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A Study of DEF Expansion Suppression Mechanism by Ground Granulated Blast Furnace Slag

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ABSTRACT

DEF (Delated Ettringite Formation) is a major problem in concrete deterioration, and the conditions under which DEF occurs have been sorted out in previous studies. However, there are cases in which DEF does not lead to expansion. In particular, it has been reported that the expansion is suppressed when ground granulated blast furnace slag (GGBS) is added to the mixture, however the mechanism of this suppression remains unclear. In this study, it was produced using mortars with GGBS replacement rates varying from 0-70%. Measurements of the amount of expansion of DEF showed that the expansion was suppressed as the replacement ratio increased. Here, a replacement ratio of 25% could suppress the expansion after 150 days. On the other hand, the XRD results showed that DEF was generated in all samples, and we speculated that the suppression mechanism might be the formation of pore structure and C(A)SH.

Keywords

DEF, DEF expansion ratio, Ground granulated Blast-furnace slag, C(A)SH

INTRODUCTION

There are many causes of the concrete deterioration, and it is becoming increasingly difficult to retain concrete for long periods. Deterioration of concrete often occurs along with corrosion of steel bar due to penetration of external causes of carbon dioxide, chloride ion and so on. The other deterioration causes are Freeze-thaw and ASR and so on, where the concrete expands from the inside. In recent years, delayed ettringite formation (DEF), in which internal expansion is a deteriorating phenomenon of concrete as well as these, has also attracted worldwide attention. It has been pointed out that the amount of expansion due to DEF, a phenomenon in which the stiffness of concrete is reduced by cracking due to the expansion of the hardened concrete caused by the internal formation of expansive ettringite over a long period, is greater than that of ASR. The phenomenon was caused by an initial high temperature history such as steam curing. It is also said to have a greater effect due to cracking of the concrete. To begin with, DEF can occur when three conditions are met: sufficient sulphate content, temperature history in the early age and adequate moisture supply. However, the relationship between the occurrence of DEF and expansion due to DEF is not clear. Such expansion due to DEF has been reported to be inhibited by the use of ground granulated blast furnace slag (GGBS). However, this mechanism is not clear. In this study, it was carried out to elucidate the DEF expansion mechanism from the relationship between the amount of Ettringite production and expansion rate using specimens with GGBS additive. Therefore, mortars with five different slag replacement rates were prepared and subjected to DEF expansion tests. Samples taken from these specimens were used to quantify the amount of delayed ettringite formation by XRD testing. In addition, the mechanism of this phenomenon was discussed.

EXPRIMENTAL DESIGN

Materials and Mix Proportions

Ordinary Portland Cement (OPC): N (density 3.15 g/cm^3, specific surface area 3530 cm^2/g, SO_3 content 2.1%) and GGBS: B (density 2.91 g/cm^3, specific surface area 4060 cm^2/g, SO_3 content 2.1%) were used in this study, with the chemical composition shown in Table1. The mix proportion of mortar is shown in Table2, with GGBS replacement rates of 5 (B5), 15 (B15), 25 (B25) and 70 (B70) wt% to confirm the effect of DEF expansion control in the added amounts and to compare pore structure changes. The mortar was kept constant at W/B=0.55 and s/c=3. In order to promote DEF, K_2SO_4 was added to adjust the SO_3 content to a total of 4.0 wt% and the specimens were prepared.

Table1. Chemical components of using materials

	SiO_2	Al_2O_3	Fe_2O_4	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3
OPC	20.19	5.18	-	65.01	1.18	0.31	0.36	0.25	0.16	2.1
GGBS	34.66	13.71	0.26	43.83	5.67	0.25	0.26	0.56	0.02	2.1

Table2. The mix proportions and amount of Al_2O_3

Mix proportions	GGBS	SO_3 in GGBS	SO_3 /Total	Total $CaSO_4$	Al_2O_3 /OPC	Al_2O_3 /GGBS	Al_2O_3 /Total
N	0%	-		-	5.18%	-	5.18%
B5	5%	2.1%		0.18%	4.92%	0.66%	5.58%
B15	15%	2.1%	2.10%	0.54%	4.40%	1.98%	6.39%
B25	25%	2.1%		0.89%	3.72%	3.72%	7.19%
B70	70%	2.1%		2.50%	1.55%	9.25%	10.81%

Specimen Preparation and Expansion Rate Test

The specimens were made of 40×40×160 mm mortar in accordance with JIS R 5201. Considering the conditions for DEF generation, the temperature history during steam curing was given as shown in Fig.1. Four hours after casting, a high temperature curing at a maximum temperature of 90°C was maintained for 12 hours at a temperature increase rate of 20°C/hr and cooled to 20°C at a temperature decrease rate of 10°C/hr. The mould was then demoulded at 26.5 h after casting and left to rest in water at 20°C. The expansion coefficient was measured by the contact gauge method, using the length at demoulding as the base length and measuring the length change.

