Flexural Behavior of Reinforced Concrete Beams with Electric Arc Furnace Slag Aggregates

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Abstract
This study estimates the flexural performance of reinforced concrete (RC) beams with electric arc furnace (EAF) oxidizing slag aggregates. EAF oxidizing slag is a byproduct of steel production. It is composed mainly of CaO and SiO₂, which are similar to the chemical properties of natural aggregates. Simply supported RC beams having various types of aggregates were tested to evaluate the applicability of EAF oxidizing slag as a concrete aggregate. The moment-curvature relationship and crack patterns up to peak load as well as the effective moment of inertia and deflection of the specimens under service load were analyzed and compared with the experimental results of natural aggregate specimens. The experimental results showed that the specimens with EAF oxidizing slag aggregates exhibited similar flexural performance to that of the specimens with natural aggregates.

Keywords: flexural behavior; bending moment; reinforced concrete beams; electric arc furnace slag aggregate

1. Introduction
The growth of the steel industry has been progressing steadily as civilization progresses. The steel industry has also generated innumerable varieties of byproducts and waste with the mass consumption of energy and raw materials. In particular, the amount of slag, the most dominant byproduct of steel and iron smelting operations, is increasing each year, thus heightening the need for devising effective recycling methods.¹,²

Electric arc furnace (EAF) slag occurs in the process of refining scrap steel. It can be categorized into oxidizing slag, which results from oxidation refining, and reducing slag, which results from reducing.³⁴ Reducing slag is rarely used as a concrete aggregate because its high free-CaO and free-MgO contents make the concrete vulnerable to collapse by expansion, whereas oxidizing slag can eliminate the risk of expansion collapse by restricting the CaO/SiO₂ ratio to 2.0 or less. Furthermore, the EAF slag has high applicability as a concrete aggregate as it consists mainly of CaO and SiO₂ similar to natural rocks and minerals. Recently, Korean and Japanese industrial standards for the use of EAF oxidizing slag aggregate have been established.³⁴

A review of related published research revealed that most studies¹,⁵⁻⁸ on EAF oxidizing slag aggregates mainly focused on their material properties to obtain the volumetric stability. An evaluation of the structural behavior of reinforced concrete (RC) members with EAF oxidizing slag aggregates should be conducted in order to use the EAF oxidizing slag aggregates for structural concrete. However, the structural performance of RC members with these aggregates is rarely reported in the literature.

This study carried out flexural tests on simply supported RC beams to estimate the flexural behavior of RC beams with EAF oxidizing slag aggregates, and the experimental results were compared with the flexural performance of RC beams with natural aggregates.

2. Experimental Program
2.1 Materials
For the natural aggregates, crushed stone with a maximum aggregate size of 25mm was used as the coarse aggregate and washed sand was used as the fine aggregate. The EAF oxidizing slag aggregates used in this study had a free-CaO content of 0.15% and a CaO/SiO₂ ratio of 1.51, which provided no danger of expansion collapse.³ The EAF oxidizing slag aggregates also satisfied the industrial criteria for concrete aggregates.³⁴

The fine EAF oxidizing slag aggregate had a density of 3.77 g/cm³, a unit volume weight of 2.66kg/ℓ, and
an absorption ratio of 0.2%. The coarse EAF oxidizing slag aggregate, with a maximum aggregate size of 20mm, had a density of 3.78 g/cm$^3$, a unit volume weight of 2.20kg/ℓ, and an absorption ratio of 0.7%.

Table 1. shows the concrete mixture proportions used in this study. Previous research$^9$ showed that the compressive strength of the concrete with EAF oxidizing slag aggregates was higher than that of the concrete with natural aggregates, in spite of having the same W/C ratio. In this study, the W/C ratio of the concrete with EAF oxidizing slag aggregates was somewhat higher than that of the concrete with natural aggregates in order to obtain the similar compressive strength of the concrete. However, the maximum difference of the W/C ratio was only 3.6% in this test.

Cylindrical specimens with a diameter of 100mm and height of 200mm were cast along with the beam casting to obtain the physical properties of the concrete. The mechanical properties of the concrete during the flexural test were measured and the results are provided in Fig.1. and Table 2. The modulus of elasticity of the concrete with EAF oxidizing slag aggregates was higher than that of the concrete with natural aggregates, as shown in Table 2. This tendency was also observed in the previous research$^9$. The stiffness and effective moment of inertia of specimens with EAF oxidizing slag aggregates can be predicted to be higher than those of specimens with natural aggregates.

