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Can Steel Slag be used as an Aggregate in Concrete and How? – A Technical approach by testing and theoretical molding

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ABSTRACT

Steel slag is the molten byproduct from steelmaking operations that is subsequently air-cooled for use. It has been used in cement manufacture and as unbound granular materials in construction. While numerous studies have revealed that concrete containing steel slag aggregate possesses good mechanical properties, and slag, as a byproduct, is cheaper than virgin aggregates, its practical use in portland cement concrete is currently a forbidden area in the construction practices. What is the practicality, where is the crux of converting research results into to real production, and how to build the bridge between the laboratory experiment and the end products? Based on the philosophy of slag utilization, i.e., laboratory testing, field demonstration, and criteria establishment, the questions to be answered includes (i) two distinct laboratory test methods to determine the expansion force generated by slag particles; (ii) conversion of the expansion force of mass slag aggregate to the expansion force of single slag particle; (iii) mechanical disruption model of slag failure; and (iv) usability criteria for the use of steel slag in a rigid or restrained matrices. The paper introduced the answers for the first two questions; and provides the mechanical model and criterion deduction to answer the other two questions that lead to criteria and specification establishment.

INTRODUCTION

The intention to use of steel slag to replace natural aggregate in concrete is initially based on its availability and good characteristics. In addition, sustainable development of construction industry and conservation of natural resources require using recycled and industrial coproducts of all kinds in construction (Brito and Saikia, 2013; USGS, 2010).

In the last approximate 30 years, researches have been conducted on steel slag use as aggregates in concrete and its advantageous properties have been reported (Arribas, Santamaria, Ruiz, Ortega-Lopez, and Manso, 2015; Montgomery and Wang, 1992; Papayianni and Anastasiou, 2010; Sinha, 2014; Sumi and Malathy, 2013). The improvement and modification of concrete mainly come from the unique characteristics of steel slag. It is known that the properties of aggregate, including geometric shape, surface texture, chemical activity and hydrophilicity have significant influence on bonding strength. Figure 1 illustrate the effects from ten different scenarios including aggregate shape, surface texture and disrupt position (Wang, 1986). If the bond strength between aggregate and cement paste in case (a) is regarded as 1; other scenarios are given in Figure 1. It can be seen aggregate particles with rough surfaces have higher bond strength. Compactness of the interface can be enhanced by improving the affinity of aggregate for moisture. Steel slag processes all the good properties that are required for high performance concrete.

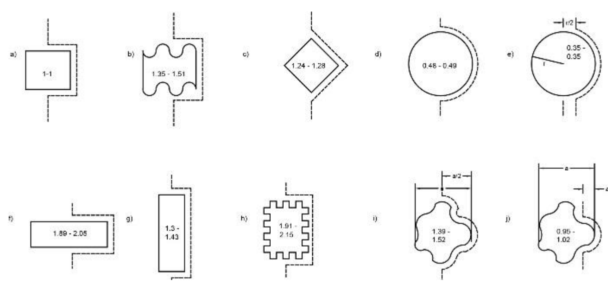

Figure 1. Sample line art illustration

However, a technical opinion or laboratory experiments unsupported by thorough characterization and performance testing is not sufficient to encourage the use of a steel slag in in concrete or other rigid matrices without misgivings or concerns. Steel slag is currently not allowed to be used in many US Departments of Transportation (DOTs) projects, although there are reports it has been used in other countries (Fronek, Bosela and Delatte, 2012). The reason for steel slag not currently used is often due to a general lack of quantification work on the properties of steel slag (expansion potential for instance).

The ASTM D 4792-00 standard test method for potential expansion of steel slag aggregate from hydration provides the method to determine the volumetric expansion as an indicator to evaluate the use of steel slag as an unbound granular material. However the volume expansion data are not directly related to the expansion behavior of steel slag under confined conditions such as in portland cement concrete. New methods are needed to evaluate the steel slag aggregate in a rigid condition.

THE QUESTION RAISED

In view of the benefits of steel slag aggregate concrete and based on the facts that some concrete, tested in the laboratory, performed well with similar or exceeding to ordinary aggregate concrete, even under the autoclave condition and long term water curing, questions are naturally raised: (i) under what degree of stability can a particular steel slag be practically and successfully used as an aggregate in a rigid (confined) matrix: (ii) how to measure the stability and expansion of steel slag for its use in concrete? (iii) what is the basic disrupture mechanism of steel slag in concrete and to what extent does the steel slag aggregate particle expand, crack and result in the disrupting of concrete? (iv) how can the relationship between the steel slag expansion characteristics and the constraining ability of the cement based matrix in which steel slag acts as an aggregate be established?