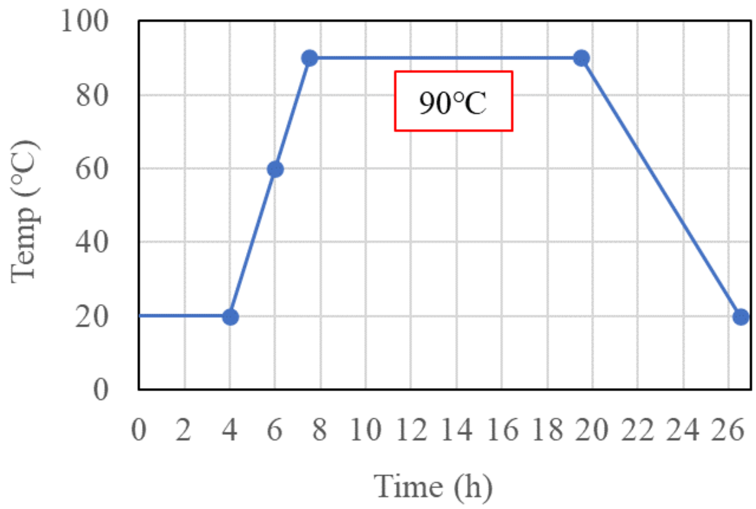

Fig.1 Thermal history of DEF samples

Quantitative Evaluation of AFT

For the determination of ettringite (AFt) formation, samples were ground and the fine aggregate was removed with a 150 µm sieve. The samples were treated with acetone to stop hydration and XRD was carried out; α-Al_2O_3 was used as a reference material and the amount of AFt produced during the temperature history increase was quantified over time using the internal standard method, and the amount of AFt most produced (I_{Ett}) before AFt decomposition started was calculated. In addition, the secondary amount of AFt produced (D_{Ett}) at 133 days of timber age was quantified.

Next, for the determination of ettringite, the purely synthesized ettringite was measured by the XRD internal standard method. Based on the results, an attempt was made to quantify the initial AFt and the secondary formation AFt.

RESULTS OF THE RELATIONSHIP BETWEEN AFt PRODUCTION AND EXPANSION RATE

The results of the length variation test are shown in Fig. 2, where N showed the greatest expansion and the addition of GGBS suppressed the DEF expansion with the rate of replacement. Furthermore, the expansion rate of B70 remained around 0.04% even at 160 days of age. In addition, DEF expansion developed gradually with long-term soaking, but the high replacement ratio resulted in almost no expansion; high GGBS replacement suppressed expansion in spite of the high Al content.

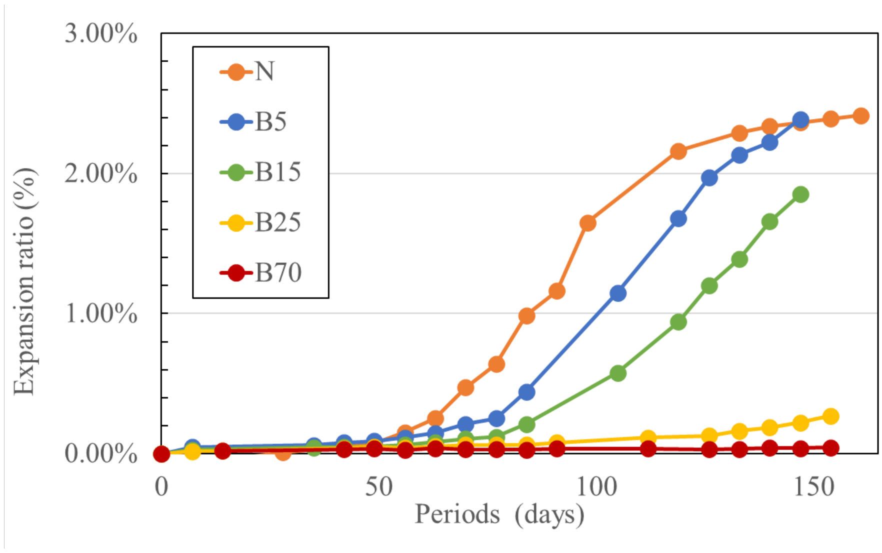

Fig.2 Expansion ratio on DEF

Fig. 3 shows the results of quantifying the amount of AFt produced (I_{Ett}) over time as the temperature history increased: with the addition of GGBS, the amount of AFt produced showed an increasing trend with the substitution rate; AFt production was greatest in all mix proportions at the curing temperature of 60°C (6h), when AFt degradation is expected to start, with B70 having the highest. This means that the initial amount of ettringite formation is higher the higher the Al content. Furthermore, AFt decreased by decomposition as the temperature increased, and AFt was found to be completely decomposed in all samples at 10 hours of age after 2 hours of curing at 90 °C. The addition of GGBS is considered to have activated the reaction of GGBS by the temperature history, leaching Al^{3+} in the chain structure and promoting AFt formation was promoted.

