sciendo

Civil and Environmental Engineering
Vol. 19, Issue 1, 108-118, DOI: 10.2478/cee-2023-0010

APPLICABILITY OF INDUCTION FURNACE STEEL SLAG IN RC COLUMNS SUBJECTED TO AXIAL AND UNIAXIAL LOADING

Zahraa H. ALI[1, *], Nibras N. KHALID[1]

[1] Civil Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.
[*] corresponding author: eama017@uomustansiriyah.edu.iq

Abstract

Carbon emissions and sand mining have generated massive environmental imbalances. Because of the impact of depleting resources, using slag in concrete is a viable alternative for minimizing environmental impact. The acceptability of using induction furnace steel slag as a partial replacement for aggregate and as an additive in concrete mixtures for columns was investigated. Ten 140 mm x 140 mm x 750 mm short columns subjected to axial and uniaxial loads were tested. The outcome demonstrates that using SS in general decreases displacement levels and increases load levels. The proposed steel slag as a 30 % sand replacement mixture is preferred over the others. All the suggested combinations showed decreases in the ductility ratio and energy absorption. Induction furnace steel slag can be used in concrete columns.

Keywords:

Concentric load;
Multiple mixes;
Eccentric load;
Fine aggregate replacement;
Reinforced concrete.

1 Introduction

Environmental regulations restrict the disposal and recycling of the industrial waste in several nations. Fly ash, rubber, glass, plastic, and many types of slag, including copper and steel slag, can all be reused to tackle this issue instead of consuming natural resources [1-3]. Steel slag (SS) is a by-product of steel production that can be made from steel scrap, iron, or both [3, 4]. Ladle furnaces, basic oxygen furnaces, induction furnaces, and electric arc furnaces are used to produce steel and steel slag [5, 6]. The concrete industry is one of the industries receiving this attention; its production process demands improvement to address global issues such as energy and environmental conservation[8]. Slag can be used in the production of concrete, either as blended cement or as a mixer addition [2, 8]. Steel slag can also be crushed and used in concrete as coarse and fine aggregate. Slag, in general, increases the compressive and tensile strength of concrete. Mechanical testing has revealed that slag aggregate has higher strength and ductility than the ordinary aggregate. Early tests on slag aggregate physical and mechanical properties, sturdiness, crushing value, shock strength, and structural stability revealed that it met standard [9, 10]. The SS fine aggregate can increase the cement matrix's hydration products, which density the matrix and decrease the microcracks. In addition, the SSA has a larger interface transition area than the natural aggregate. It can have an average hardness of 24.0 % higher than that of natural aggregate, while elastic modulus can be 67 % higher [11]. Concrete containing up to 50 % slag as fine particles can have 1.4 to 2.4 times the tensile strength and up to 1.3 times the compressive strength [2]. It has also been discovered that the compressive strength of SS concrete can be comparable to or lower than that of regular concrete. The activity of SS silicate phases is lower than that of cement silicate phases. As a result, extensive cement substitution with SS in concrete reduces its mechanical qualities and durability [12, 13].

Coarse SS aggregate can improve concrete mechanical characteristics, but low-quality slag can harm it. Large SS, due to its porous nature, can easily break and reduce the strength of concrete [14]. The slag quality affects concrete strength; therefore, it has been essential to consider various factors that affect slag quality, such as cooling methods and chemical composition.

The chemical composition of SS varies depending on the type of furnace, steel grade, and pre-treatment technique used Induction furnace steel slag (IFS) cannot be used in cement production due to its low CaO content. The substitution of river sand for IFS is an alternative procedure for its efficient utilization [6]. The main potential disadvantages of SS aggregate are its expansive qualities and unfavourable reactivity with slag and concrete components. Volume stability is a building criterion for employing SS as a construction material [9]. The expansion problem can be solved by stockpiling SS six months before use. Untreated SS can be used in unbound aggregate applications [15].

Kim et al. 2014 [16] investigated the flexural performance of reinforced concrete columns with EAF oxidising slag aggregate. The specimens were to be 250 × 250 mm in cross-section and 1,500 mm long in the test region. Columns were subjected to reversed cyclic antisymmetric moments and tested in flexure. Slag aggregates had a similar flexural strength as natural aggregates. Fine EAF oxidising slag aggregate improved the specimens' ductility. Yu et al .2016 [17] studied the axial compression of steel-tube (CFST) columns filled with concrete. Sixteen 177.5 × 540 × 3 mm circulars and seven 179× 540 × 4 mm thick squares were tested. The columns CFST utilizing SS exhibit similar initial stiffness, strength, and ductility as control limestone mix. Arumugam et al. 2020 [18] investigated the axial compressive behavior of composite columns with SS replacing fine aggregate in concrete-filled steel tubular columns with varied cross-sections. Slag replaced sand by weight in 10 % increments ranging from 0 % to 50 % of the sand wt. The result the optimal replacement amount of fine aggregate with SS is 30 %. The study found that adding SS to concrete increases its strength.

