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Application of Electric Arc Furnace Oxidizing Slag for Environmental Load Reduction†

SANG-WOO KIM[1], YONG-JUN LEE[1], JUNG-YOON LEE[2] and KIL-HEE KIM[1,*]

[1]Department of Architectural Engineering, Kongju National University, Cheonan, Republic of Korea
[2]Department of Civil, Architectural and Environmental System Engineering, Sungkyunkwan University, Suwon, Republic of Korea

*Corresponding author: Fax: +82 41 5210310; Tel: +82 41 5219335; E-mail: kimkh@kongju.ac.kr

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This paper presents the applicability of electric arc furnace (EAF) oxidizing slag in construction to reduce the environmental load. This study illustrates the properties and characteristics of EAF oxidizing slag as well as explains the advantages obtained from using EAF oxidizing slag as an aggregate for structural concrete. Furthermore, in order to expand the recyclable range of EAF oxidizing slag aggregates, its applicability to concrete for prestressed high-strength concrete (PHC) piles was experimentally estimated. The experimental results show that applying EAF oxidizing slag aggregates to PHC piles enhances the compressive strength, saves energy, lowers carbon dioxide emissions, reduces the amount of cement used and helps to cut costs.

Keywords: Electric arc furnace oxidizing slag, Slag aggregate, Concrete, Pile.

INTRODUCTION

It is not an over statement to say that climate change is an issue that the world is most concerned with today. Global warming, one of the most noticeable manifestations, is found to have been mainly caused by an increase in carbon dioxide emissions resulting from rapid industrial developments. Since the 1997 signing of the Kyoto Protocol, many countries around the world have exerted their efforts to reduce carbon dioxide emissions and protect the environment.

In the field of construction, many studies have focused on curbing carbon dioxide emissions across all stages from material production to waste processing. Concrete, the most widespread material in construction field, is comprised of cement, which has to be heated to at least 1,450 ºC. As such, approximately 900 kg of carbon dioxide is released for each ton of cement products. Common methods that allow less use of cement include (1) using mineral admixtures as a substitute and (2) reducing the unit weight of cement in the mix design.

Some examples of mineral admixtures, used in place of cement, are granulated blast furnace slag and fly ash. In particular, blast furnace slag offers the advantage of being able to replace large amounts of cement due to its latent hydraulicity. Slag, an industrial by-product of steel and iron smelting operations, must be recycled because it has increased proportionately with the development of the steel industry[1,2].

Currently, the types of slag being recycled in construction include blast furnace slag and electric arc furnace (EAF) slag. While blast furnace slag is used in cement and other high value-added purposes, EAF slag is limited to low value-added purposes like roadbed ash because of its unstable expandability. Electric arc furnace oxidizing slag, which has no risk of expanding, has been secured with recent developments in steel manufacturing and can be recycled in diverse ways.

Because EAF oxidizing slag has a high specific gravity, it can produce heavy weight concrete if used as an aggregate for structural concrete. Since most heavy weight aggregates are obtained through quarrying, substitute aggregates must be developed for environmental preservation and protection. From this point of view, the use of EAF oxidizing slag as aggregates holds great significance[3,4].

According to recent studies[5-8], the use of EAF oxidizing slag as aggregates for structural concrete not only protects the environment, but also reduce costs by reducing cement. This paper examines EAF oxidizing slag as aggregates contributing to environmental load reduction and studies its applicability to a new construction filed, such as prestressed high-strength concrete piles.

Properties and application technology of EAF oxidizing slag aggregates

Properties of EAF oxidizing slag aggregates: Due to its volume stability, blast furnace slag has been extensively

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studied[9] among the many types of steel slag. It is widely used for high value-added purposes including concrete aggregates and raw material for cement products[10]. Converter slag and EAF slag, despite being recyclable, tend to become unstable with the expansion of free-CaO and free-MgO found in slag and are thus used as roadbed material and filling[11-14].

