DEVELOPMENT AND APPLICATION OF ENVIRONMENTALLY FRIENDLY CONCRETE IN JAPAN - ENERGY·CO_2 MINIMUM (ECM) CONCRETE

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Abstract

Energy·CO_2 Minimum (ECM) concrete, one of Japan's leading environmentally friendly concrete products, achieves a reduction of 60-70 % in CO_2 emissions compared to conventional concrete by utilizing a significant amount of ground granulated blast furnace slag and using a binder that optimizes the type and dosage of gypsum, all while maintaining high quality. In this paper, slump retention, exothermic characteristics, strength development, shrinkage cracking resistance, durability and fire resistance are discussed as the properties of ECM concrete. In addition, examples of application to structures using these characteristics are described.

Keywords: CO_2 emissions; Environmentally friendly concrete; Ground granulated blast furnace slag; Gypsum; High quality.

1. INTRODUCTION

The impact of global warming has been identified as a cause of abnormal weather worldwide, and the reduction of CO_2, one of the greenhouse gases, is increasingly being focused on. A significant amount of CO_2 is generated during the production of cement, an essential material in the construction field. Approximately 4 % of total CO_2 emissions in Japan are attributed to cement manufacturing, while on a global scale, this figure is around 8 %. Cement being second only to steel among construction materials in terms of CO_2 emission, reducing the CO_2 emission of cement and concrete is imperative.

Against this backdrop, research and development of environmentally friendly concrete aimed at reducing CO_2 emissions have been actively conducted in Japan in recent years. Unit CO_2 emissions in cement production in Japan are estimated to be about 760 kg-CO_2/ton. In contrast, unit CO_2 emissions of ground granulated blast furnace slag (GGBFS) is about 26 kg-CO_2/ton, or about 1/30th those of cement. Consequently, the expanded use of GGBFS is expected to be an effective means of reducing CO_2 emissions. In the Japanese Industrial Standard JIS A 5211[1] "Portland blast-furnace slag cement," three types of Portland blast-furnace slag cement, A, B, and C, are defined, with GGBFS content ranging from over 5 to 30 % or less, over 30 to 60 % or less, and over 60 to 70 % or less, respectively. Currently, the most widely used Portland blast-furnace slag cement in Japan is Type B with a GGBFS content adjusted to around 40-45 % by mass (hereinafter, BB). BB accounts for approximately 20 % of all commercial cement in Japan and is primarily used in civil infrastructure projects.

Blast furnace cement Type C that increases the GGBFS content to 60-70 % (hereinafter, BC), is effective in reducing CO_2 emissions. However, it has issues such as low early-age strength development and a higher susceptibility to shrinkage cracking due to significant autogenous shrinkage and low creep. The authors and our group*, with the support of the New Energy and Industrial Technology Development Organization (NEDO), an auxiliary organ of the Ministry of Economy, Trade and Industry, embarked on research and development of the Energy·CO_2 Minimum (ECM) cement-concrete system in 2008, [2,3] and developed ECM concrete that solves the above issues associated with the use of BC.

We have previously reported on the suitable chemical admixture composition [4,5] and the properties of fresh concrete for ECM concrete [6]. In addition, the effect of mount of SO_3 in the binder on temperature stress [7], basic properties of ECM concrete [8], resistance to shrinkage cracking [9], evaluation of durability against carbonation [10], suppression effect on alkali silica reactivity [11], resistance to diffusion of chloride ions [12], sulfuric acid resistance and sulfate resistance [13], and the effect on explosion in the event of a fire [14]. In this paper, comprehensively provides various properties of ECM concrete that have been obtained so far.

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Then, since 2014 we have started applying ECM concrete to actual construction projects and have reported individually on its application to piles [15,16], to mass concrete [17], and to superstructures [18]. In this paper, the effectiveness of the application of ECM concrete to building structures is described based on past application results.