Because of their better qualities, slowly cooled slags are suitable for use as aggregate in concrete. The purpose of this treatment is to maintain volume while also achieving high density [2]. Rather than exploring the behaviour of RC columns, the literature has primarily concentrated on experimental investigations on small concrete specimens containing IFS slag. For these reasons, this experimental study aims to examine the structural performance of reinforced concrete columns containing IFS slag under axial and uniaxial load. The key variables were SS ratios and load eccentricities. Five columns were tested with concentric loading, and five columns were tested with eccentric loading. Steel slag (IFS) is used as a partial replacement for fine aggregate and as a cement additive. The specimens are compressed and tested using both pin-end conditions. The analysis findings are discussed in terms of ultimate load and displacement limits, ductility ratio, initial stiffness and energy absorption.

2 Experimental work program

2.1 Materials used

In this investigation, Ordinary Portland cement type I with a fineness of 4678 cm^2/g was used. Al-Rawad Technology Company for Steel and Iron provided large lumps of IFS slag. The slag was ground to a fine powder with a particle size range of 2.36-0.075 mm using a porcelain ball mill after being crushed by a jaw crusher. Fig. 1 shows steel slag. Table 1 show the chemical composition of cement and IFS slag. The fine aggregate was well-graded natural sand with a size of less than 4.75 mm, and the gravel with a 20 mm maximum size was utilised as the coarse aggregate.

Deformed steel bars Φ12 mm and Φ8 mm were utilized for longitudinal and transverse reinforcement. The yield and ultimate stress for longitudinal bars were 557 MPa and 705 MPa, respectively, and 517 MPa and 654 MPa for tied bars.

Superplasticizer (Sika Plast-400) was added to the mixture to reduce the proportion of water and enhance the workability of the concrete.

Table 1: Chemical properties of cement and IFS.

Oxides	Cement	IF slag
Loss on ignition	2.25	7.71
CaO	60.74	15.94
SiO_2	18.14	36.1
Al_2O_3	2.9	26.4
Fe_2O_3	6.71	8.35
MgO	1.28	4.43
SO_3	2.09	1.11

a) b)

Fig. 1: Induction furnace steel slag: a) raw slag, b) grinding slag.

2.2 Concrete mixing ratios

Four concrete mixes were used. The sample mixes all had the same W/C ratio. Trial mixes were created for the reference concrete mix's (regular concrete) compressive strength to be 30 MPa after 28 days. The cement dose and water/cement ratio in the mixtures are determined to be 465 kg/cm^3 and 0.36, respectively. Furthermore, a water-reducing additive in a 1 % cement weight ratio was applied. The concrete mixes were classified according to slag application: Normal concrete (N0), mixes with SS as an addition D1 to concrete in a ratio of 10 % cement weight, and two mixes with SS slag as fine aggregates within a ratio of 10 % F1 and 30 % F3 by sand weight. Table 2 and Fig. 2 summarizes the proportions of the concrete mixtures.

2.3 Specimen details

Tests were conducted using ten RC columns to determine the effect of SS on the column's behaviour under compressive loads. All column specimens have a 140 mm x 140 mm cross-section with heights of 750 from end plate to end plate. Short columns were designed to prevent secondary moments from forming due to the slenderness effect. Moreover, the relatively small height and cross-section of the RC columns were chosen due to the test instruments and apparatus that could be employed in the lab.

Deformed steel bars 4Φ12 mm and Φ8 @60 mm were utilized for longitudinal and transverse reinforcement. The space between the ties was reduced to 40 mm on both ends to prevent early failure, and longitudinal reinforcing bars were welded to the 140 x 140 x 8 mm steel endplates. The end plate facilitates specimen stabilization during testing and prevents end-local failure Fig. 3 shows the details.

Three symbols indicate each column. The first letter refers to the eccentricity series. The initials A and B refer to load eccentricities of 0, and 55 mm. The second symbol refers to concrete mixes. Normal concrete (N); sand replacement with SS (F); SS as an addition (D); and hybrid mixture (normal + slag 30 %) concrete (H). A third symbol is a number that refers to the SS ratio in specimens. (0) refers to a mix without slag; (1) refers to a 10 % SS ratio; and (3) refers to a 30 % SS ratio. While 03 denotes (Hybrid combination mix).

Hybrid column was used to determine the viability of using slag to strengthen a specific section of the column where failure is predicted to occur. The hybrid column's middle third was made of concrete that substituted 30 % of the sand with slag, which has the highest mechanical strength, and the upper and lower thirds were made of regular concrete, which had the lowest strength, as shown in Fig. 4.

For the same mixtures, a set of cylinders and prisms were cast and tested for compressive, tensile, and flexural strengths and the modulus of elasticity at 28 days. Table 2 displays the data.

Table 2: Proportions and mechanical properties of concrete mixtures.