Deformed steel bars of D22 ($A_s=387.1$mm$^2$), D19 ($A_s=286.7$mm$^2$), and D10 ($A_s= 71.3$mm$^2$) were used as the tension, compression, and shear reinforcements, respectively. The yield and tensile strengths of steel bars used in this test are illustrated in Table 2.

2.2 Specimen details and test setup

As shown in Table 2., four specimens were designed to compare flexural performance according to aggregate types. F-AN indicates the specimen having natural aggregates only; and F-AS indicates the specimen containing EAF oxidizing slag aggregates only. F-CS and F-FS indicate the specimens with coarse and fine EAF oxidizing slag aggregates, respectively.

The details and test setup of the specimens are illustrated in Figs.2. and 3. Each simply supported specimen is 3,400mm in length with a cross section of 200×350mm. The clear span and the shear span-to-depth ratio of specimens were designed to be 2,900mm and 4.0, respectively. The distance between the two loading points of the specimens is 500mm. The tensile reinforcement ratio of 0.0129 and the 150mm intervals between shear steel bars were designed to induce the flexural tension failure of the specimens.

![Fig.1. Stress Versus Strain Relationships of Concrete](JAABE1104033BS.R1)

![Fig.2. Details of Specimen](250250)

![Fig.3. Test Setup of Specimen](Load cell LVDT Loading frame Strain gauge (concrete) UTM Load cell LVDT Loading frame Strain gauge (concrete) UTM)

![Table 1. Concrete Mixture Proportions](Specimens Design strength (MPa) W/C (%) S/a (%) Unit weight (kg/m$^3$) Air (%) E$\text{c}$ (GPa) Tension reinforcement (2-D22) Comp. reinforcement (2-D19) Shear reinforcement (D10@150mm))

| Specimens | Aggregate types | f$\text{c}$ (MPa) | $E\text{c}$ (GPa) | $f_y$ | $f_y$ | $f_{ys}$ | $f_{ys}$ | $f_{ys}$ | $f_{ys}$ | $f_{ys}$ |
|-----------|----------------|----------------|----------------|-------|-------|---------|---------|---------|---------|---------|
| F-AN      | Natural        | 31.7           | 23.6           | 430.1 | 632.0 | 478.9   | 603.1   | 453.1   | 534.7   |
| F-AS      | Slag           | 24.5           | 29.7           | 464.1 | 567.2 | 528.9   | 604.0   | 461.8   | 570.4   |
| F-CS      | Natural        | 31.6           | 28.4           | 430.1 | 632.0 | 478.9   | 603.1   | 453.1   | 534.7   |
| F-FS      | Slag           | 31.6           | 27.0           | 430.1 | 632.0 | 478.9   | 603.1   | 453.1   | 534.7   |

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![Table 2. Properties of Specimens](Specimens Aggregate types f$\text{c}$ (MPa) $E\text{c}$ (GPa) Tension reinforcement (2-D22) Comp. reinforcement (2-D19) Shear reinforcement (D10@150mm))

134 JAABE vol.11 no.1 May 2012 Sang-Woo Kim
As shown in Fig.2., strain gauges with a length of 5mm were attached to the longitudinal and shear reinforcements to obtain the stress and strain of the steel bars. At the midspan of the specimens, strain gauges with a length of 60mm were installed at points with distances of 0, 20 and 40mm from the top of the specimen to track the neutral axis and the moment versus curvature relationship of the specimen (Fig.3.). The deflection of the specimen was measured using two LVDTs installed at the midspan of the specimen, as shown in Fig.3.

3. Experimental Results

3.1 Load versus deflection relationships

Fig.4. shows the experimentally obtained load versus deflection relationships of the specimens. It can be seen that the specimens exhibited not only similar first yield of the tension reinforcement but also ductile flexural behavior after the tension steel yielding, regardless of aggregate types. In all cases, flexural cracking at the center of the specimen occurred first, and then additional cracks spread toward the supports. The specimens exhibited typical flexural failure, in which final failure was caused by the concrete crushing of the compression zone of the specimen after the tension steel yielding. The flexural cracks propagated toward the loading points as the load was increased, with the crack width growing significantly.