2. OVERVIEW OF ECM CONCRETE

Figure 1 shows the material composition of the binder used in ECM concrete. Since the CO_2 emissions of concrete are mainly attributed to cement, reducing the CO_2 emission of concrete by 60-70 % can be achieved by using GGBFS, which has small unit CO_2 emissions. However, simply increasing the replacement ratio of GGBFS poses the following issues in concrete.

i. Significant decrease in slump
ii. Low early strength development
iii. High autogenous shrinkage
iv. Rapid rate of carbonation

To address these issues, the development of ECM concrete involved the creation of novel chemical admixtures that can control slump loss in systems with high GGBFS content. Additionally, optimization of the GGBFS mixing ratio in cement, types and quantities of trace additives (mainly gypsum), and the amount of SO_3 was performed to improve early-age strength development and reduce autogenous shrinkage. Owing to space limitations, we will omit details regarding carbonation, but in reinforced concrete (RC) structures, by setting the concrete water-cement ratio and cover depth, it is possible to secure a predetermined service life. ECM concrete is also applied in locations and members where carbonation need not be considered, such as concrete-filled steel tube (CFT) structures. The characteristics of ECM concrete are described next.

2.1 Slump retention

Figure 2 compares the slump losses of ECM concrete using conventional chemical admixtures for ordinary concrete (conventional products) and newly developed admixtures (developed products) under the ambient temperatures of 20°C and 30°C. When using the conventional products, the amount of chemical admixture required to achieve the target slump is lower due to lesser adsorption on GGBFS. As a result, slump loss over time is significant. On the other hand, the developed products, which have a molecular structure that primarily causes adsorption on GGBFS, [4,5] allow for sufficient chemical admixture dosage and thereby effectively suppress slump loss compared to the conventional products [6]. By utilizing the developed products, workability can be maintained until the completion of on-site placing.

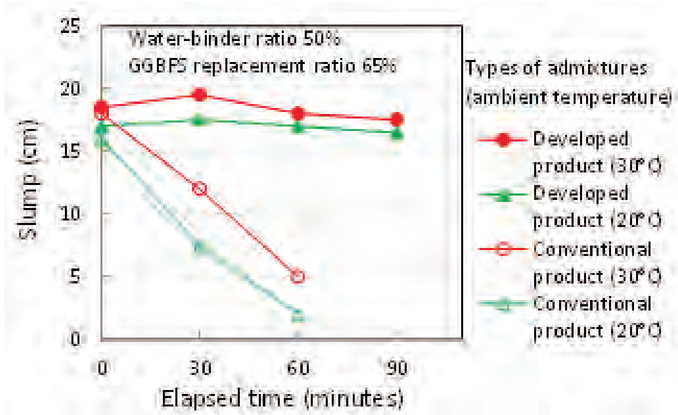


Figure 2: Comparison of slump change over time [6]

2.2 Exothermic characteristics

Figure 3 shows the results of measuring the adiabatic temperature rise in concrete using ordinary Portland cement (N), and concrete using BB or BC (ECM concrete). [7] The numbers in the legend represent the gypsum content [SO_3 content (%)]. In all the Japanese cements, the SO_3 content is adjusted to around 2 % for all types. ECM concrete is made using BC with increased SO_3 dosage (BC-4.2). The higher the GGBFS content (N < BB < BC), the smaller the adiabatic temperature rise, indicating the effectiveness of suppressing thermal stress-induced cracking in mass concrete. Comparing BC-2.0 and BC-4.2, the temperature