Concrete type	N0	D1	F1	F3
Cement [kg/m^3]	465	465	465	465
Sand [kg/m^3]	705	705	634.5	493.5
Gravel [kg/m^3]	990	990	990	990
Steel slag [kg/m^3]	0	46.5	70.5	211.5
w/c ratio	0.36	0.36	0.36	0.36
Water [kg/m^3]	170	170	170	170
Super-plasticizer [kg/m^3]	4.65	4.65	4.65	4.65
fc' [MPa]	30.51	30.92	31.2	32.1
f_{sp} [MPa]	3.81	3.84	3.85	3.89
f_r [MPa]	3.37	3.39	3.41	3.45
Ec [MPa]	31981	35548	39855	47659

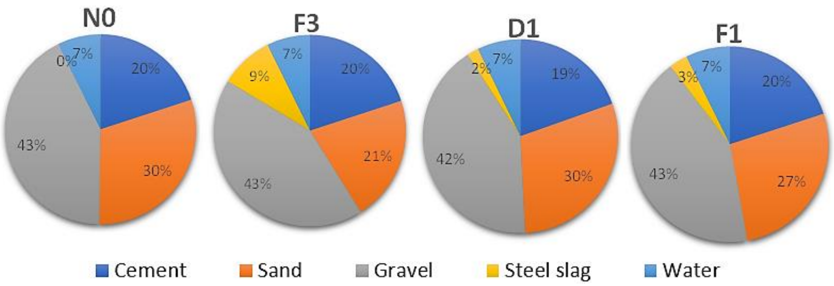

Fig. 2: Proportions of the concrete mixtures.

2.4 Column specimen installation

Before testing, the test sample's column surface was cleaned. The column specimen was positioned to ensure that it was vertical, with pin-ended conditions of support that served as pinned connections at the bottom and top for all column specimens.

Hydraulic actuator with a capacity of 3,000 kN was used to apply the load to the test column specimens. Columns were loaded in a predetermined condition using a grooving plate with a hump (half-cylinder) rebar show in Fig. 5. The hump was inserted into the plate's groove to transform the applied load into a strip load to give (e/h = 0 and e/h = 0.4) for both the upper and lower ends of the column.

One dial gauge was used at the column's mid-height to measure the axial displacement. Fig. 6 displays the specimen test setup.

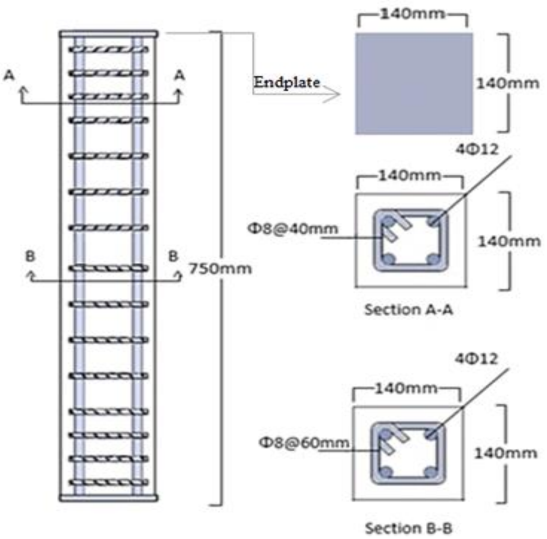

Fig. 3: Details of reinforcement.

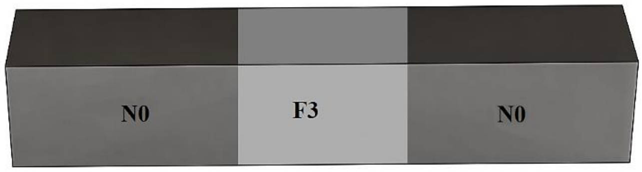

Fig. 4: Schematic of a hybrid column cast with two different mixes.

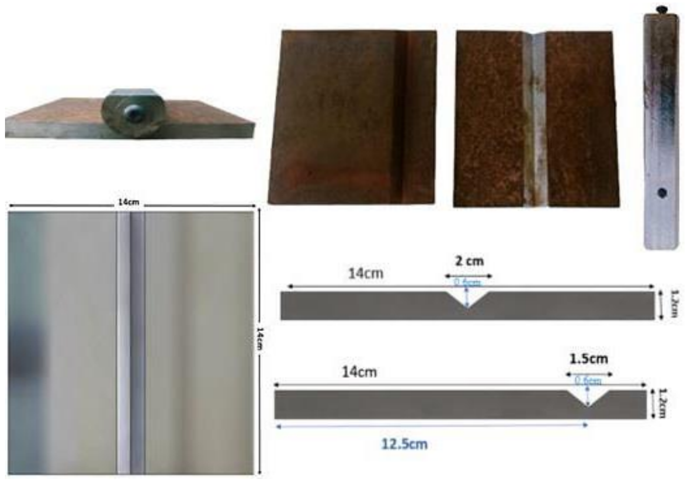

Fig. 5: Details of loading plate.

