From our previous findings, the recycling of ceramic waste aggregate (CWA) in mortar has been proved an ecological means plus an excellent outcome against chloride ingress. The CWAs were electric porcelain insulator wastes supplied from an electric power company, which were crushed and ground to fine aggregate sizes. In this study, to further develop the CWA mortar as an eco-efficient, ground granulated blast-furnace slag (GGBS) was incorporated. The GGBS was utilized as a supplementary cementitious material (SCM) at three different replacement levels of 15, 30, and 45% by weight of cement. The time dependency of the GGBS on enhancing chloride resistance in the CWA mortars was experimentally assessed by using an electron probe microanalysis (EPMA). The tests were carried out on mortar samples after immersion in 5.0% NaCl solution for 24, 48, and 96 weeks. Another set of the mortar samples was exposed to a laboratory ambient condition for 24, 48, and 96 weeks and then followed with a carbonation test. The resistance to the chloride ingress of the CWA mortar becomes more effective in proportion to the replacement level of the GGBS. Meanwhile, the carbonation depth of the CWA mortar increases with increasing the GGBS. The relationship between the apparent chloride diffusion coefficient and the GGBS replacement level was shown along with the immersion time.

Key words: Ceramic waste aggregate, GGBS, Mortar, Chloride ingress, Carbonation, EPMA

1 Introduction

Ceramic wastes discarded worldwide from ceramic industries, demolition/construction sites, and electric power companies are one of the materials possibly recyclable as aggregates and/or pozzolans. The utilization of the ceramic wastes has been investigated by many researchers. In the existing literature, there is a shortage on the utilization of ceramic waste aggregates (CWAs) provided from electric porcelain insulators. Hata et al. found that the compressive strength of concrete was increased by the micro-filler effect when fine aggregate in concrete was partially replaced with CWA powder. Senthamarai et al. investigated the mechanical and durability properties on concrete made of crushed porcelain insulator wastes as coarse CWA. They found no difference on the mechanical and permeation properties between conventional and CWA concretes. Jacintho et al. used fine CWA for aggregate in mortar. They mentioned that the compressive strength was increased by a possible pozzolanic reaction. The authors also investigated on the compressive strength and the resistance to chloride ingress into mortars containing CWAs made of crushed and ground electric porcelain insulator wastes which were discarded from an electric power company. The replacement of entire fine aggregates with the CWA in mortar reduces the chloride ion penetration when compared with river sand (RS) mortar.

On the other hand, it is well known that a mineral admixture of ground granulated blast-furnace slag (GGBS) as a supplementary cementitious material (SCM) with partial cement replacement is effective in the resistance of chloride ingress into mortar and concrete. The physical, mechanical, and durability properties of mortar and concrete with GGBS have been investigated by many researchers so far. The advantages of using GGBS are usually ascribed to long-term strength gain and resistance to weathering and aggressive chemical action. In general, the compressive strength development of concrete incorporating GGBS was lower than that of concrete without GGBS at the early age. However, at the later age, the compressive strength of concrete with GGBS was greater than that of concrete without GGBS.

In this study, GGBS was incorporated as SCM to further develop CWA mortar as an eco-efficient construction material. The cement was partially replaced with GGBS at 15, 30, and 45% by weight. The compressive strength development and durability of the CWA mortar with GGBS were investigated. Carbonation and chloride ingress which are two main issues regarding the durability of cement-based materials were studied. The former was simulated with exposure to a
2 Experimental Programs

2.1 Ceramic Waste Aggregate

Electric porcelain insulator wastes as shown in Figure 1 (suspension insulator) were first received from an electric power company. It was subsequently transformed to aggregate, namely ceramic waste aggregates (CWAs), at a recycling plant (The Kanden L&A Company, Ltd.) via the processes developed primarily by Sano et al. as follows.

Firstly, the ceramic wastes were broken by using a hammer or a jaw crusher to small pieces ranging from 50 to 100 mm size. Next, by using a cone crushe, these pieces were crushed to small gains at a particle size of 30 mm or less. These particles have sharp knife-like edges at this stage, which would be still dangerous to supply as aggregate for mortar and concrete. Therefore, removal of the sharp edges from the CWA was subsequently achieved by a grinding machine. Finally, the particle sizes ranging from 0.075 to 5.0 mm, as shown in Figure 2, were used in this study. The CWA has a specific gravity of 2.40 and water absorption of 0.7%. The grain size distribution of the CWA after going through the above process is presented in Figure 3 with the grading requirements (dashed lines) of the standard distribution specified in JIS A 5005. The grain size distribution of the CWA is within the standard distribution except for one particle size of 2.5 mm. The fineness modulus of the CWA was 3.20.