Among EAF slag, reducing slag cannot be used as concrete aggregates because of its high free-CaO and free-MgO content, which causes the concrete to expand and collapse. Free-CaO is an unstable component generated when lime is used to refine steel scraps. As shown in Fig. 1, free-CaO reacts with water to form calcium hydroxide, resulting in an expansion that almost doubles the volume. If this reaction occurs within concrete, the material will undergo cracking and pop-out. While EAF reducing slag is inadequate as concrete aggregates, EAF oxidizing slag can be used as it has a lower free-CaO and free-MgO content.

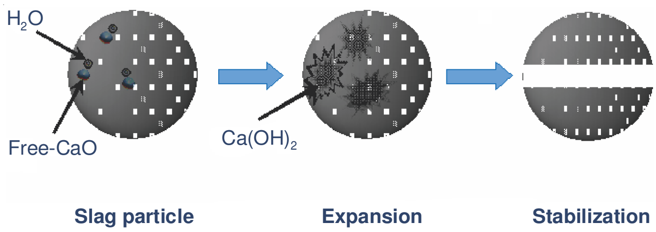

Fig. 1. Expansion mechanism of free-CaO

A CaO/SiO_2 ratio is the most import item to determine the quality of EAF oxidizing slag aggregates because higher CaO/SiO_2 ratio means higher free-CaO content. Due to this reason, the specifications[15,16] recommend that a CaO/SiO_2 ratio of EAF oxidizing slag aggregates should be equal to 2.0 or less to obtain no danger of collapse by expansion, as seen in Fig. 2. Table-1 shows chemical composition of EAF oxidizing slag aggregates used in this study. From Table-1, it can be found that the EAF oxidizing slag aggregates has a CaO/SiO_2 ratio of 1.51.

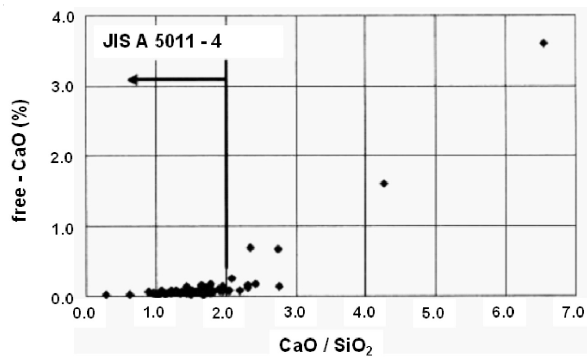

Fig. 2. Free-CaO *versus* CaO/SiO_2 relationships [Ref. 15]

TABLE-1
CHEMICAL COMPOSITION OF ELECTRIC ARC FURNACE OXIDIZING SLAG (UNIT: %)

Classification	CaO	Fe_2O_3	SiO_2	Al_2O_3	MnO	MgO
Component ratio	26.7	21.2	17.7	12.2	7.9	5.3

The EAF oxidizing slag aggregate consists of CaO and SiO_2 similar to natural rocks and has alkaline properties such as cement products[17]. In general, the specific gravity of EAF oxidizing slag aggregate is 1.5 times higher than that of natural aggregates used in normal-weight concrete. Therefore, the EAF oxidizing slag aggregate can be used to underground structures, dams, retaining wall and nuclear power plant, *etc*.

Strength development of concrete with EAF oxidizing slag aggregates: Recent studies[6,7,18] reported an increase in the compressive strength of concrete if EAF oxidizing slag aggregates are used for structural concrete, assuming that the water-cement ratio remains the same. Table-2 presents the mix design of structural concrete tested by Ryu[18] to estimate the physical properties of concrete according to replacement ratio of EAF oxidizing slag aggregate.

In order to estimate the physical properties of concrete according to the type of aggregates, the water-binder ratio and fine aggregate ratio was remained the same as 50 and 48 %, respectively. In Table-2, Base denotes a specimen with natural aggregates; ESEG50 and ESEG100 denote the specimens with EAF oxidizing slag aggregates of 50 and 100 %, respectively.

