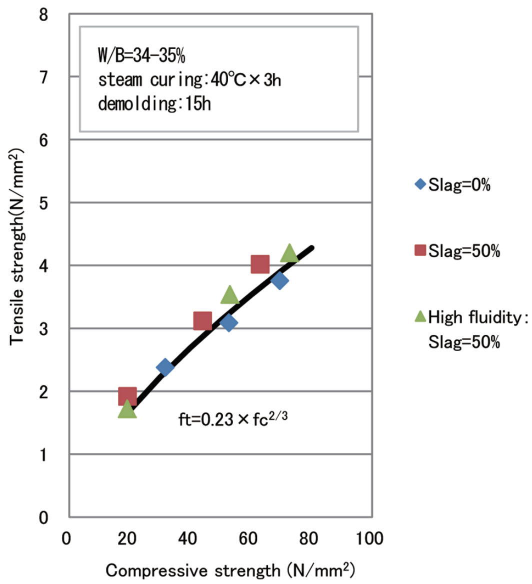

Fig. 6 Relationship between compressive strength and tensile strength

any age tends to increase linearly. This effect of slag fineness is more evident with concrete of a younger age. Thus, using ground granulated blast furnace slag with a high degree of fineness facilitates in obtaining the required strength of concrete at the time of deforming.

JIS A 6206 "Ground Granulated Blast Furnace Slags for Concrete" specifies four types of ground granulated blast furnace slag in terms of fineness: 3000, 4000, 6000, and 8000. From the standpoint of strength development, it is common practice to use ground granulated blast furnace slag 4000 for concrete products produced in 1 cycle/day and ground granulated blast furnace slag 6000 for prestressed concrete and other concrete products produced in 1.5 or more cycles per day.

3.3 Tensile strength and flexural strength

Figure 6 shows the relationships between compressive and tensile strength obtained with steam-cured concretes using ground granulated blast furnace slag, and **Fig. 7** shows the relationships between compressive and flexural strength obtained with similar steam-cured concretes.

In the case of steam-cured concretes using ground granulated blast furnace slag, the relationship between compressive and tensile strength is linear regardless of the slag ratio. It is expressed by the relationship given in the Concrete Standard Specification: Design of Japan Society of Civil Engineers. The relationship between compressive and flexural strength also agrees well with the relationship[3)] given in the former Concrete Standard Specification. On the contrast, in the case of standard-cured concretes, especially the concrete with a slag ratio of 40%, the flexural strength for the same compressive strength was more or less higher than that of steam-cured concretes.

4. Watertightness

Figures 8 and **9** show the results of a permeability test (input method: water pressure 10 kgf/cm² for 72 h) of 28-days-old concretes subjected to steam curing followed by air curing.

As previously reported,[4)] the higher the slag ratio, the smaller the water diffusion coefficient and the higher the watertightness of steam-cured concrete. With a maximum temperature of 50°C × 2 h and de-forming time of 6.5 h, the water diffusion coefficient of concrete with 20% slag was about one-tenth that of ordinary Portland cement with the same water–binder ratio. The diffusion coefficient tended to decrease with decreasing water–binder ratio. Regardless of the slag ratio, the diffusion coefficient decreased to about one-half each time the water–binder ratio was deceased by 5%. Thus, the watertightness of concrete can be improved by decreasing the water–binder ratio. However, even with ordinary Portland cement of a water–binder ratio of 30%, the diffusion coefficient is larger than that of concrete with a water–binder ratio of 40% and slag ratio of 20%. The implication is that ground granulated blast furnace slag is very effective for improving the watertightness of concrete.