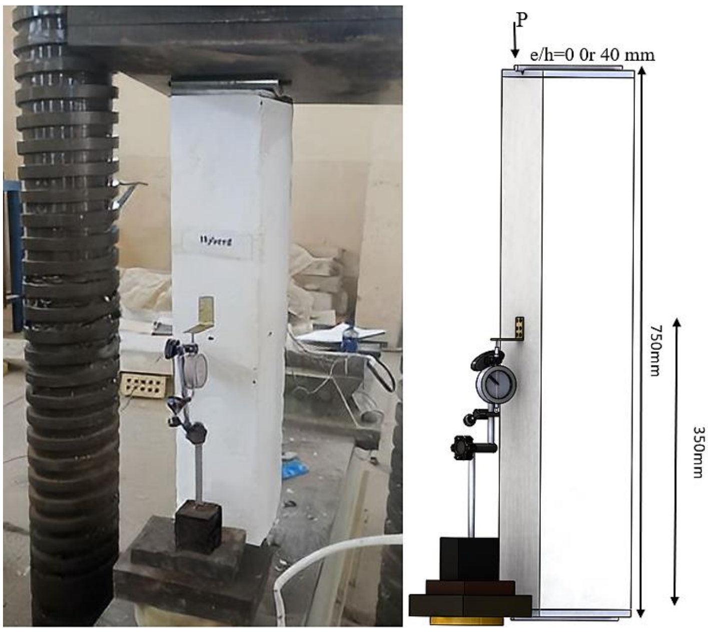

Fig. 6: Specimen test setup.

3 Results and discussions

Table 3 provide information about the initial stiffness, ductility ratio, maximum load, and displacement for all tested columns.

Table 3: Test results.

Specmen	*Py* [kN]	*Dy* [mm]	*Pu* [kN]	*Du* [mm]	∆*u*/∆*y*	*Py*/ ∆*y*
AN0	625.05	1.15	750	6.46	5.62	543.52
AF1	600.82	1.10	771	4.52	4.11	546.20
AF3	665.64	1.13	781	3.89	3.44	589.06
AD1	615.05	1.14	753	3.99	3.50	539.52
AH03	599.05	1.13	741	4.59	4.17	530.13
BN0	163	1.25	442.5	6.78	5.42	295.02
BF1	4.65	1.29	456	5.30	4.11	290.78
BF3	30.51	1.19	458.5	4.08	3.43	307.65
BD1	3.81	1.15	447	4.19	3.64	283.45
BH03	3.37	1.20	403.5	4.95	4.13	274.27

3.1 Ultimate load and axial displacement

Table 3 shows the ultimate load and ultimate axial displacement comparisons of specimens.

For eccentric loaded columns AF1, AF3, AD1 and AH03, the ultimate displacement decreased 30.03 %, 39.78 %, 38.24 % and 28.05 % respectively. Additionally, the ultimate load increased by 2.8 %, 4.13 % and 0.4 % For AF1, AF3 and AD1 respectively while such load decreased slightly by 1.23 % for AH03.

For eccentric loaded columns BF1, BF3, BD1 and BH03, the ultimate displacement decreased 29.94 %, 39.82 %, 38.20 % and 26.99 % respectively. In addition, the ultimate load increased by 3 %, 3.6 % and 1 % For BF1, BF3, BD1 respectively, while it was decreased by 8.8%. The consequent moment capacity decreased by 11.17 %, 2.99 %, 13.27 % and 8.79 % for BF1, BF3, BD1 and BH03.

In general, the displacement levels were decreased, and the load levels were increased. This refers clearly to the fact that all the proposed mixes can enhance the column behavior.

The order between the proposed specimens points a preeminence to the 30 % steel slag mix against others. This can be ascribed to the high mechanical strength of this mix.

The proposed mixes enhanced the columns behavior as reported and observed in the previous group since most of the specimens decreased the ultimate displacement and increased the related ultimate load. Turning again to Table 3, it is highly recognized that the order between the specimens is still the same with respect to ultimate load and deflection. It is argued that this behavior confirms the fact that the inherent mechanical strength (of the proposed mixes) governs the related ultimate load of the columns irrespective of the applied eccentricity. If each specimen is compared with the corresponding specimen of the first group, the effect of the applied eccentricity is obvious since the load was decreased and the deflection was increased. It is believed that further efforts should be devoted to investigate the degree of relation between mechanical strength parameters and the relevant ultimate load and ultimate axial- deflection level in column specimen. In addition, this improvement can be attributed to the paste's higher density and enhanced binding between the slag particles and the cement paste [19, 20]. Although induction furnace slag has low pozzolanic activity, it may contribute to increased concrete strength when utilised as a sand substitute. However, replacing equivalent quantities of fine aggregate with fine materials can also increase the strength of concrete [21].

The decrease in hybrid column strength could be attributed to insufficient intermixing and bonding between the two successive layers of concrete. This could also be due to insufficient consolidation due to density and workability differences between the two mixtures. The fluid nature of fresh concrete mixes cast into the same mould at nearly the same time may lead to hardened layers that deviate dramatically from the intended design [22]. Placing vertical columns of two different mixes next to one another can lead to instability [23].

