- Technical Paper -

INVESTIGATION OF FRESH BEHAVIORS AND MECHANICAL PROPERTIES OF CONCRETE PRODUCED BY AIR GRANULATED SPHERICAL SHAPED EAF SLAG FINE AGGREGATE

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ABSTRACT

This study aims to investigate the performance of spherical shaped EAF slag fine aggregate concrete. Two experimental series having W/C ratio of 0.4 and 0.6 were examined in this study to compare the effect of EAF slag fine aggregate. In each series, 4 types of concrete were produced for the slag replacement ratio of 0.0, 0.3, 0.5 and 1.0 and tested for fresh behaviors and mechanical properties after a curing age of 7 and 28 days. Higher bleeding was observed when sand is completely replaced by slag and this effect is pronounced for W/C of 0.6. Increase in mechanical behaviors with the increment of slag ratio was observed for W/C of 0.4. However, an opposite behavior was observed for W/C of 0.6. Fresh and mechanical behaviors indicate that spherical shaped EAF slag fine aggregate can be a good material for the W/C of 0.4.

Keywords: EAF slag fine aggregate, spherical shape, fresh behavior, mechanical property, pavement concrete

1. INTRODUCTION

Electric arc furnace oxidizing slag (EAF slag) is an industrial by product of steel manufacturing process. Around three million tons of EAF slag is produced annually in Japan [1]. EAF slag is produced when scrap iron is melted in the electric furnace and refined. Recently, due to the adoption of air cooling method in the production process, spherical shaped EAF slag is obtained which is different from the conventional distorted shaped EAF slag produced by smashed method as shown in Fig. 1.

(a) Distorted Shape (b) Spherical Shape

Fig. 1 Shape of EAF Slag Fine Aggregate

Spherical shaped EAF slag has several merits when aggregates in concrete are replaced by it. Firstly, fresh behavior such as flow ability of concrete can be improved because of the spherical shape [2]. Secondly, water and cement amount can be decreased because of good fresh behavior and less cement amount brings in less shrinkage [3]. Thirdly, due to the feature of high density of EAF slag, concrete incorporating EAF slag is expected to have higher mechanical properties in reference to Iffat [4]. Some demerits are also expected if spherical shaped EAF slag is used in concrete. When the replacement ratio of EAF slag is very high such as 1.0, it is difficult to avoid segregation and bleeding. Though this tendency can be improved by means of increasing viscosity of cement paste by using admixtures such as silica fume. However, the change in mechanical properties of concrete due to spherical shaped EAF slag fine aggregate is yet to be evaluated precisely.

Due to high density of EAF slag, there is possibility of high applicability of EAF slag in pavement concrete where the requirement is high flexural strength and low slump [5]. In addition, it is equally important to investigate the fundamental behavior of normal concrete produced by using EAF slag fine aggregate. Therefore, the purpose of this study is to investigate and compare the fresh behavior and mechanical properties of different type of concrete casted using EAF slag fine aggregate.

2. OVERVIEW OF EXPERIMENTS

In this study, spherical shaped EAF slag fine aggregate was used as a replacement of natural sand. Experimental results related to density and water absorption of aggregates are listed in Table 1. It can be seen from the table that, the density of EAF slag is very high compared to natural sand and gravel. However, water absorption capacity of slag is found lower in comparison to natural sand and gravel. Moisture content of slag is an important experimental parameter, which was controlled before casting. Gradation curve of EAF

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slag from manufacturer as shown in Fig. 2 indicates that the gradation of slag is beyond the JSCE limit for finer particles and presence of larger particles in slag mix is more. The fineness modulus of EAF slag was computed as 3.40, which is higher than that of natural sand (2.80) to be replaced.

In this study, two different experimental series were tested based on the water to cement ratio (W/C) and slump of 0.4, 5cm and 0.6, 12cm respectively. For the former case, target is to utilize the material in pavement concrete, hence low W/C and slump were considered. Target bending strength for this case is 4.5 MPa. For the latter case, target is to utilize EAF slag in normal concrete and investigate the influence of higher W/C and slump on fresh and physical behavior of concrete. For each case, target for air content was 5%. In each series, 4 different types of concrete were produced by using spherical shaped EAF slag fine aggregate replacing natural sand with a volume ratio of 0.0, 0.3, 0.5 and 1.0. Ordinary Portland cement (OPC), gravel (maximum size 20mm) and air entraining admixtures were used during concrete casting. Mix proportion as computed for the target W/C of 0.4 and 0.6 are shown in Table 2.