As shown in Fig.4., the stiffness of specimen F-AS was similar to that of specimen F-AN, in spite of the different compressive strength of the concrete. This is due to the fact that the modulus of elasticity of the specimen with EAF oxidizing slag aggregates was higher than that of the specimen with natural aggregates, as described in Section 2.1.

As seen in Fig.4., the extreme fiber compression strain of concrete reached 0.003 when midspan deflection was 25.2mm, 28.6mm, and 24.3mm for specimens F-AN, CS, and FS, respectively. The extreme fiber compression strain of F-AS reached 0.003 at a midspan deflection of 18.9mm due to the comparatively lower compressive strength of the concrete. When the midspan deflection of all specimens reached approximately 30mm, concrete crushing began at the compression zone between the loading points. While the test was terminated at a midspan deflection of 80mm due to excessive flexural deformation, it can be seen from Fig.4. that the overall behavior of the specimens with EAF oxidizing slag aggregates was very similar to that of specimen F-AN.

The relationship between the number of cracks and the applied moment is illustrated in Fig.7. In this case, only flexural cracks that generated from the bottom of the specimens were counted. As the moment increased, the number of flexural cracks in each specimen also increased.

In the early part of the applied moment, the specimens containing EAF oxidizing slag aggregates for the four principal cracks of specimen F-AN, as shown in Fig.5.(a). The width of cracks No. 1 and 4 increased by more than 5mm, whereas the remaining two cracks maintained a width of 2mm or less.

The growth mechanisms of the four representative cracks of specimen F-AS, which contained only EAF oxidizing slag aggregates, are illustrated in Fig.6.(b). Similarly to F-AN, the crack width grew gradually along with the increase of moment, and then began to grow remarkably after the tension steel yielding. As can be seen in Fig.6.(b), the four cracks developed continually up to approximately 6mm and 4mm widths until loading was terminated. As shown in Figs.6.(c) and (d), the growth of the crack width of specimens F-CS and F-FS was also similar to that of specimen F-AN.

The crack patterns of tested specimens after failure are shown in Fig.5. The moment versus crack width relationships of specimens are presented in Fig.6. In all cases, the crack width grew gradually as the moment increased. In particular, the cracks opened considerably after the tension reinforcements yielded. Fig.6.(a) indicates the moment versus crack width relationships

![Fig.4. Load Versus Displacement Relationships of Specimens](image)

![Fig.5. Crack Patterns of Specimens After Failure](image)
Fig. 6. Moment Versus Crack Width Relationships

Fig. 7. Number of Cracks Versus Moment Relationships

Fig. 8. Moment Versus Curvature Relationships

Table 3. Comparison between Analytical and Experimental Results for Flexural Strength of Tested Specimens

| Specimens | Experimental results | Analytical results | Exp./Ana. |
|-----------|----------------------|--------------------|-----------|
|           | $M_{cr}$ $M_e$ $M_{cr}$ $M_e$ $M_{cr}$ $M_e$ $M_{cr}$ $M_e$ | $\frac{M_{cr}}{M_e}$ | $\frac{M_{cr}}{M_e}$ | $\frac{M_{cr}}{M_e}$ | $\frac{M_{cr}}{M_e}$ | $\frac{M_{cr}}{M_e}$ | $\frac{M_{cr}}{M_e}$ |
| F-AN      | 14.7  89.5  95.4  14.5  87.5  90.0  1.01  1.02  1.06 |                |            |            |                |            |            |
| F-AS      | 13.1  84.3  88.1  12.4  94.1  93.0  1.06  0.90  0.95 |                |            |            |                |            |            |
| F-CS      | 15.3  89.2  91.5  14.5  88.4  90.0  1.06  1.01  1.02 |                |            |            |                |            |            |
| F-FS      | 16.4  90.4  94.0  14.5  87.9  90.0  1.13  1.03  1.04 |                |            |            |                |            |            |

Mean 1.06 0.99 1.02
COV 4.6% 6.3% 4.9%

Specimens with EAF oxidizing slag aggregates. The number of cracks of all specimens increased up to the yield of the tension steel, and then no changes were observed. The number of cracks in each specimen after tension steel yielding did not vary significantly, the difference remaining within 30%.