2.2 Materials and Mixture Proportions

To further develop the CWA mortar as an eco-efficient construction material, GGBS supplied from a slag cement company was employed as a SCM in this study. The GGBS was used as received having a specific gravity of 2.91 and a specific surface area of 6230 cm²/g. According to the manufacturer specifications, its activity index calculated on the basis of compressive strength was 0.97, 1.11, and 1.27 at 7, 28, and 91 days, respectively. In addition, the cement was ordinary Portland cement (OPC). The physical and chemical properties of all materials used (i.e. OPC, GGBS, and CWA) are given in Table 1.

In the mixture proportions, the water-binder (W/B) ratio
was kept constant at 0.5 by weight and CWA-binder (S/B) ratio was also kept constant at 2.0 by weight. The CWA mortar without GGBS as a control mixture was compared with the modified mixtures in which the cement was partially replaced with GGBS at 15, 30, and 45% by weight. They are denoted as CWAM0, CWAM15, CWAM30, and CWAM45, respectively. In comparison, mortar using river sand (RS) as fine aggregate without GGBS was also prepared.

The CWA was mixed in an air-dry condition due to its low water absorption while the RS was mixed in a saturated surface-dry condition. For all mixtures, the mortars were prepared in a Hobart mixer of 5 L capacity. The mixing process was started with the blending of OPC, GGBS and CWA for 1 min and was followed with the addition of water and further mixing for 3 min.

**2.3 Specimens and Test Methods**

For each mixture, eighteen cylindrical specimens of 50 mm diameter and 100 mm height were prepared; nine of which were used in a compression test at 7, 28, and 91 days (three specimens at each time) and the other nine were used in a carbonation test at 24, 48, and 96 weeks (three specimens at each time). Furthermore, three cylindrical specimens of 100 mm diameter and 200 mm height were prepared for chloride ingress test at 24, 48, and 96 weeks (one specimen at each time) which were employed in an electron probe microanalysis (EPMA). After casting, all specimens were covered with a plastic waterproof sheet for 24 h. Subsequently, they were de-molded and cured in a water tank at 20 ± 2 °C.

**2.3.1 Compression Test** A compression test was carried out on the nine specimens at the age of 7, 28, and 91 days. A compressive load was applied by using a 500 kN capacity universal testing machine and loading speed was a constant of 0.2 N/mm²/sec according to JSCE-G 505(3). A compression test was carried out on the nine specimens at the age of 7, 28, and 91 days. A compressive load was applied by using a 500 kN capacity universal testing machine and loading speed was a constant of 0.2 N/mm²/sec according to JSCE-G 505(3).

**2.3.2 Carbonation Test** At the age of 7 days, the 100 mm height cylindrical specimens for the carbonation test were trimmed down to 90 mm. The 10 mm top end was cut to eliminate the influence of segregation. After the specimens were allowed to dry in a laboratory condition at 20 ± 2 °C for 24 h, they were epoxy coated leaving only one sawn surface free of coating and were kept for additional 24 h to cure the epoxy resin. Then, they were fully immersed in a 5.0% NaCl solution in hermetic tanks at 20 ± 2 °C as shown in Figure 4.

After 24, 48, and 96 weeks of the immersion, the specimens were sawn into 25 mm width and 60 mm length as shown in Figure 5. By using the JEOL JXA-8200 instrument, the resized specimens were scanned to identify the amount of chloride ions at tiny single spot throughout its surface. The measurement conditions were an accelerating voltage of 15 kV, a beam current of 0.2 μA, a pixel size of 200 μm, a probe diameter of 150 μm, and the number of mapping points of 400 × 400 pixels as per JSCE-G 574(4). Subsequently, the distribution of those chloride concentrations on the surface was obtained. Moreover, the chloride concentration profiles were plotted and were analyzed to find the apparent chloride
3 Results and Discussion

3.1 Compressive Strength Development

The compressive strength results of the CWA mortars incorporating the GGBS at the age of 7, 28, and 91 days are shown in Table 2. The compressive strength developments of all mortars are shown in Figure 6. The CWA mortar with the 15% and 30% GGBS replacement, CWAM15 and CWAM30, did not exhibit the strength loss at any age when compared with the CWA mortar without the GGBS, CWAM0. On the other hand, some retardation of the compressive strength was observed in the 45% GGBS replacement, CWAM45, at the early age (7 and 28 days). However, its retardation of the compressive strength is 11% or less when compared with the CWAM0. Furthermore, as shown in Table 2 and Fig. 6, all CWAM mortars tested have the higher compressive strength than the CWAM0. On the whole, the compressive strength level of the CWAM mortars containing the GGBS is appropriate in practice.