It can be seen from the table that water and cement amount reduce with the increase in slag ratio for both the cases of W/C of 0.4 and 0.6. This feature indicates the possibility of obtaining strong and durable concrete with the incorporation of EAF slag.

Table 1 Material Properties

Aggregate	Density (g/cc)	Absorption (%)
Gravel	2.60	1.16
Natural Sand	2.55	1.57
EAF Slag	3.60	0.53

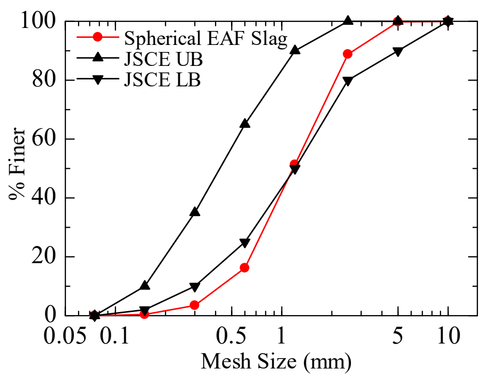


Fig. 2 Gradation Curve of EAF Slag

In order to investigate the characteristics of EAF slag fine aggregate concrete, fresh behavior such as slump, air content, fresh density and bleeding, physical properties such as density distribution and shrinkage and mechanical properties such as elastic modulus, strength and fracture energy were examined. Cylinders of Φ100x200mm were used for measuring density distribution, compressive and split tensile tests. Whereas prisms of 100x100x400mm were used for bending test. For each mechanical test under each series, 3 representative specimens were used and each experiment was conducted after underwater curing of specimens for 7 and 28 days.

3. EXPERIMENTAL RESULTS

3.1 Fresh Behavior

3.1.1 Slump, Air Content and Fresh Density

Results related to the fresh behavior of concrete such as slump, air content and fresh density for the W/C of 0.4 and 0.6 are shown in Table 3. Fresh density was measured by the method described in ASTM C 138 [6]. Target slump for the W/C of 0.4 and 0.6 was 5cm ± 2.0cm and 12cm ± 2.0cm respectively. Whereas target for air content was 5% ± 1.5%. The values of slump and air content as shown in Table 3 are closer to the target value. Fresh density was found to be increasing linearly with the increase in slag ratio irrespective of the W/C. In fact, this is due to the incorporation of high density slag in concrete.

3.1.2 Bleeding

Fig.3 depicts the experimental result related to the distribution of bleeding water for the W/C of 0.4. It can be seen from Fig. 3 that for the W/C of 0.4, bleeding of concrete occurs gradually in between 10-140 mins and shows similar trend as of normal concrete up to 50% replacement of sand by slag. However, for 100% replacement, high bleeding is observed at 70 mins.

Table 3 Fresh Concrete Behavior

Slag Ratio	Slump (cm)		Air Content (%)		Fresh Density (kg/m^3)	
	W/C 0.4	W/C 0.6	W/C 0.4	W/C 0.6	W/C 0.4	W/C 0.6
0.0	6.8	12.0	4.2	4.4	2345	2334
0.3	6.6	12.2	5.2	5.5	2428	2405
0.5	3.5	13.7	5.6	4.8	2487	2469
1.0	3.4	12.1	5.8	6.2	2665	2659

Table 2 Mix Proportions

Slag Ratio	W/C	Slump (cm)	Air Content (%)	Water (kg/m^3)	Cement (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Slag (kg/m^3)	AE Admixture (cm^3/m^3)
0.0	0.4	5	5	165	411	1045	666	0	1028
0.3				164	410	1030	464	281	1025
0.5				160	400	1005	332	464	1000
1.0				155	388	1005	0	929	969
0.0	0.6	12		170	283	1070	700	0	707
0.3				169	282	1076	492	298	705
0.5				168	279	1060	346	489	698
1.0				160	267	1065	0	983	667