4. Discussion of Experimental Results
4.1 Moment versus curvature relationships

The experimental and analytical results for the moment versus curvature relationship of each specimen are shown in Fig. 8. and Table 3. The cracking moment, $M_{cr}$, was calculated using the following equation:

$$ M_{cr} = \frac{f_r I_c}{y_i} $$

where $f_r$ is the modulus of rupture, taken as 0.63 MPa, $I_c$ is the moment of inertia of the gross concrete section neglecting reinforcement, and $y_i$ is the distance from the centroid axis of the cross section.
section neglecting reinforcement to the extreme fiber in tension.

In the analytical results, flexural strength and curvature at first yield of the tension reinforcement and the ultimate state of the specimen were calculated using the traditional analytical method based on the equilibrium and compatibility conditions. The compressive stress distribution of concrete is assumed to be triangular and rectangular at first yield and ultimate state of the specimens, respectively. The experimentally measured curvature was obtained from the strain gauges attached to the tension reinforcement and the extreme fiber in compression of the specimen.

As seen in Fig. 8., the analytical results for the moment versus curvature relationship coincide closely with the experimental results. Furthermore, as illustrated in Table 3., the moments at cracking, first yield, and ultimate state calculated using conventional analytical methods agreed well with the experimental results, with a mean of 1.06, 0.99, and 1.02, respectively, and a coefficient of variation (COV) of approximately 5%.

4.2 Effective moment of inertia and deflection

The ACI 318-08 code recommends the following effective moment of inertia, \( I_e \) proposed by Branson to calculate the deflection of RC members under service load.

\[
I_e = \left( \frac{M_{cr}}{M_a} \right)^3 I_g + \left[ 1 - \left( \frac{M_{cr}}{M_a} \right)^3 \right] I_{cr}
\]  

(2)

where \( M_a \) is the maximum moment in member at stage deflection is computed and \( I_{cr} \) is the moment of inertia of the cracked section transformed to the concrete.

When a simply supported beam under four-point loading is subjected to bending moment \( M_a \), the theoretical deflection of the beam under service load can be calculated as follows based on the theory of elasticity:

\[
\Delta_e = \frac{M_a}{24E_c I_e} (3L^2 - 4a^2)
\]

(3)

where \( a \) is the shear span, \( L \) is the clear span measured center to center of the supports, and \( E_c \) is the elastic modulus of the concrete. This study used the experimentally obtained elastic modulus of the concrete, as listed in Table 2.

Similar to Eq. (3), the moment of inertia of the specimen measured from the experiment at loading stage \( M_a \) can be derived as follows:

\[
I_{exp} = \frac{M_a}{24E_c \Delta_{exp}} (3L^2 - 4a^2)
\]

(4)

where \( \Delta_{exp} \) is the deflection measured by the LVDTs installed under the midspan of the specimen.

The analytical and experimental results of the effective moment of inertia of the specimens under service load are given in Fig. 9. and Table 4. As seen in Fig. 9., all specimens showed a similar effective moment of inertia. In particular, the difference of the effective moment of inertia between F-AS and F-AN was small, in spite of the low compressive strength of the concrete of F-AS. This is due to the fact that the modulus of elasticity of F-AS was greater than that of F-AN, as described in Section 2.1.

As shown in Fig. 9. and Table 4., the effective moment of inertia changed rapidly when the ratio of \( M_a/M_e \) varied from 1 to 3, but remained nearly constant from approximately 4. This tendency was similarly observed in both analytical and experimental results, as seen in Fig. 9. Furthermore, it can be seen that the predicted behavior was shown to be in reasonable agreement with the experimental response.

As seen in Table 4., the analytical results of the effective moment of inertia and deflection coincided relatively well with the experimental results, with a mean of 0.83 and 1.20 respectively, and a COV of 5.8% and 6.1%, respectively. In particular, predicted results for the effective moment of inertia and the deflection of the specimens with EAF oxidizing slag aggregates, F-AS, F-CS, and F-FS, were shown to be in successful agreement with the experimental results with an average of 0.85 and 1.17 respectively, and a COV of 4.3%.

5. Conclusions

The flexural performance of RC beams with EAF oxidizing slag aggregates was examined to evaluate the applicability of EAF oxidizing slag aggregates to RC members. Based on this study, the following conclusions can be drawn:

(1) Specimens with EAF oxidizing slag aggregates exhibited flexural strength similar to the specimen with natural aggregates. It was also confirmed that the experimentally obtained flexural strength of the specimens having EAF oxidizing slag aggregates satisfied the structural requirements proposed by the ACI 318-08 code.