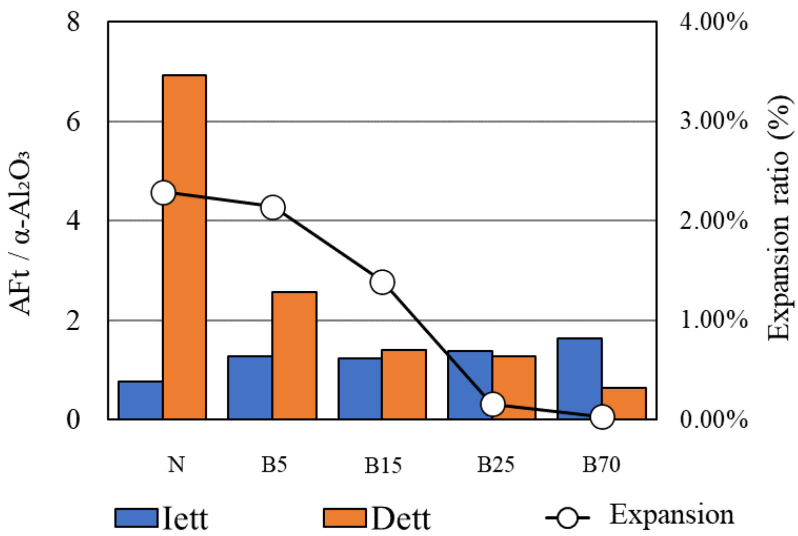

Fig.3 Relationship between Aft and Expansion ratio

Fig. 4 shows the amount of secondary ettringite formation (D_{Ett}) for each of the samples at 133 days of age. It was observed that D_{Ett} was produced in both mix proportions and DEF was generated. However, the amount was suppressed by the addition of GGBS. Therefore, XRD was carried out using the trial genuine ettringite and the test results of the quantification of each ettringite from the quantification ratio are shown in Figure 5. It is clear from this that the amount of lagging ettringite is higher at lower slag substitution rates and more suppressed at higher GGBS substitution rates. The relationship between the amount of AFt and the rate of expansion of I_{Ett} and D_{Ett} at 133 days of age is therefore shown in the figure. A relationship was found between the rate of expansion and the amount of DEF produced, but no relationship was found between the initial amount of ettringite produced and DEF.

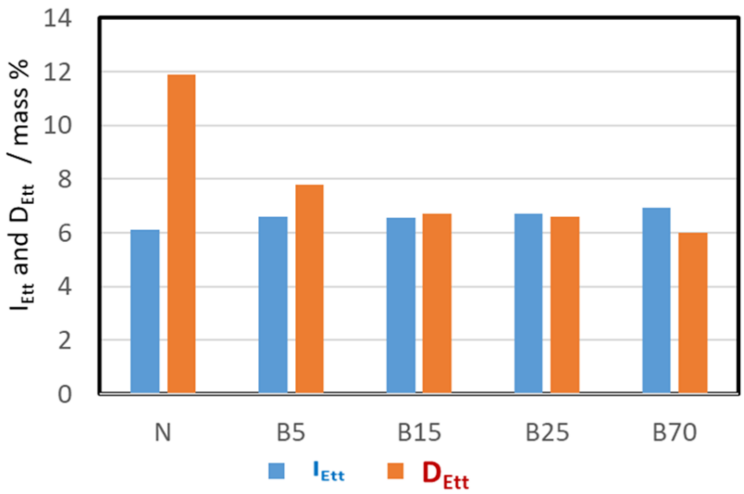

Fig.4 The amount of I_{Ett} and D_{Ett}

DEF EXOANSION MECHANISM

Differences in Void Structure

Fig.5 shows the total porosity of hardened cement compared with a constant 20°C environment and temperature history. The Archimedes method was used to measure the porosity. It can be seen that the higher the GGBS replacement ratio, the higher the porosity. The total porosity increased when the temperature history was given. This means that when Initial ettringite (I_{Ett}) disappears due to temperature history, it can be imagined that it forms voids. Fig.6 describes the image. The higher the GGBS replacement rate, the larger the porosity volume. Considering that the DEF is formed under these conditions, the lower the GGBS replacement ratio such as N, the less cushioning D_{Ett} has in the expansion, and the more crack propagation is assumed. On the other hand, it can be imagined that in high volume GGBS contain mix proportions with large total porosity, even if expansive products are produced, they will not develop into cracks.