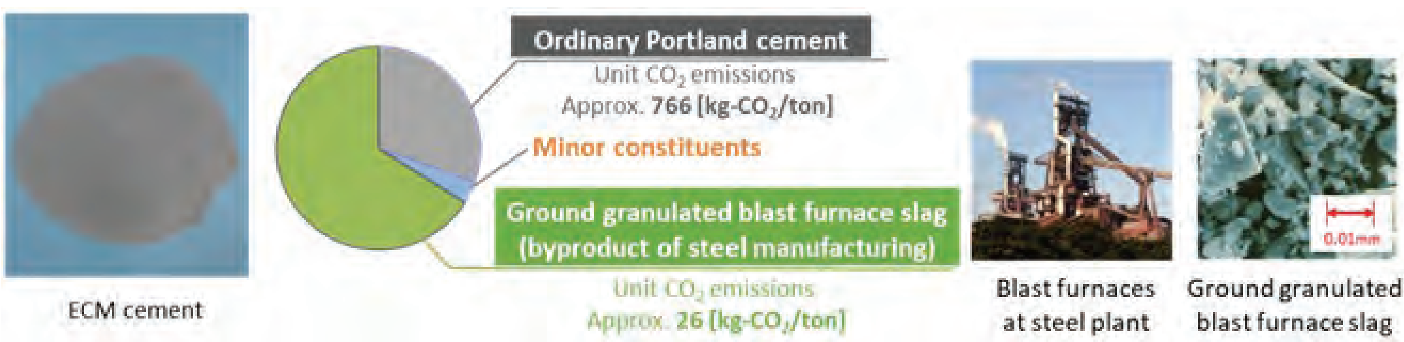


Figure 1: Material composition of ECM concrete

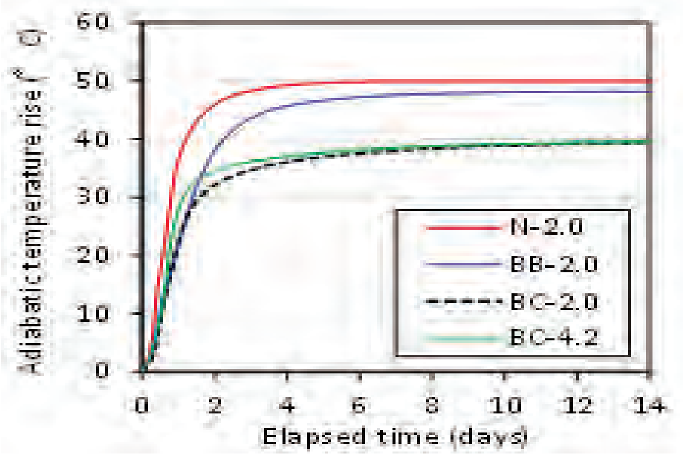


Figure 3: Comparison of adiabatic temperature rise curves [7]

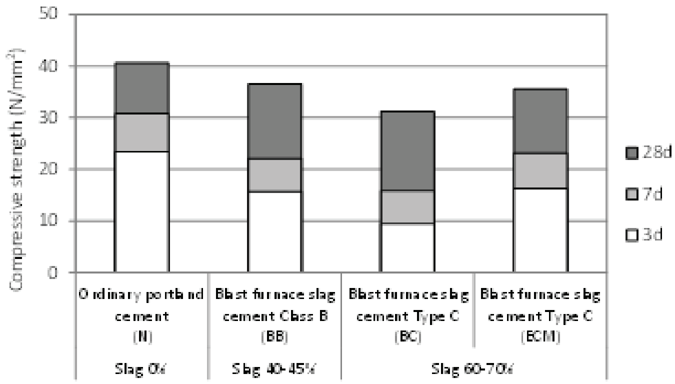


Figure 4: Comparison of strength development of ECM concrete [8]

rise is similar, but the ECM concrete with increased SO_3 content (BC-4.2) exhibits slightly faster temperature rise.