3.2 Carbonation Depth

The resulting carbonation depths of all CWA mortars along the exposure time are shown in Figure 7. The carbonation depth of mortar containing the GGBS increased along the exposure time. Furthermore, the carbonation depth of mortar containing the GGBS replacement increases with the replacement level. Ngala and Page19) have confirmed that the GGBS reduces the amount of calcium hydroxide in the cement paste and the pore volume in the cement paste containing the GGBS becomes porous after carbonation.

In general, the carbonation depth increases with the square root of time. Therefore, the carbonation speed factor was calculated by using the following equation:

\[ y = b\sqrt{t} \] (1)

where, \( y \) is the carbonation depth (mm), \( b \) is the carbonation speed factor (mm/year\(^{1/2}\)), and \( t \) is the exposure time (year).

However, as shown in Fig. 7, the carbonation depth did not show the relationship with the square root of the exposure time in this test. It might be needed to expose them for further long time. Therefore, only the carbonation speed factor at 96 weeks exposure calculated from Eq. (1) is shown with the GGBS replacement level in Figure 8. It is noted that the carbonation speed factor is observed in the 45% GGBS replacement, CWAM45, at the early age (7 and 28 days). However, its retardation of the compressive strength is 11% or less when compared with the CWAM0. On the other hand, some retardation of the compressive strength was observed in the 45% GGBS replacement, CWAM45, at the early age (7 and 28 days). However, its retardation of the compressive strength is 11% or less when compared with the CWAM0. On the whole, the compressive strength level of the CWAM mortars containing the GGBS is appropriate in practice.

### Table 2 Results of compression test.

| Mortar  | GGBS replacement (%) | Compressive strength (N/mm\(^2\)) 7 days | 28 days | 91 days |
|---------|----------------------|----------------------------------------|--------|--------|
| CWAM0   | 0                    | 34.7                                   | 55.3   | 60.8   |
| CWAM15  | 15                   | 36.5                                   | 57.5   | 70.8   |
| CWAM30  | 30                   | 34.3                                   | 58.3   | 71.5   |
| CWAM45  | 45                   | 31.3                                   | 52.5   | 61.9   |
| RSM     | 0                    | 34.7                                   | 55.3   | 60.8   |

Fig. 6 Compressive strength development.

Fig. 7 Carbonation depth along the exposure time.

Fig. 8 Relationship between the carbonation speed factor and the GGBS replacement level at 96 weeks exposure.
carbonation speed factor at the 96 weeks exposure linearly relates to the GGBS replacement level.

### 3.3 Chloride Ion Penetration Depth

By using the EPMA method, the $25 \times 60$ mm cross sectional area of specimens was scanned to quantify the chloride concentration. The EPMA measurement resulted in the distribution of chloride concentration (namely, chloride concentration profile) along the depth as shown in Figures 9(a) to (e) corresponding to the CWAM0, CWAM15, CWAM30, CWAM45, and RSM, respectively. The chloride concentration profile averaged at 0.2 mm intervals obtained from the EPMA measurement. In order to avoid the influence of fine aggregate, the chloride concentration was employed only in the cementitious matrices. The CWAM0 evidently exhibits lower chloride penetration depth than the RSM as is revealed in the previous study by the authors5). In concrete, the volume of capillary pores highly influence the diffusion of chloride16,17). From the previous study16, the volume of capillary pores from 0.007 to 10 µm pore diameter in the CWAM0 was lower than the RSM.