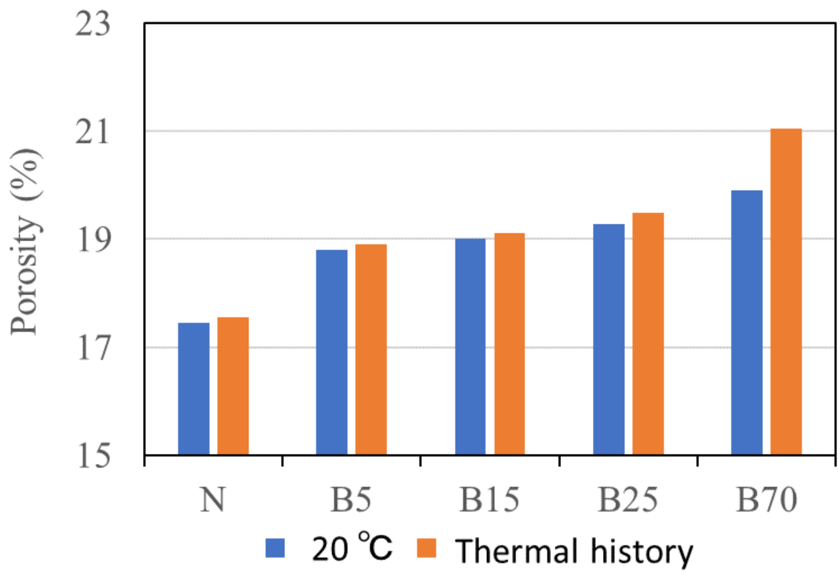

Fig.5 Total porosity on 20 degree Celsius and thermal history

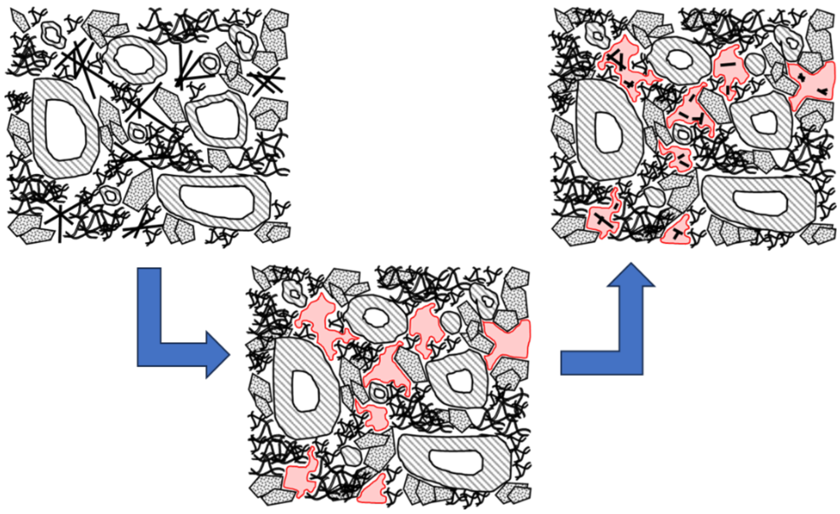

Fig.6 Image of porosity changes and the site of DEF production

Suppression of DEF by the formation of C-(A)-S-H

Al^{3+} and SO_4^{2-} released from AFt decomposed by temperature history are considered to be surface adsorbed or electros orbed on the surface of the liquid phase or C-S-H. During curing at ambient temperature, the re-release of Al^{3+} and SO_4^{2-} adsorbed on the surface of CH and C-S-H creates the conditions for the formation of AFt, resulting in DEF; in the case of GGBS addition, the formation of D_{Ett} is suppressed with the substitution rate, which is due to the solid solution substitution of part of Si in C-S-H with Al^{3+}. The formation of C-(A)-S-H is thought to be due to the formation of C-(A)-S-H, which prevents Al^{3+} from re-emitting into the liquid phase during curing under ambient temperature conditions, thus making it difficult to meet the conditions for DEF formation and suppressing D_{Ett} formation.

I_{Ett} increases with the substitution rate, which also increases the Al^{3+} leached from the decomposed AFt in the temperature history. Therefore, the higher substitution of GGBS is considered to have reduced D_{Ett} due to the increase in C-(A)-S-H produced, which reduced the amount of Al^{3+} required for AFt regeneration.

SUMMARY

The following findings were obtained through this study.

(1) In this study, delayed ettringite formation was observed on mortar of different cement type satisfying the conditions for DEF.

(2) When GGBS was added more than 25%, DEF expansion was not observed even after 150 days of soaking.

(3) The mechanism of DEF expansion suppression by GGBS admixture was examined, but the possibility of pore structure change or C(A)SH formation is not clear. This is a subject for future study.

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