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Use of steel slag as a granular material: Volume expansion prediction and usability criteria

George Wang[a,*], Yuhong Wang[a], Zhili Gao[b]

[a] Department of Construction Management, East Carolina University, Greenville, NC 27858, USA
[b] Department of Construction Management and Engineering, North Dakota State University, Fargo, ND 58108, USA

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ABSTRACT

The theoretical equation for predicting volume expansion of steel slag is deduced based on both chemical reaction and physical changes of free lime in steel slag during the hydration process. Laboratory volume expansion testing is conducted to compare the results with the theoretical volume expansion. It is proved that they correlated well. It is furthermore experimentally proved that certain volume expansion of steel slag can be absorbed internally by the void volume in bulk steel slag under external surcharge weight making the apparent volume expansion equal zero. The minimum (lowest) absorbable void volume is approximately 7.5%, which is unrelated to the free lime content. A usability criterion is then developed based on the volume expansion of steel slag (%) and the minimum percentage of the volume that can take the volume expansion of steel slag (%). Eventually the criterion (relationship) is established based on the free lime content, the specific gravity and bulk relative gravity of a specific steel slag sample. The criteria can be used as guidance and specification for the use of steel slag and other expansion-prone nonferrous slags, copper, nickel for instance as a granular material in highway construction.

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1. Introduction

Slag is the molten byproduct of many metallurgical operations, that is subsequently cooled (air, pelletized, foamed or granulated) for use, or, unfortunately in too many cases, disposal. The overall use of blast furnace slag, which is from iron making, is relatively well known for a range of highway construction applications from granular base, concrete or hot mix asphalt aggregate, to supplementary cementitious materials. In contrast to blast furnace slag, which is volumetrically stable and straightforward in its construction uses, steel slag from basic oxygen furnace (BOF) and electric arc furnace (EAF) contains free (unhydrated) lime (CaO) that can result in volumetric instability (expansion) that must be dealt with through appropriate steel slag aging, testing and quality control to ensure its appropriate use in construction. Each specific slag, in terms of type, process and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for bulk uses.

Research has been conducted by material scientists and civil engineers to open avenues for steel slag use in construction applications. It has been found that steel slag can be use in broad areas of construction applications, for example, the use in blended cement manufacturing [1,2]; the use as a granular material in road base or subbase courses [3–5]; the use as an aggregate in various asphalt mixes or pavement surfaces [6–8]. Although there are advantages in each application, the use of steel slag as a granular material is a promising area due to the following reasons (i) larger quantities of steel slag can be used as a granular material in unbound conditions, such as road base or subbase, compared with other usage; (ii) the process for granular use is technically sound, simpler and well developed; (iii) there is less concern on long term stability in unbound conditions, highway granular base and subbase, for instance; (iv) volume expansion test method has also been developed [9]; (v) the steel slag processing industry has maturely placed their production and marketing emphasis on granular materials and aggregate for unconfined utilizations. Steel slag treating and processing technology has been well developed for the last couple of decades which have made it possible for steel slag to be used as granular base or subbase materials in highway construction in large scales [3,10,11]. However, the fact is that steel slag aggregate has not been extensively used in construction, especially its use as a granular material. In the US, approximately 13 mt of steel slag was discharged, only 1.7 mt was used in construction in 2000 [12].

The main reason for the low scale utilization is the lack of quantified criteria to guide the appropriate use for a special steel slag in a special use. It is imperative to establish different criteria for different utilizations of steel slag. Slag processing, laboratory testing

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* Corresponding author. Tel.: +1 252 737 1887; fax: +1 252 328 1165.
E-mail addresses: wangg@ecu.edu, gcw2006@yahoo.ca (G. Wang).

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and quantifying the properties of steel slag and the end product (criteria establishment) are the trilogy of slag utilization development. Different application should have different criteria to guide the appropriate use. For example, for the use of steel slag in concrete or other rigid matrices, expansion force of steel slag and the distribution of the force in the rigid matrices governs the usability [13]. There is no single criterion governing different uses of steel slag. When steel slag is used as a granular material, road base or subbase for instance, the apparent volume expansion of the base or subbase is to be restricted to zero. However, a bulk granular material contains void content even it is fully compacted (the maximum compaction value of laboratory Proctor value). Can the void content in the compacted bulk slag aggregate absorb any volumetric expansion generated by the expansive steel slag? To answer this question, the following work must be conducted: (i) determine the theoretical volume expansion rate of steel slag; this can be determined based on the chemical reactions incurred in the slag samples when reacting with moisture; (ii) laboratory volume expansion testing with and without surcharges, i.e., the weight surrounding the sample three dimensionally; (iii) establishing the relationship between free lime content and theoretical expansion under constraint force; and furthermore, development of the usability criteria. The criteria should be based on the relationship between the estimated volume expansion equation (in %, derived from chemical and physical changes of free lime in steel slag) and the minimum percentage of void volume that can take the expansion of steel slag under certain external weight (surcharge).