The GGBS significantly decreased the penetration depth of chloride ion in the CWA mortar. In contrast, the surface chloride concentration in the CWA mortar containing the GGBS increased when compared with the CWA mortar without the GGBS. This is attributed to the more refined pore structure of the hydrated cementitious material using the GGBS and the binding adsorption capacity which is chloride ions onto the hydrated slag walls. Elakneswaran et al.19) have reported that, in the hydrated cementitious materials containing GGBS, the negatively charged phases due to the zeta potential, the Blaine fineness, and the large amount of aluminum oxide are responsible for the chloride adsorption on the surface of GGBS. Mineral admixtures such as GGBS and fly ash reduce large pores in cement-based material with diameter exceeding 0.05 µm such as macro pore17). Then, mineral admixtures inhibit the chloride ingress.

### 3.4 Apparent Chloride Diffusion Coefficient

![Fig. 9 Chloride concentration profile.](image-url)
The apparent chloride diffusion coefficient was determined by fitting Eq. (2) to the corresponding measured chloride concentration profile. The chloride concentration \( C(x, t) \) is given by

\[
C(x, t) = C_i + C_0 \left( 1 - \text{erf} \left( \frac{x}{2\sqrt{D_a t}} \right) \right)
\]

(2)

where \( C(x, t) \) is the chloride concentration (kg/m\(^3\)) at depth \( x \) (cm) and exposure time \( t \) (year), \( C_i \) is the initial chloride concentration (kg/m\(^3\)), \( C_0 \) is the surface chloride concentration (kg/m\(^3\)), \( D_a \) is the apparent chloride diffusion coefficient (cm\(^2\)/year), and \( \text{erf} \) is the error function.

In the analysis of the chloride concentration profile, \( C_0 \) was the maximum value obtained by the EPMA and \( D_a \) was calculated by the curve fitting. For one sample, the calculated result of the chloride concentration profile is presented in
Figure 10. The apparent chloride diffusion coefficients for all the mortars are given in Table 3. A relationship between the apparent chloride diffusion coefficient and the immersion time is shown in Figure 11. The apparent chloride diffusion coefficient of the CWAM0 and the RSM relatively decreased being sharp at early age. However, the changing of the apparent chloride diffusion coefficients of mortars containing the GGBS is small along the immersion time. The time dependency of the apparent chloride diffusion coefficients of tested mortars can be expressed as follows.

\[
D_a = 0.804 t^{-0.331} \quad \text{for CWAM0}
\]
\[
D_a = 0.436 t^{-0.180} \quad \text{for CWAM15}
\]
\[
D_a = 0.313 t^{-0.608} \quad \text{for CWAM30}
\]
\[
D_a = 0.167 t^{-0.500} \quad \text{for CWAM45}
\]
\[
D_a = 1.679 t^{-0.385} \quad \text{for RSM}
\]

Furthermore, a relationship between the apparent chloride diffusion coefficient and the GGBS replacement level at each immersion time is shown in Figures 12(a) to (c). It can be expressed by an exponential equation as follows.

\[
D_a = 0.9796 e^{-0.0324 GGBS} \quad \text{at 24 weeks immersion}
\]
\[
D_a = 0.8264 e^{-0.0327 GGBS} \quad \text{at 48 weeks immersion}
\]
\[
D_a = 0.6425 e^{-0.0355 GGBS} \quad \text{at 96 weeks immersion}
\]

Consequently, the chloride resistance of the CWA mortar is more effective with increasing the GGBS replacement among the test results in this study.

4 Conclusions

In this study, the mechanical and durability properties on the CWA mortar containing the GGBS with different replacement levels were investigated. The following conclusions can be drawn.

(1) The CWA mortar with the 15% and 30% GGBS replacement did not exhibit the strength loss at any age when compared with the CWA mortar without the GGBS. On the other hand, some retardation of the compressive strength was observed in the 45% GGBS replacement at the early age. At the later age of 91 days, all CWA mortars with the GGBS have the higher compressive strength than the CWA mortar without the GGBS.

(2) The carbonation depth increases along the exposure time. Furthermore, the carbonation depth of mortar containing the GGBS replacement increases with the replacement level of the GGBS. The carbonation speed factors at 96 weeks exposure have linear relationship with the GGBS replacement level.

(3) The GGBS significantly decreased the penetration depth of chloride ion in the CWA mortar. In contrast, the surface chloride concentration in the CWA mortar containing the GGBS increased when compared with the CWA mortar without the GGBS. The changing of the apparent chloride diffusion coefficients of mortars containing the GGBS is relatively small along the immersion time. Consequently, the chloride resistance of the CWA mortar is more effective with increasing the GGBS replacement up to 45% tested in this study.

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