Construction and Building Materials 162 (2018) 781–793

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Ductile capacity of reinforced concrete columns with electric arc furnace oxidizing slag aggregate

Jae-Man Lee [a], Yong-Jun Lee [b], You-Jin Jung [c], Jung-Han Park [d], Bum-Sik Lee [e], Kil-Hee Kim [b,*]

[a] Research & Development Institute, Lotte Engineering & Construction, 2nd Floor, Saerom Building, 3, Naruteo-ro 10-gil, Seocho-gu, Seoul 06527, Republic of Korea
[b] Department of Architectural Engineering, Kongju National University, 1223-24, Cheonandaero, Seobuk, Cheonan 31080, Republic of Korea
[c] Yeonwoo ENG Engineering, 811-6, Bangbae-dong, Seocho-gu, Seoul, Republic of Korea
[d] Science & Technology Policy Coordination Division, Ministry of Science, ICT and Future Planning, 47, Gwanmun-ro, Gwacheon 13809, Republic of Korea
[e] Korea Land & Housing Corporation, 99, Expo-ro 539-gil, Yuseong-gu, Daejeon, Republic of Korea

HIGHLIGHTS

- Effect of EAF oxidizing slag aggregates on the ductility of RC column was observed.
- Less concrete crushing was achieved at columns with EAF oxidizing slag aggregates.
- Lateral expansion was restrained in RC columns with EAF oxidizing slag aggregates.
- EAF oxidizing slag aggregate was effective for the prevention of fatal collapse.

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 6 November 2017
Accepted 6 December 2017

Keywords:
EAF oxidizing slag aggregates
Strong-column weak-girder
Crushing
Plastic hinge
Lateral expansion
Ductile capacity

ABSTRACT

This study investigated the structural characteristics of reinforced concrete column comprised of EAF (Electric Arc Furnace) oxidizing slag aggregates, which are less detrimental to the environment, because they are generated during the steel-making process and are considered a form of recycling. Six column specimens were prepared with the axial force ratio and the amount of EAF oxidizing slag aggregates as the variables. Static loading tests were performed to analyze the load versus strain relationship, failure mode, distribution of the axial and transverse strain, plastic hinge length, and energy dissipation capacity. The analysis showed that reinforced concrete columns made from EAF oxidizing slag aggregates had a superior ductile capacity after they reached their ultimate strength compared to those made from natural aggregates. The former also experienced significantly less crushing at the column ends up to the limit state. The use of EAF oxidizing slag aggregates in the columns delayed the initiation of plastic hinges at the column ends and enabled the plastic hinges to occur first in the beams, thereby effectively establishing a strong-column weak-beam mechanism (if the slag is used in the structural design).

1. Introduction

In recent years, the use of eco-friendly materials and the development of related techniques have gained much attention to reduce the amount of industrial waste and lower CO_2 emissions. Concrete, a key material in the construction industry, amounts to 6 billion tons in annual production [1]. Because 410 kg/m^3 of CO_2 is released for every 1 m^3 of concrete [2], the amount of CO_2 emissions caused by manufacturing concrete is about 1 billion tons. Recently, there has been research on utilizing steel slag as aggregates, a by-product of the steel industry, to prevent the depletion of natural aggregates and to establish a recycling system in construction [3,4]. Steel slag can be classified into blast furnace slag and steel making slag [5], and about 400 million tons are produced around the world [6].

Steel making slag can be divided into EAF slag and BOF (Basic Oxygen Furnace) slag. Japan has consistently conducted research on EAF slag, which is generated in large amounts; Japan has promoted the use of EAF oxidizing slag by enacting regulations on its use [7] in construction [8]. However, most academic research on EAF oxidizing slag has been limited to its material properties [9–19], and few case studies are available on the use of EAF oxidizing slag as material for building structures [20–25].

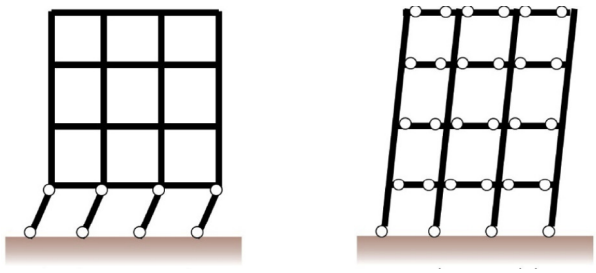
* Corresponding author.
E-mail addresses: masqurade2@gmail.com (J.-M. Lee), lyj8315@kongju.ac.kr (Y.-J. Lee), hayjoujin@kongju.ac.kr (Y.-J. Jung), jhanp@korea.kr (J.-H. Park), bslee417@lh.or.kr (B.-S. Lee), kimkh@kongju.ac.kr (K.-H. Kim).