TEST METHOD DEVELOPED

Disruption Ratio Test

Concrete failure is ultimately force (stress) related. Also the structure sensitivity should be considered. Only the unstable steel slag particle(s) contributes the instability of the structure. Figure 2, left side shows one unstable slag particle can cause damage of the concrete matrix; right side shows the same unstable particle used with stable particles may also cause the damage the concrete. The stability is controlled by the unstable particle. Firstly it has be found how many unstable particles (which contribute the expansion) in a given steel slag aggregate. A *Disruption Ratio* test was developed for this purpose (Wang, 1992; 2010) which gives the indicator the percentage of coarse steel slag aggregate which generate expansion force to concrete (Figure 3). The disruption ratio (*R*) is then used in evaluation of the expansion potential. The next question is to determine the expansion force generated by a single steel slag particle.

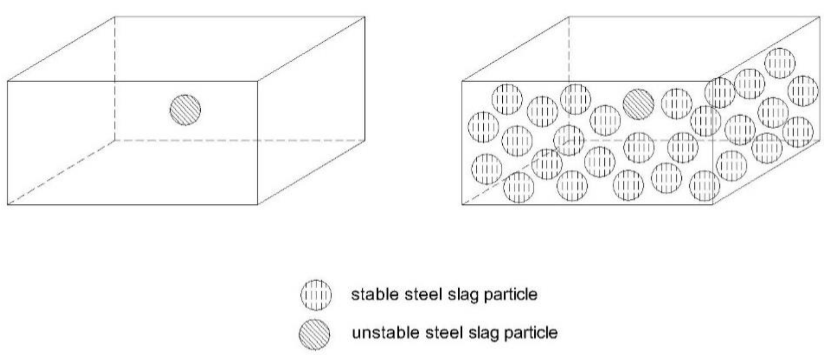

Figure 2. Unstable steel slag aggregate particle(s) contributes the failure of concrete

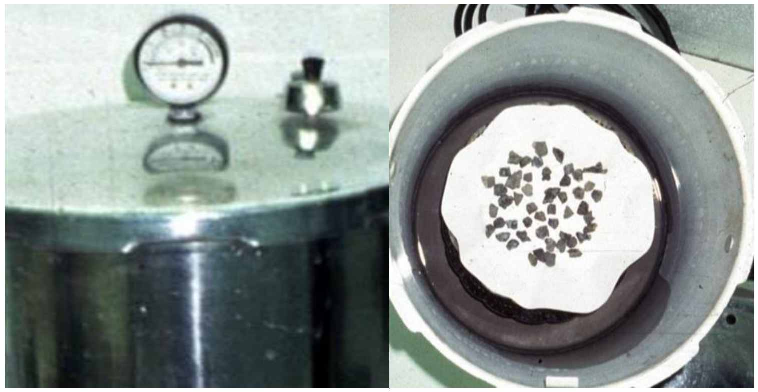

Figure 3. Steel slag aggregate particle *Disruption Ratio* test under autoclave

Bulk Expansion Force Test and Expansion Force Generated By a Single Unstable Steel Slag Particle

The apparatus for testing the bulk expansion force of steel slag aggregate was developed as shown in Figure 4 (Wang, 1992; 2010) and modified portable device is being developed (Wang, 2016).

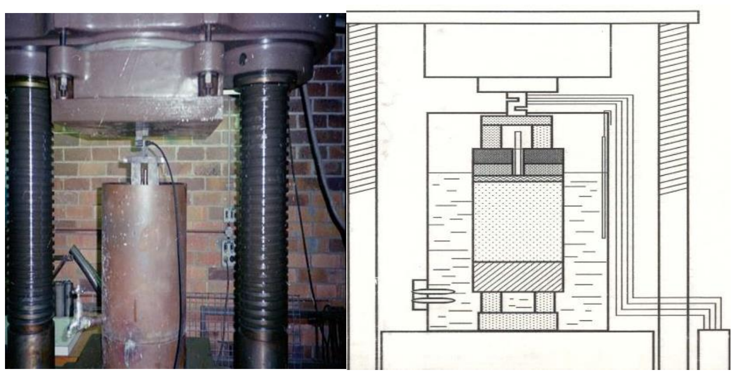

Figure 4. Bulk expansion force test for steel slag coarse aggregate

A portable expansion force testing apparatus is being designed and fabricated. Figure 5 presents the preliminary embryonic form of the portable expansion force testing apparatus developed. This device simulates the trial expansion testing presented above.