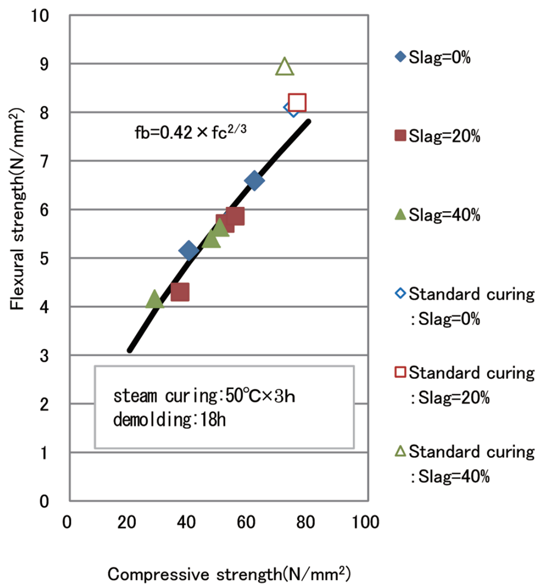

Fig. 7 Relationship between compressive strength and flexural strength

The diffusion coefficient reduces by about one-ninth for ordinary

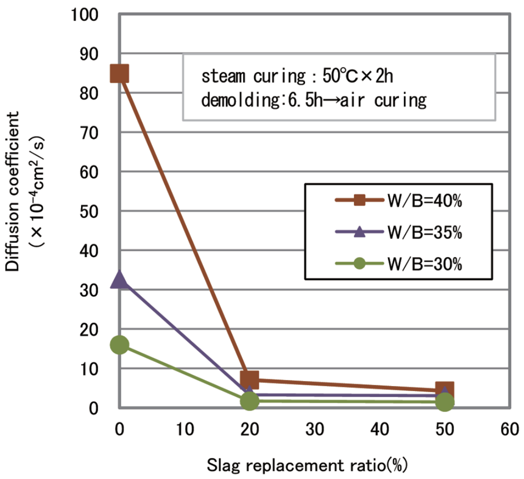

Fig. 8 Relationship between slag replacement and diffusion coefficient

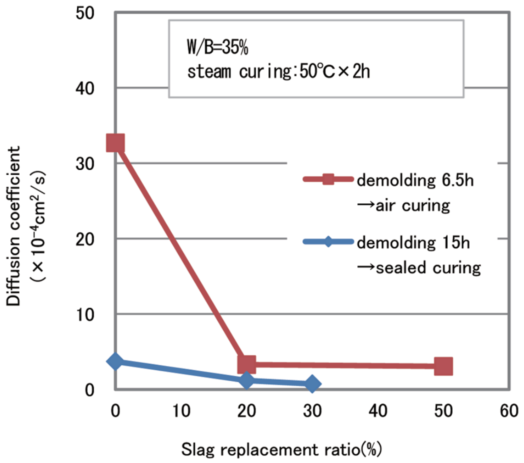

Fig. 9 Effect of curing condition on diffusion coefficient

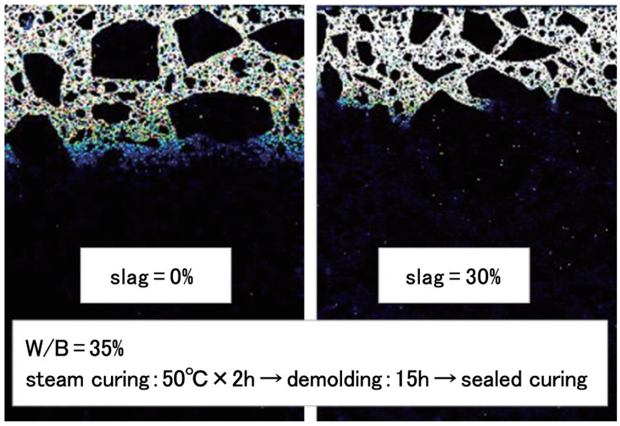

Fig. 10 Test results of salt penetration depths by EPMA (Cl)

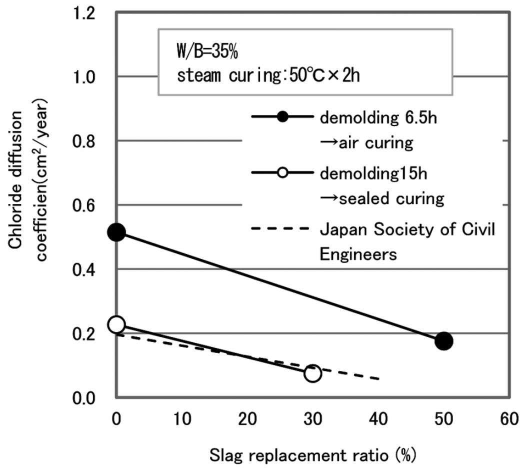

Fig. 11 Relationship between slag replacement and chloride diffusion coefficient

Portland cement and about one-third for concrete with a 20% slag ratio when the de-forming time is extended from 6.5 h to 15 h. Thus, also from the viewpoint of watertightness, it is desirable to extend the de-forming time.

5. Salt Resistance

Figure 10 shows the results of the electron microprobe analysis of the depths of salt invasion into concretes, and **Fig. 11** shows the relationships between slag ratio and chloride ion diffusion coefficient. The specimens were subjected to steam curing followed by air curing. They were immersed in artificial seawater at the age of 28 days and tested 33 months later.