2. Basic properties of steel slag

2.1. Chemical and mineral compositions

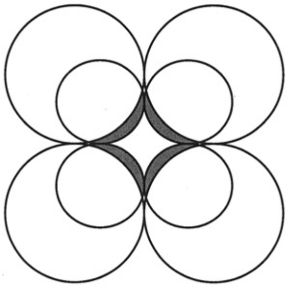
Solid steel slag exhibits block, honeycomb shape and high porosity. Most steel slag consists primarily of CaO, MgO, SiO_2, and FeO. In low-phosphorus steel-making practice, the total concentration of these oxides in liquid slags is in the range of 88–92%. Therefore, the steel slag can be simply represented by CaO–MgO–SiO_2–FeO quaternary system. However, the proportions of these oxides and the concentration of other minor components are highly variable and change from batch to batch even in one plant depending on raw materials, type of steel made, furnace conditions, etc. The chemical compositions of steel slag from different steel-making processes have been reported in the literature [2,14], which can be summarized in Table 1.

Steel slag can be air-cooled or water quenched. Most of steel slag production for granular materials use natural air-cooling process following magnetic separation, crushing and screening. Air-cooled steel slag may consists of big lumps and some powder.

The mineral composition of cooled steel slag varies and is related to the forming process and chemical composition. Air-cooled steel slag is composed of $2CaO{\cdot}SiO_2$, $3CaO{\cdot}SiO_2$ and mixed-crystals of MgO, FeO and MnO (i.e. MgO·MnO·FeO) which is expressed as RO. CaO can also enter the RO phase. In addition, $2CaO–Fe_2O_3$, $CaO{\cdot}Fe_2O_3$, $CaO{\cdot}RO{\cdot}SiO_2$, $3CaO{\cdot}RO{\cdot}2SiO_2$, $7CaO{\cdot}P_2O_3{\cdot}2SiO_2$ and some other oxides exist in steel slag [2,15]. It was reported that the XRD pattern of steel slag is close to that of Portland cement clinker.

2.2. Expansion mechanism

During steel-making process, fluxes which consist of lime (CaO) or dolomitic lime, with iron and scraps are charged to the furnace. There is certain amount of free lime (F-CaO) in steel slag. Free lime, with a specific gravity of 3.34, can react with water to produce $Ca(OH)_2$, with a specific gravity of 2.23, which results in volume increase. This is considered to be the primary reason to make steel slag expand volumetrically [16].



Small spheres: initial volume of solid phase
Large spheres: final volume of solid phase
Space between small spheres: initial volume of void
Hatched areas: increment of void
Space between large spheres including hatched areas: final volume of void

Fig. 1. Effect of increase of solid phase on the void volume.

MgO in steel slag is in the form of wüstite, i.e., Fe (Mn, Mg, Ca)O, in glassy state, mixed crystal or solid solution mainly with FeO and MnO, i.e., RO phase. The free form of MgO (periclase) is volumetric unstable which can only be formed in low basicity condition. Due to the high basicity condition in molten steel slag and the close radii of Mg^{++}, Fe^{++} and Mn^{++} (0.78, 0.83 and 0.91 Å), MgO, FeO and MnO usually form solid solution. In this study, free lime is considered to be the major contribution to the volume expansion of steel slag.

3. Theoretical volume expansion

The volume change of free lime due to its hydration includes two parts, i.e., chemical and physical parts, which can be calculated. However, the physical portion of volume change has been neglected previously. In the following deduction, volume changes due to both chemical and physical changes are considered.

3.1. Hydration of free lime and volume change

The hydration speed of free lime in steel slag is relatively slow compared with that of burnt lime in which the hydration can be completed within 30 min [17]. This is because the structure of free lime in steel slag is denser due to the calcining temperature of approximately 1700 °C and the decreased ability for moisture to react with free lime.

The reaction of free lime and water can be expressed in Eq. (1):

$$CaO + H_2O \Rightarrow Ca(OH)_2 \pm 15.5\ \mathrm{Cal/Mol} \qquad (1)$$

Under ambient temperature, the reaction proceeds to right-hand. The reaction proceeds to left-hand only at 547 °C or above [18].

The volume change, due to chemical reaction, of lime–water system and solid phase (lime) can be calculated which is presented in Table 2.