This test can provide the bulk expansion force of steel slag aggregate sample, P_e, (N) and three dimensional expansion force per unit volume, σ_e (N/mm^3). The volumetric expansion force per unit volume, σ_e, is defined as P_e/V. The following corresponding relationships exist (proportionality constant):

Resultant expansion force (P_e) $\propto$ Volume of steel slag (V);

Expansion force per unit volume (σ_e) $\propto$ Volume expansion of steel slag (%).

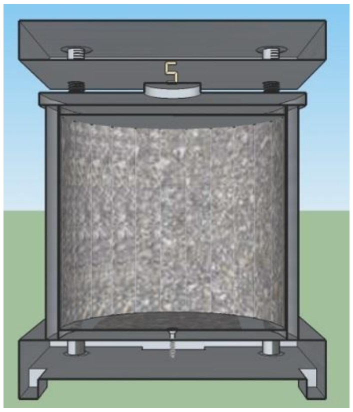

Figure 5. The embryonic form of the portable expansion force testing apparatus to be developed (Wang, 2016)

Based on theoretical reduction, the expansion force generated by an unstable single steel slag particle is found as the form (Wang, 2010):

$$F_{ss} = f_{eus}V_{ss} = \frac{f_{ex}\pi d^3}{6R\Phi} = \frac{F_{ex}\pi d^3}{6V_{sl}R\Phi} \qquad (1)$$

Here F_{ss} is the expansion force from a single steel slag particle, (N); f_{eus} is the expansion force of steel slag that is unstable in concrete, (N/m^3); V_{ss} is the volume of the single steel slag aggregate particle, ($\frac{\pi d^3}{6}$) (m^3); d is the nominal particle size of the steel slag aggregate, (m); R is disruption ratio, (%); f_{ex} is the expansion force generated by a dense compacted steel slag in a unit volume, (N/m^3); V_{sl} is the volume of compacted steel slag, (m^3); Φ is the solid volume of spheres under tightly compacted condition which is approximately 67%. The equation is illegal when R = 0, i.e., when the steel slag particles are volumetric stable (disruption ratio is zero).

DISRUPTION MODELING AND CRITERIA ESTABLISHMENT

How F_{ss} is distributed on the single particle and how to convert the plane stress F_{ss} to the dangerous stress in a particular use is the next key task that is discussed as follows.

The ultimate goal is to determine the plane stress resulted from a slag particle expansion, in other words, the maximum tensile stress in a slag particle, σ_t (N/m^2) in order to establish the relationship between this stress and the allowable tensile stress, F, of mortar or cement paste. For steel slag used as a coarse aggregate in portland cement concrete, the resulting integrity and volume stability are basically controlled by the allowable stress of the matrix materials, cement mortar for instance, and the expansion stress. A usability criterion for steel slag use in confined conditions can be developed by relating the allowable stress of a known matrix material and the maximum expansion force (stress) of a steel slag particle. Since concrete is a structural sensitive material, one localized failure (one particle failure) will be regarded as failure of the concrete. Therefore the basic disruption model for steel slag concrete should be based on a single steel slag particle.

Incorporating the material presented previously, it is possible to derive the usability criterion shown as follows. Three simplifying assumptions are made: (i) steel slag aggregate particle is spherical; (ii) steel slag aggregate with single particle size is used (for simplification of the basic model); (iii) steel slag particle breakage results in the breaking of mortar matrix (from the structural sensitivity property). The aggregate tensile splitting force is produced from the resultant force of normal volume stress, and can be obtained by integrating the expansion force per unit volume in the volume of the half particle (Figure 6).

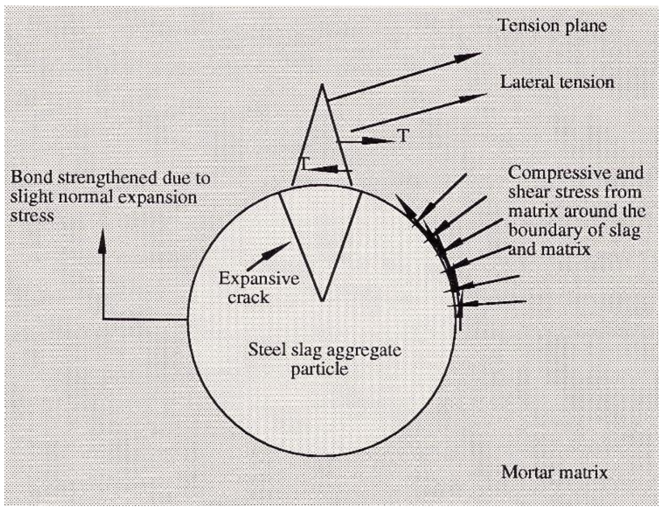

Figure 6. The steel slag disruption modeling

The aggregate tensile splitting force is produced from the resultant force of normal volume stress, and can be obtained by integrating the expansion force per unit volume in the volume of the half particle (Figure 5):