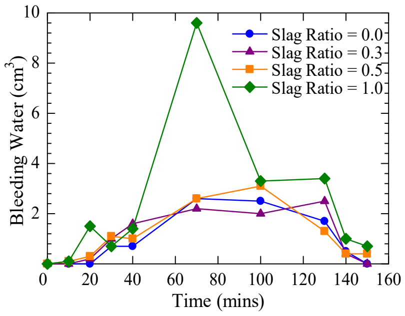


Fig. 3 Bleeding for W/C = 0.4

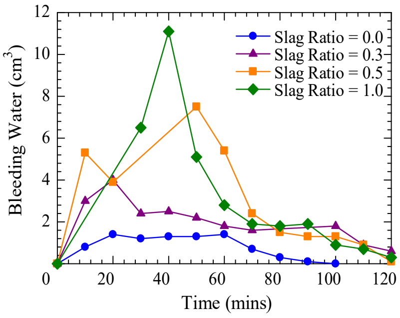


Fig. 4 Bleeding for W/C = 0.6

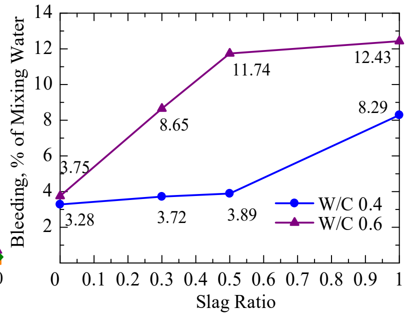


Fig. 5 Rate of Bleeding

For the W/C of 0.6, bleeding of concrete is shown in Fig. 4. Similar trend and slightly higher bleeding in comparison to normal concrete were observed for 30% replacement of sand by slag in between 10-120 mins. For 50% and 100% case, higher bleeding is observed at 50 and 40 mins respectively.

Fig. 5 shows the bleeding rate (bleeding in percentage of mixing water) computed as per ASTM C232 [7] for the W/C of 0.4 and 0.6. The figure indicates that, incorporation of slag in concrete increases the rate of bleeding especially for the case of high water cement ratio. For the W/C of 0.4, rate of bleeding is found to be increasing steadily up to a slag ratio of 0.5. Whereas, for the slag ratio of 1.0, bleeding rate is found to be 2.5 times of normal concrete.

For the W/C of 0.6 as shown in Fig. 5, rate of bleeding is found to be increasing with the increment of slag ratio. However, steady bleeding rate is observed from 0.5 slag ratio to 1.0. For the slag ratio of 1.0, bleeding rate is found to be very high and the value is approximately 3.3 times higher than normal concrete.

The fresh behavior demonstrates that, lesser water and cement is required for the concrete mix when sand is replaced by slag. Even though, incorporation of slag in concrete increases the bleeding of concrete which might be due to the utilization of spherical shaped EAF slag in concrete.

3.2 Physical Properties

3.2.1 Density Distribution

Due to high slag density and subsequent bleeding associated with the increase in slag in concrete, possibility of slag sedimentation in the specimen were investigated because of material segregation. For this reason, in this experiment, each cylinder specimen was sliced at a thickness of 50mm horizontally along its length in 4 distinct parts as shown in Fig. 6 and then oven dried at a temperature of 105°C for 24 hours. Dimension and weight of each sliced part were measured and average density of two representative specimens in absolute drying condition was computed.

The density distribution for the W/C of 0.4 and 0.6 is shown in Fig. 7 and 8 respectively. For each case, the average density is also provided in those figure. It can be clearly seen from the figure that the density increases along with the increment of slag ratio. The differences of density from top and bottom in case of 0.0, 0.3, 0.5 and 1.0 are 0.07, 0.62, 1.63 and 1.66%, respectively. This indicates the settlement of slag from