2.3 Strength development

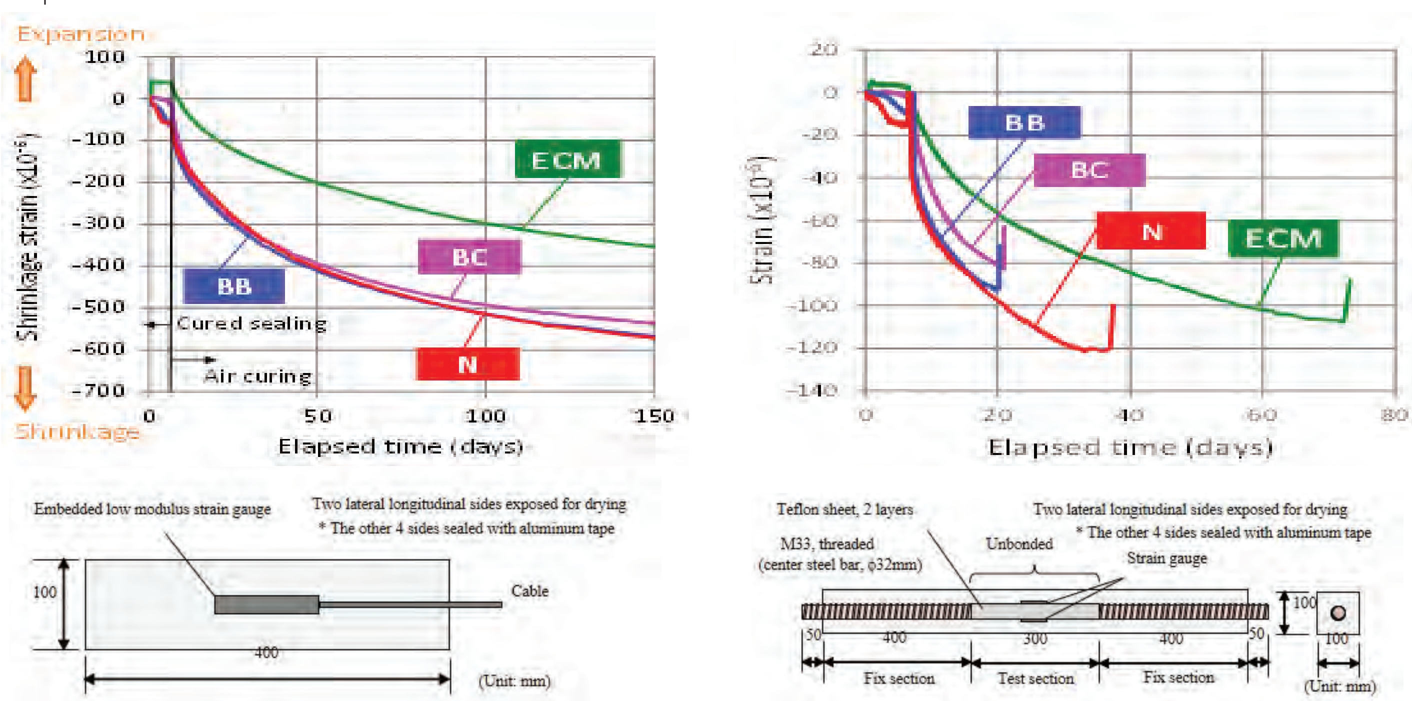
Figure 4 shows strength development up to 28 days when using ECM cement [8]. Despite a higher replacement ratio of GGBFS, ECM concrete achieves higher early-age strength development compared to conventional BC by increasing the gypsum content. At 28 days, ECM concrete exhibits strength development comparable to that of BB. This is thought to be due to accelerated early-age hydration reaction caused by the higher gypsum dosage, as evidenced by the faster rate of temperature increase mentioned above.

2.4 Shrinkage and crack resistance

Optimizing the SO_3 dosage in ECM concrete reduces the shrinkage rate compared to conventional cement, as shown in Figure 5 [9]. As a result, in the restrained cracking test with embedded reinforcing bars, the crack initiation age was later than in the case of any of the other cements, indicating an advantage in suppressing drying shrinkage cracks.

i. Free shrinkage test specimen and observed strain

ii. Restrained cracking test specimen and observed strain



(i) Free shrinkage test specimen and observed strain

(ii) Restrained cracking test specimen and observed strain

Figure 5: External restraint test [9]

2.5 Durability

An example of accelerated carbonation test results is shown in Figure 6 [10]. Tested under the conditions of temperature 20±2°C, relative humidity (60±5) %, and carbon dioxide concentration (5±0.2) % specified in Japanese Industrial Standard (JIS) A 1153:2012 [19] "Method of accelerated carbonation test for concrete" carried out. At the same compressive strength level, ECM concrete exhibits a higher carbonation rate coefficient compared to using N or BB. This is due to the lower amount of Portland cement and lower calcium hydroxide content. However, even in the case of ECM concrete, by applying the reliability-based design method outlined in the "Recommendations for durability design and construction practice of reinforced concrete buildings (2016): Architectural Institute of Japan," [20] it is possible to achieve a service life of 200 years by appropriately setting the water-binder ratio and cover depth.