The strength enhancement of concrete according to replacement ratio of EAF oxidizing slag aggregate is shown in Fig. 3. The compressive strength of concrete with EAF oxidizing slag aggregates was higher than that of concrete with natural aggregates. Furthermore, this tendency was remarkable as the replacement ratio increased. The compressive strength of concrete increased up to 1.5 times.

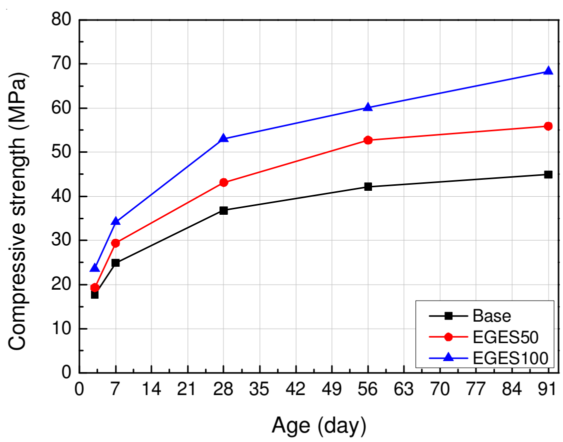

Fig. 3. Strength enhancement of concrete with EAF oxidizing slag aggregates

TABLE-2
MIX DESIGN OF STRUCTURAL CONCRETE

Specimens	W/B (%)	S/a (%)	Unit weight (kg/m^3)							
			W	C	Natural		EAF slag		FA[a]	AD[b]
					S	G	S	G		
Base	50.0	48.0	175	297	829	909	–	–	53	2.45
EGES50					414	455	603	656		
EGES100					–	–	1206	1312		

[a]Fly ash, [b]Water reducing admixture.

From this test result, it is noted that a higher water-binder ratio is needed to obtain the same compressive strength when EAF oxidizing slag aggregates are used in the structural concrete. A higher water binder ratio implies a decrease in the amount of cement required to obtain the same compressive strength. Thus, this is economical and even environmentally-friendly in terms of reduced carbon dioxide emissions.

EXPERIMENTAL

Applicability of PHC piles with EAF oxidizing slag aggregates: Concrete mix design for PHC piles is shown in Table-3. A small amount of anhydrite, 10 % of portland cement, was used in this study to obtain high early-age concrete strength by accelerating cement hydration. The coarse and fine EAF oxidizing slag aggregate had densities of 3.78 and 3.77 g/cm^3, respectively and absorption ratios of 0.7 and 0.2 %, respectively. As seen in Table-1, free-CaO content and CaO/SiO_2 ratio of EAF oxidizing slag aggregates were found to be 0.15 and 1.51 %, respectively. Therefore, the EAF oxidizing slag aggregates used in this test satisfied current code provisions[15,16].

The coarse natural aggregate had a density of 2.68 g/cm^3 and a absorption ratio of 0.7 %, whereas the fine natural aggregate had 2.53 g/cm^3 and 0.9 %. The maximum size of aggregates was 20 and 13 mm for EAF oxidizing slag aggregates and natural aggregates, respectively. Fig. 4 shows coarse and fine EAF oxidizing slag aggregates used in this test.

(a) Coarse aggregate (b) Fine aggregate

Fig. 4. View of EAF oxidizing slag aggregates

Specimens: Three specimens were prepared based on concrete mix proportions. Each specimen had a diameter of 200 mm, height of 300 mm and thickness of 40 mm in accordance with KS F 2454[19]. To satisfy the target thickness, this study used centrifugal casting method having three different stages, that is, low-, medium- and high-speed, as shown in Table-4. The speed for each stage was designed to be the average of the minimum and maximum values.

The results of centrifugal casting are given in Fig. 5. The target thickness of specimens was 40 mm and the average thickness of specimens with natural aggregates was found to be 42.7 mm. Slight discrepancies were observed for P-CS and P-AS specimens, measuring 38.3 and 35.8 mm, respectively. The specimens appeared satisfactory and were of an acceptable quality although some protruding coarse aggregates could be seen.