Fig. 7 shows the load – axial displacement diagram of the columns with *e*/*h* = 0 within this group, it can be noticed that all the proposed mixes specimens illustrated low extension levels for plastic deformation than control concrete columns due to the strength gain in most of these mixes.

The load – deflection paths showed three phases, the first is liner which begins at the starting of test till about 45 % - 55 % times ultimate load. The second is non – linear till about 75 % - 85 % times ultimate load. The third phase is linear and begins after these levels till the ultimate load occurrence.

It can be seen from these curves that there are no clear inflection point that stated the beginning of plastic deflection.

Fig. 8 shows the load – axial displacement diagram of the columns with *e*/*h* = 0.4 within this group, it can be observed that all the proposed specimens. The gap between plastic deformation extensions is slightly lower than the preceding group. It is thought that this is a consequence to the applied eccentricity and the related stress distribution.

The load deflection paths don't show clear differences with respect to the previous group. However, the same three load deflection paths can be pointed within the load deflection response as shown. In addition, the limits between thus phases are relatively same as the second group and there are no clear points of inflection for plastic deformation starting as reported in the previous group.

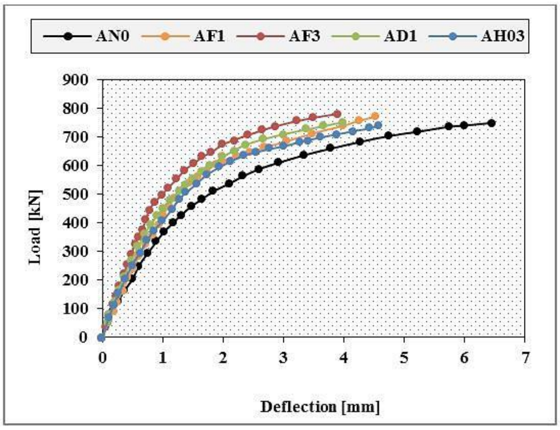

Fig. 7: Load - deflection curves for columns.

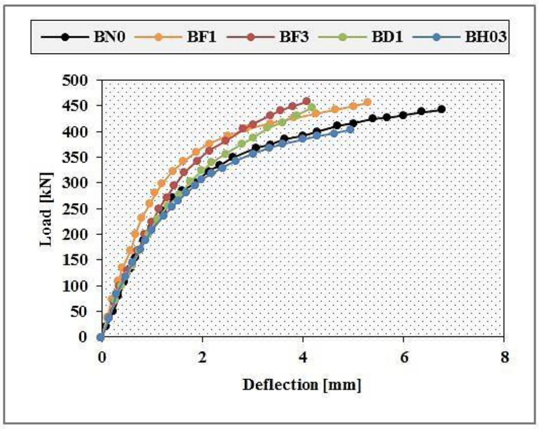

Fig. 8: Load - deflection curves for group two, *e*/*h* = 0.4.

3.2 Ductility ratio

Ductility ratio can be defined as the capability of any structural element to experience displacement after the yielding and before fracture (plastic deformation).The ductility behavior is characterized here by the approach of Azizinamini et al., (1999) [24] which defines the ductility ratio as

$$Ductility\ ratio = \frac{\textbf{\textit{Ultimate dispalcement}}}{\textbf{\textit{Yielding dispalcement}}} = \frac{\Delta u}{\Delta y}\ , \tag{1}$$

where "Ultimate displacement" is the displacement level at the final load "In fracture" and the "yielding displacement" is the displacement corresponds the intersection between two tangential lines between the initial elastic phases and the "post elastic" linear phase.

It can be recognized that the ductility ratio of the column specimen report 5.62, 4.11, 3.44, 3.50 and 4.17 for AN0, AF1, AF3, AD1and AH03 respectively. However, the rate of change in such ratio report 26.87 %, 38.79 %, 37.72 % and 26.51 % for AF1, AF3, AD1 and AH03 respectively if compared with normal concrete specimen AN0.

Table (3) shows the ductility ratio variation between the proposed specimens in group two. It can be recognized that the ductility ratio of the column specimen reports 5.42, 4.11, 3.43, 3.64 and 4.13 for BN0, BF1, BF3, BD1 and BH03 respectively. However, the rate of change in such ratio report 24.17 %, 36.90 %, 32.84 % and 23.80 % for BF1, BF3, BD1 and BH03 respectively if compared with normal concrete specimen BN0.

The ductility ratio levels were decreased for all the specimens as per the reference reading, even with applying eccentricity. This can be interpreted by the fact that for any mechanical strength gain in brittle material like concrete, there are consequent losses in ductility. These characteristics of fine slag aggregate concrete were comparable to those of regular concrete.

This contradicts the findings of Kim et al. (2014 and 2013) [16, 25], which showed that using slag raises the ductility ratio; the explanation for this might be related to the slag type they utilized, as they employed high-expansion EAF oxidizing slag. This is because EAF oxidizing slag aggregates have a greater lateral expansion capability than natural aggregate concrete.