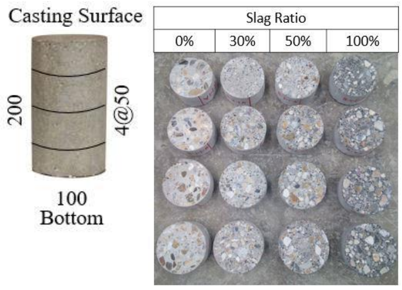


Fig. 6 Sliced Specimen for Density Distribution

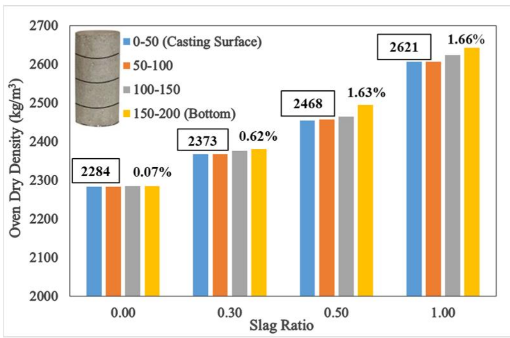


Fig. 7 Density Distribution for W/C 0.4

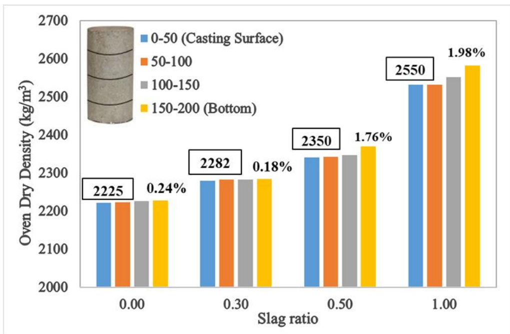


Fig. 8 Density Distribution for W/C 0.6

concrete mix with the increase in slag ratio but the settlement values are very small.

The density distribution for the W/C of 0.6 as shown in Fig. 8 shows similar pattern as of W/C of 0.4 shown in Fig. 7. The differences of density from top and bottom in case of 0.0, 0.3, 0.5 and 1.0 specimen are 0.24, 0.18, 1.76 and 1.98%, respectively.

In so far as physical properties of slag concrete is concerned, segregation and sedimentation of slag particles from concrete mix are observed irrespective of water cement ratio. However, overall particle segregation from the concrete mix is very small.

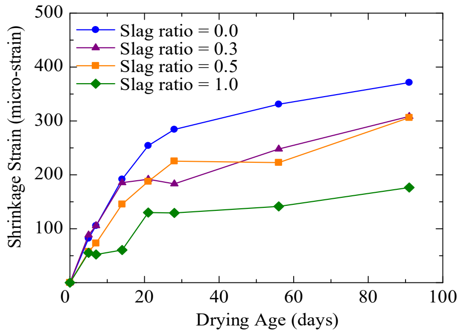


Fig. 9 Shrinkage Strain for W/C 0.6

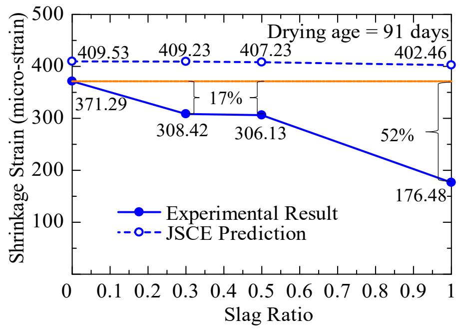


Fig. 10 Experimental and Predicted Shrinkage

3.2.2 Shrinkage

Results related to shrinkage test for the W/C ratio of 0.6 are depicted in Figs. 9 and 10. For each slag ratio, two representative prisms having size of 100x100x400mm each were used. The specimens were cured under water for 3 days after casting. Later the specimens were removed from water and stored in the curing room at a temperature and humidity of 20°C ± 5°C and 60% ± 10% respectively for drying and drying shrinkage of each specimen was measured. On each specimen in each side, 2 contact chips were attached at center part of the specimen at a spacing of 300mm. At a certain drying age, length change of all four sides of a specimen was measured and average shrinkage strain was computed. The experiment was conducted up to a drying age of 91 days.

It is evident from Fig. 9 that the shrinkage strain decreases with the increase in slag ratio. Shrinkage strain for the slag replacement ratio of 0.3 and 0.5 are almost similar. In comparison to normal concrete, for the age of 91 days, 17% reduction in shrinkage strain is observed for the slag replacement ratio of 0.3 and 0.5. In addition, this value is almost 52% when the slag ratio is 1.0.