(a) P-AN (b) P-CS (c) P-AS

Fig. 5. Specimens after centrifugal casting

After centrifugal casting, the specimens were subjected to 24 h steam curing to ensure the same conditions as that of producing PHC piles. The steam curing process was followed by air curing. Piles usually undergo steam curing and autoclave curing to obtain required quality, but this experiment assessed the quality of pile specimens after the first steam curing without autoclave curing.

RESULTS AND DISCUSSION

The specimens were tested in compression at 3 days of curing. Fig. 6 shows the test set-up of a typical specimen. An axial load was applied to specimens using universal testing machine (UTM) having a load capacity of 5,000 kN. The average compressive strengths of specimens were found to be 58.4, 71.2 and 98.5 MPa for P-AN, P-CS and P-AS specimens, respectively. That is, the compressive strengths of P-CS and P-AS were 1.2-1.7 times higher than that of P-AN. It can be found from experimental results that the pile specimens with EAF oxidizing slag aggregates have superior strength enhancement capacity.

TABLE-3
MIX DESIGN OF CONCRETE FOR PHC PILES

Specimens	W/B (%)	S/a (%)	Unit weight (kg/m^3)							
			W	C	Natural		EAF slag		AG[a]	AD
					S	G	S	G		
P-AN					670	1078	–	–		
P-CS	20.0	38.5	114.8	517	670	–	–	1562	57	11.5
P-AS					–	–	975	1562		

[a]Anhydrous gypsum.

TABLE-4
CENTRIFUGAL CASTING

Diameter (mm)		Low speed		Medium speed		High speed	
		Centrifugal force (f)	Time (min)	Centrifugal force (f)	Time (min)	Centrifugal force (f)	Time (min)
Min.	Below 350	3	1	7	1	25	3
Max.	Below 350	9	5	20	5	60	10
Mean	Below 350	6	3	14	3	43	6.5

Fig. 6. Test setup of a typical specimen

As described earlier, the specific gravity of EAF oxidizing slag aggregates is 1.5 times higher than that of natural aggregates. The segregation of concrete is extremely important because materials with higher specific gravities get placed on the outer sides during centrifugal casting of PHC piles. As can be seen from the failed typical specimen in Fig. 7, all specimens do not have any segregation. Furthermore, the 2-3 mm sludge layer of specimens was highly satisfactory.

Fig. 7. P-CS specimen after failure

The experimental results verified that strength enhancement is remarkable when EAF oxidizing slag aggregates are used for PHC pile specimens. As described earlier, the concrete with EAF oxidizing slag aggregates can be allowed a higher water-binder ratio than the natural aggregate concrete. This implies that less cement is required to produce concrete having the same strength. The reduction in cement is not only economical, but also environmentally desirable as it also reduces carbon dioxide emissions.

In general, PHC piles require a high compressive strength and they are thus subject to steam curing followed by autoclave curing. To create high temperature and pressure conditions, autoclave curing involves a great deal of energy, which then leads to significant carbon dioxide emissions. As discussed, autoclave curing is unnecessary for piles with EAF oxidizing slag aggregates because they exhibit outstanding early-age concrete strength compare to piles with natural aggregates. The application of EAF oxidizing slag aggregates to PHC piles can offer many advantages such as energy savings, less costs and lower carbon dioxide emissions.

Conclusion

This study introduced several methods of using EAF oxidizing slag in construction and experimentally estimated its applicability to concrete for PHC piles. The experiments showed that PHC piles had a higher compressive strength when EAF oxidizing slag was used as aggregates for the concrete. Since less cement is needed to obtain the same compressive strength, the use of EAF oxidizing slag aggregates is economical and is expected to reduce carbon dioxide emissions. When applied to PHC piles, sufficient strength development was seen even without autoclave curing, indicating a further decrease in energy and carbon dioxide emissions. More studies are needed to maximize the diverse applications of EAF oxidizing slag in construction.

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