Figure 7 shows the length change rate when using aggregate with high alkali-silica reactivity. ECM concrete [11], which utilizes a significant amount of GGBFS, exhibits greater suppression of alkali-silica reactivity compared to using BB.

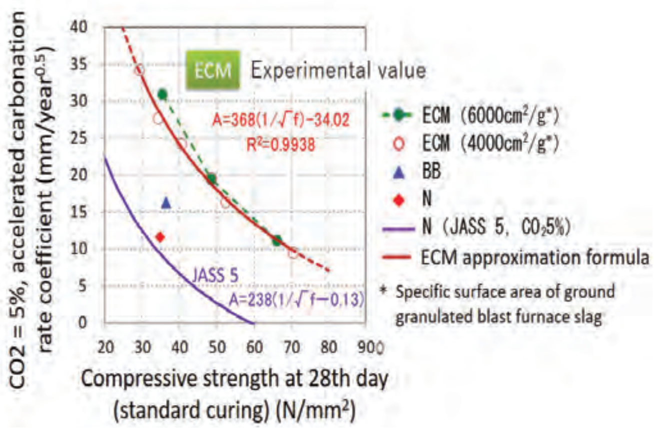


Figure 6: Relationship between carbonation rate of accelerated test and compressive strength [10]

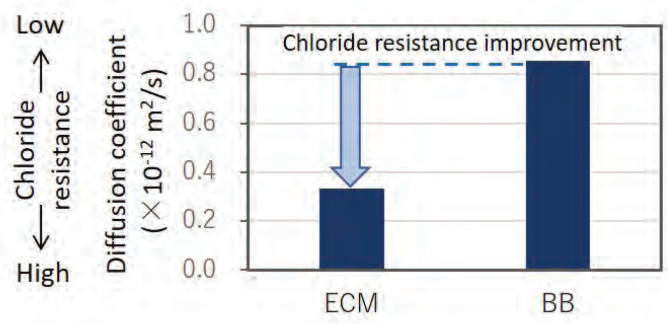


Figure 8: Comparison of diffusion coefficients of chloride ions [12]

Figure 8 shows a comparison of chloride ion diffusion coefficients[12]. ECM concrete, which utilizes a significant amount of GGBFS, exhibits higher resistance to chloride ingress compared to BB. Moreover, the use of GGBFS also enhances resistance to sulfuric acid and sulfate attack [13].

2.6. Fire resistance

While increasing the amount of gypsum in cement improves the properties discussed above, too much gypsum adversely affects fire resistance. Concrete was cast in a cylinder of φ10 × 20 cm, wet cured for 4 days, demolded, and steam cured at 45°C for 6 hours. After that, dry curing was performed at 20°C and 60 % RH until the material age was 14 days, and heating was performed for 40 minutes using the IS0-834 [21] heating curve. Figure 9 shows the results of an explosive spalling test conducted at the specimen level, with the SO_3 content in BC as the factor level [13]. Excessive SO_3 content can lead to explosive spalling during fire. Additionally, although not covered in this paper, excessive SO_3 content also has a detrimental effect on freeze-thaw resistance. Therefore, it is important to consider the comprehensive impact of SO_3 content on various characteristics and determine the optimal amount accordingly.

a) Heating furnace
b) ISO-834 [21] standard fire curve
c) Arrangement of specimens
d) Specimen appearance after fire resistance test