Further research is needed to suggest reasonable solutions to this shortcoming including adding steel fibers in order to enhance the related ductility of the concrete. In addition, the degree of relation between the mechanical strength characteristics of the concrete and the related ductility ratio should be investigated.

3.3 Initial stiffness

During the present study, the initial stiffness of the column specimens is defined as the yield load that corresponds the yielding displacement” to the inherent yielding displacement.

Initial stiffness = (*Ultimate displacement*)/(*Yielding displacement*)= P_y/Δ_y. (2)

Table 3 shows the variation in the initial stiffness of specimens. The initial stiffness increased by 0.49 %, and 8.38 % for AF1 and AF3 respectively and decreased by 0.74 % and 2.46 % for AD1 and AH03 respectively if compared with the reference specimen AN0.

It can be seen from these outcomes that AF1 and AF3 specimens have good degrees of stiffness improvement. This can be interpreted by the inherent strength gain of concrete according to the concrete mix. The other specimens show a slight decrease in the initial stiffness factor, although the clear accession of load-deflection curves of such specimens against the reference. Generally, it is believed that this happened due to the followed characterization method and the inherent ascending slope of the third state of these specimens.

It is clear that the arrangement between specimens is reflected in accordance with the mechanical control properties. It is also common that the concrete modulus of elasticity is the frequent characterization criterion to represent the stiffness of concrete (as a material), in this way, understanding the correlation between such modulus and the consequent initial stiffness of the column should be taken.

For columns with e/h = 0.4 the initial stiffness decreased by 1.44 %, 3.92 %, and 7.03 % for BF1, BD1, and BH03, respectively, while it increased by 4.28 % for BF3.In fact, all the specimens showed inhibiting stiffness except for BF3.

It can be pointed that this can be related decrease in yielding load due to the eccentric load circumstances. In the same context, the initial stiffness levels of the current group are less than the correspondence in the first group due to the effect of eccentric load.

3.4 Energy absorption

Within the current study, the energy absorption of the columns can be characterized by the area under the curve of the load – axial displacement response.

Fig. 9 shows the variation in the energy absorption of the tested columns of this group.

It is reported that the energy absorption decreased by 30.78 %, 37.90 %, 39.89 % and 28.94 % for AF1, AF3, AD1 and AH03 respectively if compared with the reference specimen, AN0.

It can be recognized from the results that the energy absorption was decreased for all the proposed mixes. In addition, the best performance between the proposed mixes is AF1 because of the high level of P_y and P_u. This behavior dissociates the conflict that resulted in initial stiffness results about AD1 and AH03.

Fig. 10 shows the variation of the energy absorption of the tested columns of this group.

It is reported that the energy absorption decreased by 18.32 %, 43.84 %, 45.36 % and 35.97 % for BF1, BF3, BD1 and BH03 respectively if compared with the reference specimen, BN0.

The energy absorption levels of the proposed mixes and circumstances were decreased as reported and recognized in the concentrically loaded columns.

In the same context, when each specimen is compared with the corresponding specimen within the preceding group, the energy absorption levels of this group are significantly low due to the clear effect of eccentricity and the relevant low levels of yielding and ultimate load.

However, it is recommended to include further research to understand the degree of relation between the levels of eccentricity and the related energy absorption levels for a certain concrete mix.

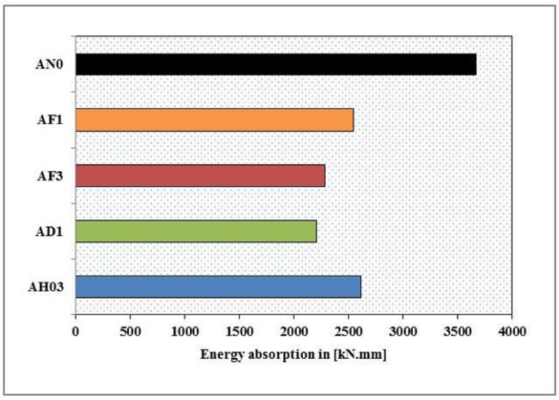

Fig. 9: Energy absorption for group one, *e*/*h* =0.

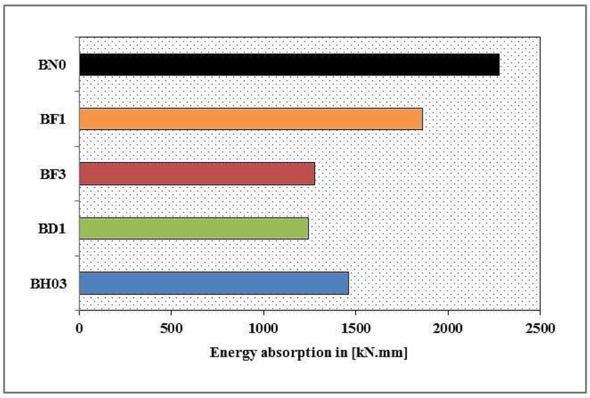

Fig. 10: Energy absorption for group two, *e*/*h* = 0.4.