$$P_t = \sigma_{euv} \iiint_V dv = \sigma_{euv} \int_0^{\pi} \sin\theta \sin\theta d\theta \int_0^{\pi} d\varphi \int_0^{d/2} r^2 dr = \tfrac{\pi^2 d^3}{48} \sigma_{euv} \qquad (2) \text{ or}$$

$$P_t = \tfrac{\pi^2 d^3 \sigma_e}{48 R\Phi} \qquad (3)$$

The tension stress (at) acts on the diametrical section of the steel slag particle and is given by:

$$\sigma_t = \frac{P_t}{A_{ms}} = \frac{\pi d \sigma_e}{12 R\Phi} \qquad (4)$$

Where A_{ms} is the area on a diameter of a steel slag particle. This force will produce a normal compressive stress in the mortar matrix under uniform expansion condition. The normal stress acting on the surface of the steel slag particle is

$$\sigma_n = \tfrac{P_{es}}{A_s} = \tfrac{\sigma_e d}{6 R\Phi} \qquad (5)$$

Where, A_s is the whole surface area of a steel slag particle, (equals πd^2). It can be seen that the tension stress at is larger than the normal stress σ_n. Therefore the dangerous (maximum allowable) stress is governed by the tension stress σ_t.

$$\sigma_d = k\sigma_t \leq [\sigma], \text{ i.e.} \qquad (6) \text{ or}$$

$$\sigma_d = k \frac{\pi d \sigma_e}{12 R \Phi} \leq [\sigma] \qquad (7)$$

LABORATORY EXPERIMENTAL STUDY

Preliminary laboratory testing has been conducted to verify (i) the maximum expansion force generated by bulk slag samples and a single steel slag particle with a given particle size; (ii) disruption ratio (Table 1); (ii) the volumetric stability of portland cement concrete containing the steel slag samples as an coarse aggregate.

Table 1 Disruption Ratio and Expansion Force Readings for Steel Slag Samples

	BOF-1		**BOF-2**		**BOF-3**	
Disruption ratio R (%)	3		2		5	
Nominal size (mm)	20		20		20	
Testing days	**Expansion force, F_{ex} (N)**	**Expansion force on a single particle (N)**	**Expansion Force, F_{ex} (N)**	**Expansion force on a single particle (N)**	**Expansion Force, F_{ex} (N)**	**Expansion force on a single particle (N)**
1	31	3	375	52	479	26
2	120	11	549	76	562	31
3	230	21	723	99	843	47
4	348	32	825	114	1120	62
5	472	43	1011	140	1394	77
6	510	47	1329	183	1780	98
7	652	60	1665	230	2146	119
8	1023	94	1971	272	3573	196
9	1464	135	2301	318	6680	369
10	1896	174	2637	364	9600	530
11	2430	224	3237	446	8500	470
12	2876	265	3573	493	10650	588
13	3452	318	4023	556	13680	756
14	4231	397	4023	556	15884	878
15	4937	454	4021	555	18054	998
16	5830	536			20049	1109
17	6240	574			22870	1265
18	7420	682			23560	1303
19	8754	806			25500	1410
20	8751	805			26780	1481
23					28994	1603
26					29100	1609

Portland cement concrete cylinders were prepared using BOF-1, BOF-2 and BOF-3 steel slag samples as coarse aggregate. As many research results indicated, the strength related properties of the concrete are competitive to natural aggregate concrete. The volume stability has been excellent under three hrs autoclave testing at 357 kPa, 137 ^{o}C, for the concrete specimens containing BOF-1 and BOF-2 samples. The concrete specimens containing BOF-3 slag indicated surface pop-out although the autoclave testing result is marginally acceptable. Figure 7 shows a concrete slices containing BOF-2 slag after three hrs autoclave testing at 357 kPa, 137 ^{o}C.