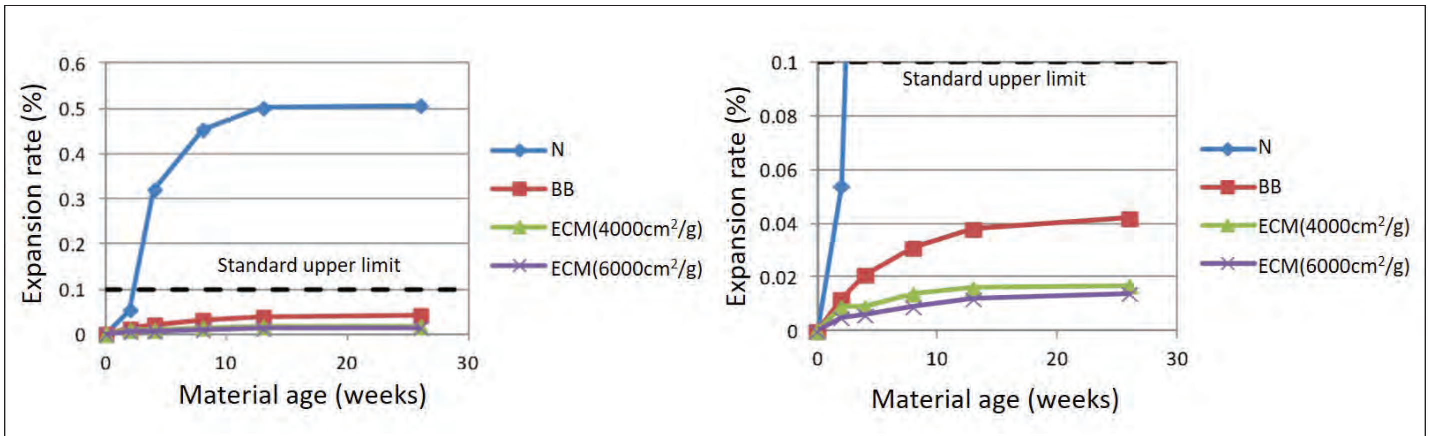
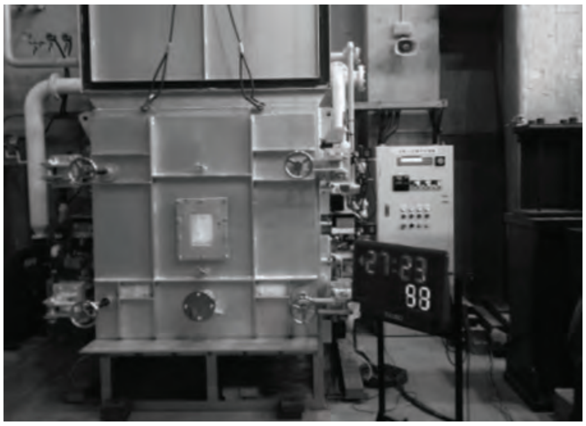
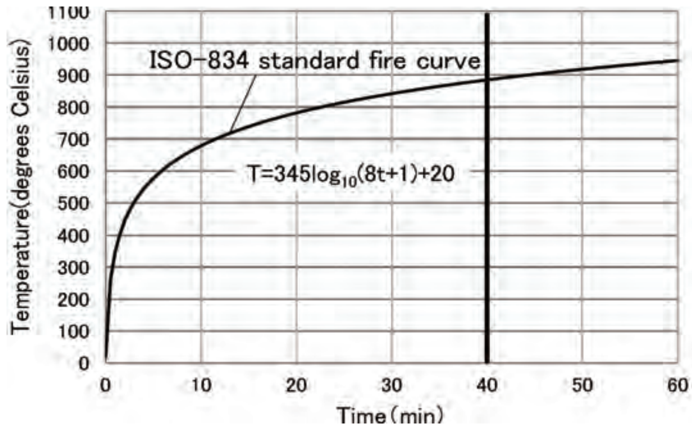