Prediction of shrinkage by JSCE equation [8] for the drying age of 91 days is shown in Fig.10. For normal concrete, JSCE prediction is closer. For other slag ratio cases, predicted results are slightly smaller than slag ratio 0.0 case due to the decrease in mix water content. However, prediction of shrinkage by JSCE equation for the slag ratio of 0.3, 0.5 and 1.0 are nowhere near to the experimental results. This behavior might be attributed with the shape and some of signature physical properties of EAF slag fine aggregate.

3.3 Mechanical Properties

Results related to the mechanical properties of concrete for the W/C of 0.4 and 0.6 tested after 7 and 28 days of curing are depicted in Figs. 11-14. Each figure shows an average plot of the obtained results from 3 representative specimens.

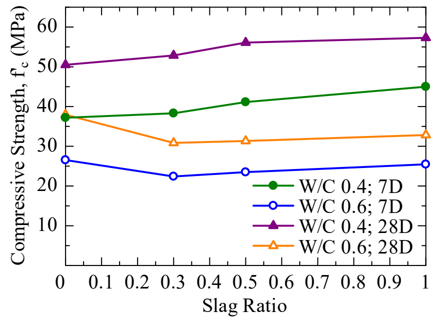


Fig. 11 Compressive Strength with Slag Ratio

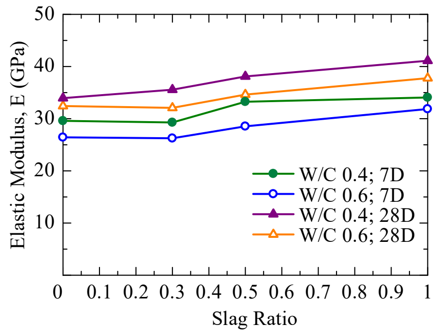


Fig. 12 Elastic Modulus with Slag Ratio

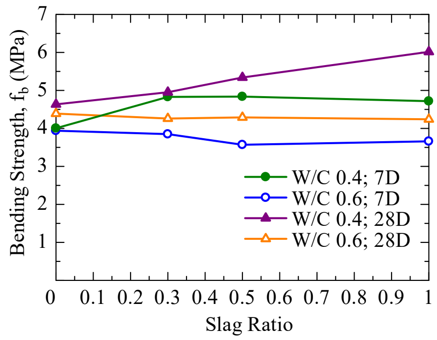


Fig. 13 Bending Strength with Slag Ratio

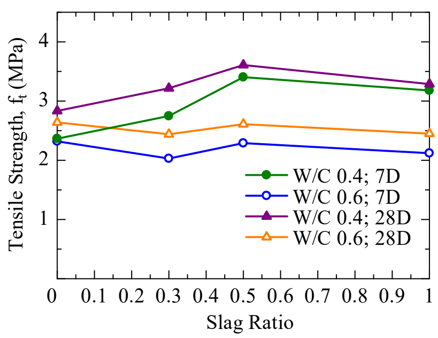
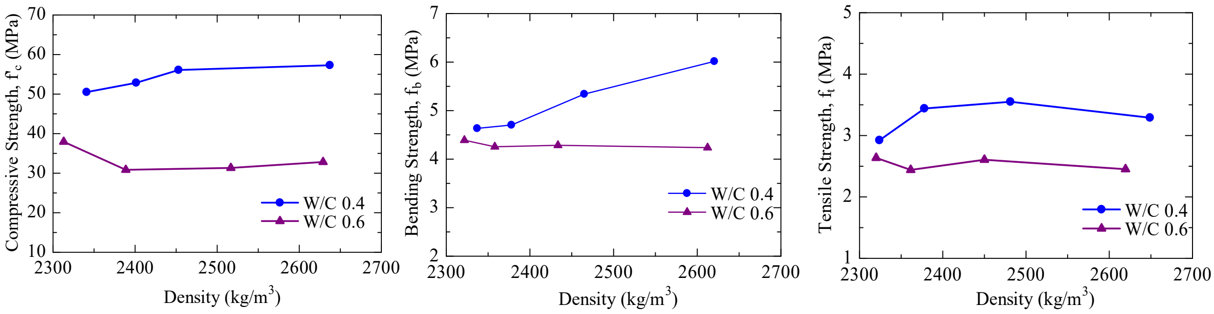