https://doi.org/10.1016/j.conbuildmat.2017.12.045
0950-0618/

Notations

b	sectional width of concrete column
D	sectional depth of concrete column
E_c	modulus of elasticity of the concrete cylinders
f_{ck}	compressive strength of concrete
f_{ry}	yield strength of longitudinal reinforcement
f_{sy}	yield strength of transverse reinforcement
N	axial force applying the column
P_{peak}	lateral load at peak strength
P_u	lateral load at ultimate state corresponding to $0.85P_{peak}$
P_y	lateral load at yield of longitudinal reinforcement
Δ_{peak}	lateral displacement at peak strength
Δ_u	lateral displacement at ultimate state
Δ_y	lateral displacement at yielding of longitudinal reinforcement
η	axial force level ($=N/bdf_{ck}$)
ω	density of electric arc furnace oxidizing slag aggregate/-density of total aggregate in concrete.

To protect human life and property in buildings against earthquakes, etc., the fatal collapse of buildings must be avoided. It is thus necessary to design structures based on the strong-column and weak-beam mechanism. Structures with such a mechanism, as shown in Fig. 1, experience a plastic hinge in the beams before the columns during an inelastic behavior. According to research on the structural characteristics of concrete made from EAF oxidizing slag, improvements in the initial stiffness and ductility were observed in concrete made from EAF oxidizing slag compared to those made from the natural aggregates [25,26]. Additionally, the compressive strength of concrete that uses the EAF oxidizing slag aggregates increases by 20–40% compared to the compressive strength of the concrete using the natural aggregates [23,27]. It seems that if concrete made from EAF oxidizing slag aggregates remains stable without any crushing when subject to a large strain after yielding of a longitudinal reinforcement, the development of the plastic hinge can be delayed thus establishing the strong-column mechanism.



(a) Weak-column strong-beam (b) Strong-column weak-beam

Fig. 1. Two collapse mechanisms of building.

The ultimate purpose of this study was to analyze the structural characteristics of reinforced concrete columns made from EAF oxidizing slag aggregates to produce economical and eco-friendly structures based on the strong-column mechanism.

Building upon past research on the structural characteristics of concrete made from EAF oxidizing slag [26], this study performed static loading tests on six specimens with the amount of EAF oxidizing slag aggregates and the axial force ratio as the variables. The results of the analysis are presented for the load versus strain relationship, failure mode, ductile capacity, and distribution of the axial and transverse strain.

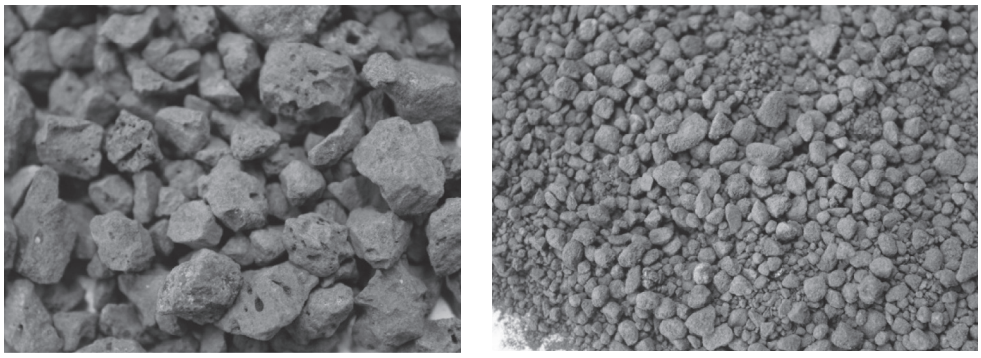
2. Significance of research

This research covers the structural performance of reinforced concrete columns with EAF oxidizing slag aggregates. As a result of using EAF oxidizing slag aggregates, the dilation and crushing of the concrete are delayed, and the energy dissipation capacity of the RC column is increased. This result implies that EAF oxidizing slag aggregates contribute to achieving the weak beam-strong column mechanism. Moreover, using EAF oxidizing slag aggregates can contribute to the establishment of a recycling system for structural materials in the construction industry. Therefore, this research considers the significant environmental impact of structural materials used in reinforced concrete structures.

3. Experimental program

3.1. Aggregates in concrete

EAF oxidizing slag aggregates (Fig. 2) have a CaO/SiO_2 ratio of 1.51 and contain 0.15% free-CaO. These values satisfy the code requirement of [8] and [28] ($CaO/SiO_2 \leq 2.0$, free-Cao $\leq 0.3\%$) for



(a) Coarse aggregate (b) Fine aggregate

Fig. 2. Electric arc furnace oxidizing slag aggregates.