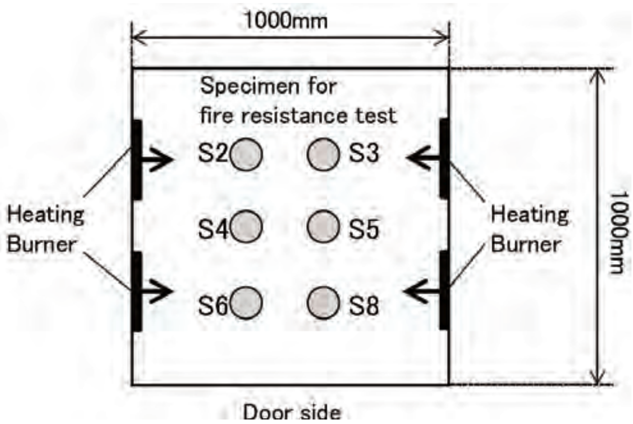
Figure 7: Length change due to alkali-silica reaction (left: overall view, right: enlarged view) [11]



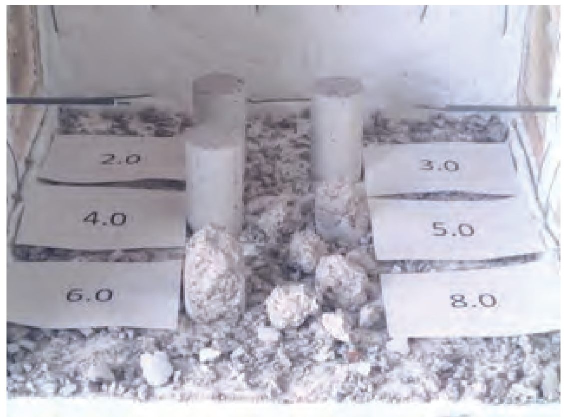
(a) Heating furnace



(b) ISO-834 standard fire curve



(c) Arrangement of specimens



(d) Specimen appearance after fire resistance test

Figure 9: Explosion test of concrete containing high blast furnace slag with different gypsum contents [14]

3. APPLICATION TO STRUCTURES

From October 2014 to March 2023, Takenaka Corporation has applied ECM concrete to a total of 86 projects, amounting to a combined volume in excess of 270,000 m^3, and plans to apply ECM concrete to many more projects in the future.

The types purposes of use) of the structures include commercial facilities (offices, hotels), sports facilities (theaters, exhibition halls), educational and cultural facilities (schools), medical and welfare facilities (hospitals), and production and distribution facilities (plants). The specified design strength (Fc) ranges from 24 to 36 N/mm^2. The application targets primarily consist of underground structures, with cast-in-place piles and foundations, mat slabs, and grade beams accounting for nearly 90 % of all applications. An overview of each of the various application targets is provided next.

3.1 Application to cast-in-place piles [15,16]

Cast-in-place piles are suitable for the application of concrete using high volume blast furnace slag cement and binder because they are underground or underwater, making them less susceptible to carbonation progress and requiring no consideration for formwork removal like conventional RC structures. The use of GGBFS improves chemical resistance to chloride ion ingress, acid degradation, and sulfate degradation, thereby enhancing durability in degrading environments such as seawater, hot spring areas, and sewage tanks. The use of new chemical admixtures specifically for ECM concrete ensures high workability and slump flow retention, as well as good structural strength development, as confirmed by large-scale pile construction experiments (Figure 10).

Figure 10: Excavation and filling of cast-in-place piles [16]

3.2 Application to substructures (mass concrete) [17]

ECM concrete exhibits low temperature rise, as shown in Figure 3, and excellent resistance to temperature-induced cracking. Taking advantage of these characteristics, ECM concrete has been applied to many substructures. Figure 11 shows an example of such construction. Furthermore, Figure 12 shows an example of quality control results for slump, air content, and compressive strength when ECM concrete was applied to mass concrete with specified design strength of 30 N/mm^2, water-binder ratio of 46 %, and unit water content of 176 kg/m^3. The results indicate that the target quality levels were achieved. Thus far, application to substructures (mass concrete) account for approximately three-quarters of the total number of application cases.

3.3 Application to superstructures [18]

In one project, ECM concrete was used for the entire concrete structure of a hydrogen station. Figure 13 shows the application site. Almost no plastic cracks were observed after casting. The drying shrinkage rate was 450 μm or less in preliminary tests. Approximately four years since the completion of the structure, the exposed concrete of the exterior walls remains free of noticeable shrinkage cracks and deformation.