Fig. 14 Tensile Strength with Slag Ratio

Increase in mechanical behavior with the increment of slag ratio in comparison to normal concrete is noted for all cases when W/C is 0.4. Moreover, 28 days bending strength is observed more than the target strength of 4.5MPa and the highest strength is observed for the slag ratio of 1.0. However, slightly different tendency is observed for the case of tensile strength. It



(a) Compressive Strength (b) Bending Strength (c) Tensile Strength

Fig. 15 Relationship between Concrete Strength and Density

can be noted that, after the curing age of 28 days tensile strength for the slag ratio of 1.0 is higher than normal concrete although it is a bit lower than that of 0.5 case. Hence, all mechanical behaviors of EAF slag fine aggregate concrete are higher than normal concrete even if all sand are replaced by slag. This indicates that EAF slag fine aggregate concrete seems to be a good alternative for pavement concrete especially for low W/C ratio.

For W/C 0.6, for the curing age of 7 and 28 days, compressive strength clearly decreases with the increase in slag ratio. For the case of bending and tensile strength the trend is constant or slightly decreasing with the increase in slag ratio. However, elastic modulus increases in association with the increment of slag ratio. Interestingly, increase in strength with the increase in slag ratio is observed for compressive strength and elastic modulus from the slag ratio of 0.3.

Fig. 15 shows the relationship of mechanical properties with hardened concrete density for the W/C of 0.4 and 0.6 after a curing age of 28 days. It can be seen from the figure that, mechanical behaviors for W/C of 0.4 increase with concrete density and W/C of 0.6 cases show inverse trend. Generally, mechanical behaviors increase in association with increment of concrete density [4]. According to this information, these tendencies might be interpreted by the strength of cement matrix and adhesion between slag aggregate and cement paste.

The influence of W/C on the mechanical behavior of EAF slag fine aggregate concrete can be further discussed in light of fracture energy. Fig. 16 depicts the relationship between slag ratio and normalized tensile fracture energy after a curing age of 28 days. First, tensile fracture energy, G_{ft} (N/mm) was computed by the method described in JCI-S-001-2003 standard [9] by using the load displacement curve obtained from the experimental results. Then, normalization was done by dividing the tensile fracture energy with respective concrete compressive strength $f'c^{1/3}$ (N/mm^2) for the W/C of 0.4 and 0.6.

It can be observed from the figure that, normalized tensile fracture energy for the W/C of 0.4 is lower than that for W/C of 0.6. Generally, higher strength concrete undergoes brittle fracture and fracture energy decreases in comparison to lower strength concrete. Thereby, the results that tensile fracture energy for W/C of 0.6 is higher than W/C of 0.4 is reasonable.

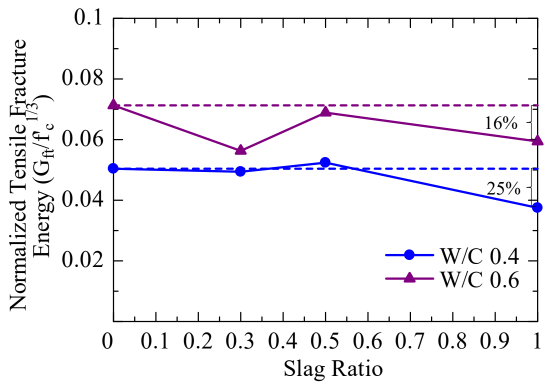


Fig. 16 Normalized Tensile Fracture Energy

For the W/C ratio of 0.4, normalized tensile fracture energy remains constant up to a slag ratio of 0.5. However for the slag ratio of 1.0, a 25% reduction in normalized tensile fracture energy in comparison to normal concrete is observed. This behavior is similar to the decreasing trend of tensile strength after the slag ratio of 0.5. This result indicates that inclusion of slag beyond the slag ratio of 0.5 increases the brittle behavior of concrete for the W/C of 0.4.