Figure 7. Concrete containing steel slag coarse aggregate after autoclave testing

From Table 1, it can be seen that the maximum expansion force generated from single steel slag particles for BOF-1, BOF-2 and BOF-3 are 806 N, 556 N and 1609 N, respectively. The expansion forces generated from BOF-1 and BOF-2 did not cause concrete specimens disrupt and unacceptable surface distress under rigorous autoclave testing conditions. However the concrete containing BOF-3 sample with maximum expansion force 1,609 N of single particle showed surface pop-outs. There must be an inherent relationship between the allowable stress of rigid matrix, such as portland cement mortar and the maximum stress of a steel slag particle which is volumetrically unstable. Table 2 gives a steel slag sample for 21-day test. Table 3 presents the expansion force at 21 days (become stable) of a steel slag sample.

Table 2 Expansion Reading (T) From Dial Gauge for The Sample

Age	**1-day**	**2-day**	**3-day**	**4-day**	**5-day**	**6-day**	**7-day**
Expansion force (N)	30	120	230	348	472	510	654
Age	**8-day**	**9-day**	**10-day**	**11-day**	**12-day**	**13-day**	**14-day**
Expansion force (N)	789	1023	1460	1896	2430	2876	3452
Age	**15-day**	**16-day**	**17-day**	**18-day**	**19-day**	**20-day**	**21-day**
Expansion force (N)	4231	4937	5830	6240	7420	8754	8750

Now, suppose that it is planned to use the steel slag as an aggregate in Portland cement concrete and that the cement to be used is Type I which has an allowable tension stress of 2 MPa, 3.2 MPa and 4.5 MPa at 3 days, 7 days and 28 days respectively. Assuming a factor of safety (k) of 1.5, is it possible to use this slag in the concrete?

The resultant expansion force is six times the readings in the Table I, i.e. $P_e = 6T$, where T is the expansion force acting on the top surface of the sample, i.e., dial gauge reading (Wang, 1992).

At 28 days, the dangerous stress is given by:

$$\sigma_d = k\frac{\pi d\sigma_e}{12R\Phi} = \frac{1.5\times\pi\times0.02\times8750\times6\times10^6}{12\times0.03\times0.67\times2260} = 9.07MPa > [\sigma] = 4.5MPa$$

Therefore, the given steel slag cannot be used in concrete. If the steel slag is to be used in cement based matrix, the dangerous stress produced from the expansion stress of the steel slag at each age should be less than the allowable stress of Portland cement at the corresponding age. If this situation exists, then we can say that the utilization of the steel slag as a coarse aggregate in the cement matrix is safe.

Another 16 mm steel slag sample received the maximum expansion force occurred at 13 days, 4023.6 Newton. The dangerous stress is given by (7)

$$\sigma_d = k\frac{\pi d\sigma_d}{12R\Phi} = \frac{1.5\pi\times0.016\times40236\times10^6}{12\times0.03\times0.67\times2260} = 0.56MPa < [\sigma] = 3.2MPa$$

The dangerous stress is less that the allowable stress of Type I portland cement at 7 days, therefore, this steel slag is acceptable to be used in the cement matrix.

CONCLUSION

The comprehensive criterion for the use of BOS slag as an aggregate in concrete is established based upon four basic steps. They are: experimental determination of expansion stress; calculation of expansion stress; disruption model of steel slag in concrete and theoretical development of criterion.

From theoretical analysis and experiments, it can be concluded that the maximum expansion stress, as discussed above, is useful and reliable for evaluating if a given steel slag is suitable for use in a given matrix with a constrained stress. The concrete made with the steel slag aggregate conforming to the criterion deduced in is volumetrically stable under both autoclave test and water soaking for long term curing.

To simplify the calculation of the surface area of a steel slag particle, a sphere shape is assumed and the nominal particle size is used for the diameter of the sphere shape of a steel slag particle.

The expansion force test and disruption ratio test can be used jointly or separately to evaluate the expansive properties of steel slag and other nonferrous slag aggregates especially when the slag is used as coarse aggregates under confined conditions. The equations deduced can convert the expansion force of bulk slag sample to the expansion force of a single slag particle that can be used to establish usability criteria based on appropriate disruption modeling(s) of steel slag in confined conditions. Based on the visual observation on the concrete specimens containing the three slag samples after rigorous autoclave testing and the expansion forces and tension stresses of the steel slag samples, usability criteria for the use of coarse steel slag in concrete established based on steel slag concrete disruption model is correlated and reliable.

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