It can be seen that with steam-cured concrete, the use of ground granulated blast furnace slag restrains the diffusion of chloride ions inside the concrete. The chloride ion diffusion coefficient of concretes subjected to sealed curing after 15 h of de-forming was nearly the same as that obtained by the estimation formula given in the Concrete Standard Specification: Design (0.196 cm^2/year for ordinary Portland cement, 0.058 cm^2/year for equivalent of blast furnace slag cement B), with both concrete slag ratios of 0% and 50%. Conversely, the chloride ion diffusion coefficient of a concrete subjected to air curing after 6.5 h of de-forming was larger than the above value, indicating that the de-forming time and air curing after steam curing influence the diffusion of chloride ions in the concrete. For reinforced concrete segments, there are cases in which the prescribed durability is obtained by implementing steam curing followed by underwater curing or sealed curing.

6. Application to Concrete Products

Many types of concrete products are subjected to steam curing. They cannot be properly classified because they differ in manufacturing conditions, performance requirements, dimensions, and so on. However, in terms of slag ratio, they can roughly be classified, as shown in **Table 1**. Ground granulated blast furnace slag is used in many different concrete products, mainly to improve the salt resistance and watertightness of concrete, restrain the alkali–silica reaction, and increase the fluidity of concrete. It is also used, though less frequently, to reduce the efflorescence, adjust the color tone, improve the fire resistance, and so on, of concrete products.[5)]

For various concrete products, using a suitable type of ground granulated blast furnace slag and a suitable slag ratio, as shown in Table 1, it is possible to improve the properties such as watertightness, and salt resistance of concrete without varying the concrete mix proportion widely (e.g., water–binder ratio).

Table 1 Examples showing the use of slag to concrete products

<table>
<tr><th>Product classification</th><th>Cement type</th><th>Manufacture cycle (cycle/day)</th><th>Slag classification</th><th>Slag replacement (%)</th><th>Main purpose</th><th>Concrete products</th></tr>
<tr><td rowspan="4">Precast concrete</td><td rowspan="4">Ordinary Portland cement</td><td>1</td><td rowspan="3">Grade 4000</td><td>20 - 50</td><td rowspan="4">• Improve fluidity
• Salt damage countermeasure
• Water-tightness
(restraint of alkali silica reaction)</td><td rowspan="4">Concrete block
Precast side ditch
Box calvert</td></tr>
<tr><td rowspan="3">1.5 - 2</td><td>- 20</td></tr>
<tr><td rowspan="2">20 - 50</td></tr>
<tr><td>Grade 6000</td></tr>
<tr><td>Precast concrete (large size)</td><td>Ordinary Portland cement</td><td>1</td><td>Grade 3000
Grade 4000</td><td>20 - 50</td><td>• Salt damage countermeasure
• Water-tightness
(restraint of alkali silica reaction)
(restraint of temperature rise)</td><td>Concrete segment
Box calvert</td></tr>
<tr><td>Prestressed concrete</td><td>High-early strength Portland cement</td><td>1</td><td>Grade 6000</td><td>20 - 50</td><td>• Salt damage countermeasure
• Water-tightness
(restraint of alkali silica reaction)</td><td>Prestressed concrete girder
Prestressed concrete slab</td></tr>
</table>

Attention) Restraint of alkali sillica reaction : Slag replacement ratio ≧ 50%
Restraint of temperature rise : Slag replacement ratio ≧ 50%

7. Conclusion

The strength characteristic, watertightness, and salt resistance of steam-cured concrete using ground granulated blast furnace slag are summarized below.

(1) Assuming slag ratio as 50%, the required strength of concrete can be obtained without widely varying the water–binder ratio using ground granulated blast furnace slag 4000 for any concrete product produced in 1 cycle/day and ground granulated blast furnace slag 6000 for prestressed concrete or any other concrete product produced in 1.5 cycles or more per day.

(2) The relationship between compressive and tensile strength or compressive and flexural strength of steam-cured concrete using ground granulated blast furnace slag can be evaluated by the formula given in the Concrete Standard Specification: Design as in the case of ordinary concrete.

(3) Compared with the improvement in concrete watertightness by the decrease of the water–binder ratio, the improvement in water diffusion coefficient by the addition of ground granulated blast furnace slag is very clear. Under a maximum temperature of 50°C × 2 h and de-forming time of 6.5 h, the water diffusion coefficient of concrete decreased to about one-tenth when the slag ratio was 20%.

(4) Regardless of the steam curing conditions and de-forming time, the chloride ion diffusion coefficient decreases when ground granulated blast furnace slag is used. Under a maximum temperature of 50°C × 2 h and de-forming time of 15 h, the chloride ion diffusion coefficient after steam curing followed by sealed curing became nearly the same as that obtained by the formula given in the Concrete Standard Specification: Design.

(5) Regardless of the slag ratio, as the maximum temperature of steam curing is reduced and the de-forming time is extended, 14-day and 28-day concretes increase in compressive strength and improve in watertightness and salt resistance.

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