3.5 Failure mode

The failure mechanisms of the reference and proposed specimens for all concentrically loaded columns were observed to be gradual. At a certain level, vertical cracks in concrete usually emerge in the centre third of the columns. Except for the hybrid column, the failure occurred in the regular concrete section of the column's upper third.

Vertical cracks are the earliest symptom of failure development, and these cracks spread quickly once the concrete cover spalls.

Due to the coupling confinement effect of ties, the concrete core carries the imposed axial load at this stage.

Then the failure occurred in a brittle and explosive form, with the longitudinal bars buckling and crushing the concrete.

However, the first cracking occurrence level does not illustrate indicative results. Typically, the mode of failure can be classified as pure compression failure, as shown in Fig. 11. This represents an expected result within short columns.

The eccentrically loaded columns showed the same progressive character of the failure mechanism as the preceding group.

On the column's tension face, horizontal cracks were visible, and concrete started crushing on the compression face of the specimen. Fragments of concrete started to appear once the cracks spread, as shown in Fig. 12. In general, the use of steel slag had no discernible effect on the failure mode of the test specimens.

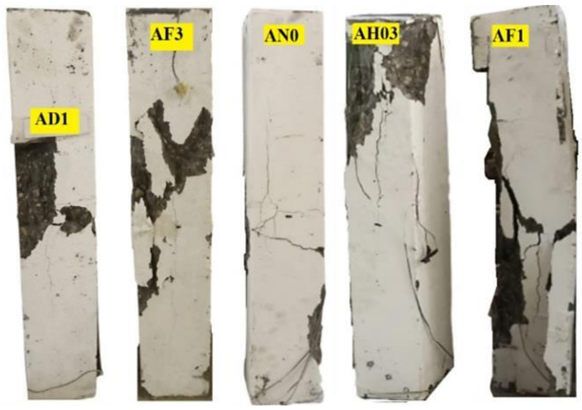

Fig. 11: The failure mode of axial loaded column.

Fig. 12: The failure mode of uniaxial loaded column.

4 Conclusion

The behaviours of RC columns containing SS when subjected to axial and uniaxial loads were evaluated using the experimental test results of ten columns. Induction-furnace steel slag (IFS) was used as a cement additive and a partial replacement for fine aggregate.

1) In general, for columns with steel slag, the displacement levels were decreased, and the

load levels were increased.

2) Regardless of the applied eccentricity, the sequence of the specimens remains the same with regard to the ultimate load and deflection.

3) The order between the proposed specimens points a pre-eminence to the 30 % steel slag mix against others. This can be ascribed to the high mechanical strength of this mix.

4) The ductility ratio levels were decreased for all the specimens as per the reference reading, even with applying eccentricity.

5) The energy absorption was decreased for all the proposed mixes. In addition, the best performance between the proposed mixes is when slag replaces 10 % sand.

6) The failure mode of columns composed of IFS slag concrete was comparable to that of conventional concrete.

7) The short-term results of using slag as an aggregate are favourable, but further research is required to ascertain the long-term results. But before recommending slag for use in concrete columns, its durability and resistance need to be investigated.

References

[1] FALIH, R. S - DAWOOD, A. O. - HAYDER, A. K.: Structural Behavior of Reinforced Concrete Beams Containing Pet Waste Particles as Sand Replacement. Civil and Environmental Engineering, Vol. 18, Iss. 1, 2022, pp. 209–220.

[2] NETINGER GRUBEŠA, I. - BARIŠIC, I. - FUCIC, A. - BANSODE, S. S. - GRUBEŠA, I. N.: Characteristics and Uses of Steel Slag in Building Construction. Elsevier, 2016, doi: https://doi.org/10.1016/C2014-0-03994-9.

[3] JORGE DE BRITO - FRANCISCO AGRELA: New trends in eco-efficient and recycled concrete. Woodhead Publishing, 2018.

[4] ZHAO, Y. et al.: Recycling hazardous steel slag after thermal treatment to produce a binder for cemented paste backfill. Powder Technology, Vol. 395, 2022, pp. 652–662, doi: 10.1016/J. POWTEC.2021.10.008.

[5] WANG, J. - ZHONG, M. - WU, P. - WEN, S. - HUANG, L.- NING, P.: A Review of the Application of Steel Slag in CO2 Fixation. ChemBioEng Reviews, Vol. 8, No. 3, 2021, pp. 189–199, doi: 10.1002/CBEN.202000021.

[6] BAALAMURUGAN, J. et al.: Utilization of induction furnace steel slag in concrete as coarse aggregate for gamma radiation shield, ing. Journal of Hazardous Materials, Vol. 369, 2019, pp. 561–568, doi: 10.1016/J.JHAZMAT.2019.02.064.

[7] LI, Z. - ZHAO, S. - ZHAO, X. - HE, T.: Leaching characteristics of steel slag components and heir application in cementitious property prediction. Journal of Hazardous Materials, Vol. 199–200, 2012, pp. 448–452, doi: 10.1016/J.JHAZMAT.2011.07.069.