For the W/C of 0.6 decrease in normalized tensile fracture energy in comparison to normal concrete is observed with the increase in slag ratio. In addition, for the slag ratio of 1.0 this reduction is 16%. Therefore, it is quite clear that ductility decreases with the inclusion of slag in concrete in high amount.

4. COMPARISON WITH ANGULAR SLAG

The results as discussed above are true for spherical shaped EAF slag utilized in this study. A similar study by using angular shaped EAF slag fine aggregate was carried out by Qasrawi et al. [10]. The study was conducted for three different W/C ratio of 0.38, 0.45 and 0.62. For each W/C case, natural sand was replaced by angular slag with a ratio of 0.0, 0.15, 0.3, 0.5 and 1.0 keeping all other mix parameters constant.

Table 4 shows the comparison of results related to the fresh behavior of angular and spherical slag concrete. It is clear from the table that slump decreases with the increase in slag ratio for angular slag under constant water content. This indicates that angular shaped EAF slag requires more water to attain same slump. This result is opposite to the findings of this study. In case of angular slag 40% particles in slag mix are finer than

Table 4 Effect of Shape on Fresh Behavior

Slag Ratio	Angular Slag W/C 0.38 (Qasrawi et.al. [10])		Spherical Slag W/C 0.40	
	Water Content (kg/m^3)	Slump (cm)	Water Content (kg/m^3)	Slump (cm)
0.00	205	12.0	165	6.8
0.15		11.0	-	-
0.30		10.0	164	6.6
0.50		9.0	160	3.5
1.00		2.0	155	3.4

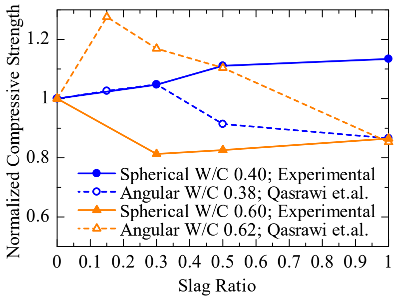


Fig. 17 Normalized Compressive Strength

0.15mm which is due to the preparation of slag by smashed method whereas for spherical slag, this amount is only 3%. This could be the reason of obtaining different slump by using two types of slag.

Result related to normalized compressive strength of slag aggregate concrete is depicted in Fig. 17. The figure indicates an initial increase in strength with the increase in slag ratio up to 30% replacement of sand by angular slag for the W/C of 0.38. However, strength decreases with the increase in slag ratio from 0.3. In particular, angular slag fine aggregate concrete shows improved behavior when the W/C ratio is high although that of spherical slag fine aggregate decreases in this study. In fact, the presence of more finer particles in angular slag brings in higher adhesion with cement matrix in comparison with spherical one. This is why, the difference of normalized compressive strength due to shape of slag is obtained.

5. CONCLUSIONS

Spherical shaped EAF slag fine aggregate is found to be advantageous when utilized in concrete due to the following reasons.

1) Despite of the characteristic property of high density, spherical slag aggregate concrete requires less water and cement compared to normal aggregate concrete. Moreover, spherical slag concrete exhibits half of shrinkage in comparison to normal concrete when all sand in concrete is replaced by slag. These results indicate that spherical slag concrete is beneficial from durability and economic point of view.
2) Though high bleeding is observed with the increase in slag ratio, very low slag separation and settlement is observed which broadens the scope of its utilization.
3) Results related to the mechanical properties of concrete suggested that, spherical shaped EAF slag fine aggregate concrete possess the merit of improved mechanical behaviors compared to normal aggregate concrete with the increase in slag ratio when low W/C of 0.4 is used. At low W/C, constant tensile fracture energy up to a slag ratio of 0.5 indicates similar fracture behavior as of normal concrete with improved mechanical performance.

These results, however, broaden the scope of utilizing spherical shaped EAF slag in pavement concrete with W/C ratio and slump of 0.4 and 5cm respectively. Nevertheless, utilization of this otherwise waste industrial by product in pavement concrete will be environment friendly and sustainable to the industry.

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