(2) When the moments at cracking, first yield of the tension reinforcement, and ultimate state of specimens with EAF oxidizing slag aggregates were
Table 4. Comparison between Analytical and Experimental Results for Effective Moment of Inertia and Deflection Under Service Load

| Specimens | $M_c$ (kN·m) | $M_e$ | Experimental results | Analytical results | Exp./Ana. |
|-----------|---------------|-------|----------------------|-------------------|-----------|
|           | $\frac{M_e}{M_c}$ | $I_{exp.}$ ($10^6$ mm$^4$) | $\Delta_{exp.}$ (mm) | $I_{ana.}$ ($10^6$ mm$^4$) | $\Delta_{ana.}$ (mm) | $\frac{\Delta_{exp.}}{\Delta_{ana.}}$ |
| F-AN      | 1.3           | 352.8 | 1.90                | 493.2             | 1.36      | 0.72      | 1.40 |
|           | 2.0           | 306.5 | 3.32                | 383.5             | 2.65      | 0.80      | 1.25 |
|           | 2.7           | 289.2 | 4.73                | 357.6             | 3.83      | 0.81      | 1.24 |
|           | 3.5           | 276.1 | 6.35                | 348.1             | 5.04      | 0.79      | 1.26 |
|           | 4.2           | 267.1 | 7.89                | 344.5             | 6.12      | 0.78      | 1.29 |
| F-AS      | 1.3           | 396.9 | 1.17                | 461.1             | 1.01      | 0.85      | 1.17 |
|           | 2.0           | 297.7 | 2.34                | 336.7             | 2.07      | 0.88      | 1.13 |
|           | 2.7           | 250.6 | 3.75                | 304.8             | 3.08      | 0.82      | 1.22 |
|           | 3.5           | 239.3 | 5.16                | 292.6             | 4.22      | 0.82      | 1.22 |
|           | 4.2           | 225.6 | 6.55                | 288.5             | 5.12      | 0.78      | 1.28 |
| F-CS      | 1.3           | 400.8 | 1.34                | 485.0             | 1.11      | 0.83      | 1.21 |
|           | 2.0           | 309.8 | 2.72                | 342.8             | 2.46      | 0.90      | 1.11 |
|           | 2.7           | 280.7 | 4.04                | 313.6             | 3.62      | 0.90      | 1.12 |
|           | 3.5           | 253.5 | 5.78                | 302.6             | 4.84      | 0.84      | 1.19 |
|           | 4.2           | 245.8 | 7.05                | 298.9             | 5.80      | 0.82      | 1.22 |
| F-FS      | 1.3           | 412.6 | 1.42                | 472.2             | 1.24      | 0.87      | 1.14 |
|           | 2.0           | 317.7 | 2.79                | 353.4             | 2.51      | 0.90      | 1.11 |
|           | 2.7           | 287.4 | 4.15                | 325.0             | 3.67      | 0.88      | 1.13 |
|           | 3.5           | 271.5 | 5.60                | 314.8             | 4.83      | 0.86      | 1.16 |
|           | 4.2           | 259.0 | 7.10                | 310.6             | 5.92      | 0.83      | 1.20 |

| Mean | 0.83 | 1.20 |
| COV  | 5.8% | 6.1% |

calculated using the existing analytical methods used for the RC beams with natural aggregates, the resulting values agreed well with the experimental results. Furthermore, the calculated moment-curvature response using existing bending theory successfully traced the observed behavior. Based on the analytical and experimental results, therefore, it is concluded that the flexural performance of RC beams with EAF oxidizing slag aggregates can be reasonably predicted using the existing bending theory.

(3) The effective moment of inertia recommended by the ACI 318-08 code was successfully used to predict the deflection of the specimens containing EAF oxidizing slag aggregates under service load.

To apply the EAF oxidizing slag aggregates to the structural concrete, further research with various test variables (for example, tension reinforcement ratio, compressive strength of concrete, etc.) should be conducted on the flexural performance of RC members with EAF oxidizing slag aggregates.

Acknowledgments
This work was supported by the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0022977). In addition, this research was also financially supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (20114010203040) grant funded by the Korea government Ministry of Knowledge Economy.

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