[8] YÜKSEL, İ.: A review of steel slag usage in construction industry for sustainable development. Environment, Development and Sustainability, Vol. 19, No. 2, 2017, pp. 369–384, doi: 10.1007/S10668-016-9759-X.

[9] YI, H. - XU, G. - CHENG, H. - WANG, J. - WAN, Y. - CHEN, H.: An Overview of Utilization of Steel Slag. Procedia Environmental Sciences, Vol. 16, 2012, pp. 791–801, doi: 10.1016/J.PRO ENV.2012.10.108.

[10] QASRAWI, H.: Use of relatively high Fe2O3 steel slag as coarse aggregate in concrete. ACI Materials Journal, Vol. 109, No. 4, 2012, pp. 471–478, doi: 10.14359/51683922.

[11] XUE, G. - FU, Q. - XU, S. - LI, J.: Macroscopic mechanical properties and microstructure characteristics of steel slag fine aggregate concrete. Journal of Building Engineering, Vol. 56, 2022, p. 104742, doi: 10.1016/J.JOBE.2022.104742.

[12] BELHADJ, E. - DILIBERTO, C. - LECOMTE, A.: Properties of hydraulic paste of basic oxygen furnace slag. Cement and Concrete Composites, Vol. 45, 2014, pp. 15–21, doi: 10.1016/J. CEMCONCOMP.2013.09.016.

[13] PELLEGRINO, C. - GADDO, V.: Mechanical and durability characteristics of concrete containing EAF slag as aggregate. Cement and Concrete Composites, Vol. 31, No. 9, 2009, pp. 663–671.

[14] YU, X. .- TAO, Z. - YU, X. -. TAO, Z - SONG, T. Y.: Behaviour of concrete-filled steel tubular stub columns with different aggregates.11th International Conference on Advances in Steel and Concrete Composite Structures, 2015, pp. 291–298.

[15] WANG, G. - WANG, Y. - GAO, Z.: Use of steel slag as a granular material: Volume expansion prediction and usability criteria. Journal of Hazardous Materials, Vol. 184, No. 1–3, 2010, pp. 555–560, doi: 10.1016/J.JHAZMAT.2010.08.071.

[16] KIM, S. W. - KIM, Y. S. - LEE, J. M. - KIM, K. H.: Structural performance of spirally confined concrete with EAF oxidising slag aggregate. European Journal of Environmental and Civil Engineering, Vol. 17, No. 8, 2013, pp. 654–674, doi: 10.1080/19648189.2013.810178.

[17] YU, X. - TAO, Z. - YU, X. - TAO, Z. - SONG, T. Y.: Effect of different types of aggregates on the performance of concrete-filled steel tubular stub columns. Materials and Structures/Materiaux et Constructions, Vol. 49, No. 9, 2016, pp. 3591–3605, doi: 10.1617/S11527-015-0742-Z.

[18] ARUMUGAM, V. - MUTHUKUMARAN, N. - ELLAPPAN, P.: CFST Compression members with steel slag as a partial replacement for fine aggregate. iopscience.iop.org, Vol. 955, No. 1, 2020, doi: 10.1088/1757-899X/955/1/012059.

[19] OWAID, H. M. - AL-RAWI, K. - ESSA, M.: Effect of adding slag to concrete on drying shrinkage cracking and some mechanical properties. University of Technology, 2006.

[20] ACI COMMITTEE 233R-03, Slag Cement in Concrete and Mortar. Reapproved 2011.

[21] JOHN, A. - JOHN, E.: Study on the partial replacement of fine aggregate using induction furnace slag. American Journal of Engineering Research, Vol. 4, No. 1, 2013.

[22] BRAULT, A. - LEES, J. M.: Wet casting of multiple mix horizontally layered concrete elements. Construction and Building Materials, Vol. 247, 2020, p. 118514, doi: 10.1016/J.CONBUILD MAT.2020.118514.

[23] TORELLI, G. - LEES, J. M.: Fresh state stability of vertical layers of concrete. Cement and Concrete Research, Vol. 120, 2019, pp. 227–243, doi: 10.1016/J.CEMCONRES.2019. 03.006.

[24] AZIZINAMINI, A. - DARWIN, D. - ELIGEHAUSEN, R. - PAVEL, R. - GHOSH, S. K.: Proposed Modifications to ACI 318-95 Tension Development and Lap Splice for High-Strength Concrete. Structural Journal, Vol. 96, No. 6, 1999, pp. 922–926, doi: 10.14359/766.

[25] KIM, S. W. - LEE, Y. J. - JUNG, Y. J. - LEE, J. Y. - KIM, K. H.: Applicability of electric arc furnace oxidizing slag aggregates for RC columns subjected to combined bending and axial loads. Materials Research Innovations, Vol. 18, 2014, pp. S2793–S2798. doi: 10.1179/1432891714Z. 000000000560.