Figure 11: Application to underground structure [17]

Figure 13: Application to superstructure [18]

4. CONCLUSIONS

The characteristics of ECM concrete with 60-70 % GGBFS and increased amount of gypsum are concluded as follows.

1. By using a chemical admixture suitable for ECM concrete, it is possible to maintain a workable slump even when the replacement rate of GGBFS is high.
2. By using 60-70 % GGBFS, low heat generation can be achieved.
3. By increasing the amount of gypsum in cement, the initial strength can be improved. It can also reduce shrinkage and increase crack resistance.
4. By using 60-70 % GGBFS, the neutralization resistance of the durability is lowered, but the service life of 200 years can be realized by appropriately setting the water binder ratio and cover thickness. In addition, the effect of suppressing the alkali-silica reaction is enhanced, and the diffusion coefficient of chloride ions is greatly reduced.

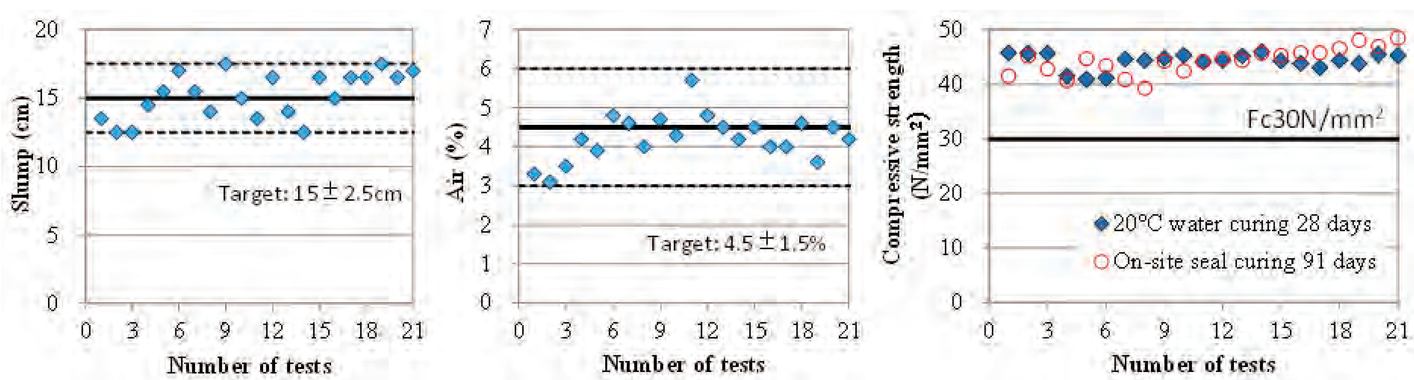


Figure 12: Concrete quality control test results [17]

5. When the amount of gypsum is increased, the explosion occurs in case of fire. Too much gypsum adversely affects fire resistance, When the amount of gypsum is increased, explosion occurs during fire. Explosion can be suppressed by increasing the amount of gypsum to an appropriate amount.
6. ECM concrete with the above properties is highly applicable to piles, underground framework (mass concrete), and above-ground framework.

Since research and development began in 2008, ECM concrete has now entered the stage of widespread adoption. Takenaka Corporation has set reduction targets for CO_2 emissions, aiming for a 30 % reduction in scope 1 and 2 emissions and a 35 % reduction in scope 1-3 emissions by 2030 (base year: 2018), with the further goal of achieving 100 % reduction in scope 1-3 emissions by 2050. To achieve these targets, it is essential to not only promote zero energy buildings but also reduce the CO_2 emissions of construction materials, including the replacement of a significant portion of concrete by environmentally friendly concrete. Currently, ECM concrete is actively being deployed as a weapon for reducing CO_2 emissions. To achieve carbon neutrality by 2050, further development of new concrete with greater CO_2 reduction is necessary. Under the Green Innovation Fund Projects of the Japanese government, subsidies from NEDO are being received to advance the development of innovative carbon-negative concrete [22]. To realize a sustainable society through construction, we aim to promote the spread of ECM concrete and the development and spread of new carbon-negative concrete.

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