From Table 2, the absolute volume of the solid phase increases by 97.92%. However, in the free lime–water system, the total volume does not increase, instead, it decreases by 4.54%. The chemical reduction occurs when lime reacts with water, which is the same as for other cementitious materials such as Portland cement and gypsum.

Table 1
Typical chemical composition range of steel slag.

Chemical composition (%)	FeO	MnO	P_2O_5	SiO_2	CaO	Al_2O_3	MgO	TiO_2
BOF slag	10–35	2–15	0.2–3.0	8–20	30–55	1–6	5–15	0.4–2
EAF slag	15–30	3–10	0.1–2.0	9–20	35–60	2–9	5–15	

3.2. Volume expansion due to physical change

The void volume of free lime particles can be explained in Fig. 1. When hydration occurs, the void volume increases in conjunction with the increase of the solid phase. It is assumed that the particles of lime are spherical before and after hydration and are fully compacted in ideal hexagonal form. Under these conditions, the volume of solids is 74% of the total volume and the void volume accounts for 26% of the total volume. The relative contents or the ratio of solid to void are constant and are not related to the particle size. However, the absolute value of the void volume is variable with the change of solid phase.

In Fig. 1, if the surfaces of the small spheres absorb other substances (during the process of hydration, lime particles absorb water molecules thereby increasing the solid phase volume), small spheres will become large spheres although the ratio of spheres (solid) to void does not change and the absolute volume increases. This means that if the volume of spheres increases by 1%, the void volume will increase by 26/74 × 1% = 0.351%. In the above deduction, very fine particles of free lime (normally ∼100 μm) are assumed spherical shape. Due to the tiny particle size and the volume change due to physical shape change contributes only ∼25% of the total volume change, it is consider to be acceptable in the estimated volume expansion equation deduction.

From Table 2, for complete reaction, the solid phase will increase by 97.92%. Therefore, the void volume will increase by 26/74 × 97.92% = 34.40%.

When lime hydrates, the increase in solid phase results in increase of void volume, and the combined increase of solid phase and void will surpass the volume change of the lime–water system resulting in an increase in lime volume. The increase will be 34.40% + 97.92% = 132.32%. The expansion of the solid phase is larger than that of the lime–water system. Therefore, the actual volume expansion of free lime in steel slag after complete reaction is 132.32–4.54% = 127.78%.

3.3. An equation for prediction of steel slag volume expansion

From the expansion mechanism of free lime, an equation for estimating the potential volume expansion of steel slag can be deduced.

A bulk steel slag aggregate sample is considered. The apparent total volume is V_o, the volume of solid is V and the ratio V/V_o (or γ_o/γ_s) is a measure of the denseness of the mass of steel slag (expressed as D). The volume expansion is defined as the ratio of increase in volume to the real volume (solid) of steel slag, i.e.

$$E_s = \frac{\Delta V}{V} \tag{2}$$

Here ΔV is the volume increase of steel slag. As indicated, the increase in volume of the steel slag is entirely due to increase in volume of free lime in the steel slag. The mass of the steel slag is $V\gamma_s$, the mass of the free lime is $V\gamma_s F$ and the volume of free lime in the steel slag is $V\gamma_s F/\gamma_l$. Therefore, the volume expansion, E_s, of the steel slag can be expressed as:

$$E_s = \frac{1}{V_o D} \times \frac{V_o D \gamma_s F}{\gamma_l} \times \frac{E_l}{100} \tag{3}$$

Here E_l is the volume expansion of lime (%) equals 127.78% as calculated above; E_s is the volume expansion of steel slag, (%); V_o is the apparent total volume of steel slag, (cm^3); D is the denseness of steel slag (γ_o/γ_s); F is the free lime content of the steel slag (%); γ_o is the bulk density of steel slag samples with voids (g/cm^3); γ_s is the specific gravity of steel slag (g/cm^3); γ_l is the compacted density of lime (g/cm^3).

Substitute $\gamma_l = 3.34$ and $E_l = 127.78\%$ into Eq. (3),

$$E_s = 0.38 \times \gamma_s F \tag{4}$$

From Eq. (4), it can be seen that the volume expansion of steel slag is related to the compacted density γ_s and the free lime content of the steel slag, F. However, γ_s is a constant for a particular slag (g/cm^3). Therefore, the volume expansion is directly related o the free lime content. It is noted that 0.38 has a unit reversing to the unit of γ_s.

4. Laboratory volume expansion testing

4.1. Test method and equipment employed

In the deduction of Eq. (4), the real volume V, i.e., $V_o D$, was considered. However, when steel slag is used as a granular such as road base or subbase, it must be treated as an entirety. Internally, the void content is normally not zero, or the denseness D is not 100%. To verify if the void volume in a bulk steel slag sample can absorb volume expansion 'internally', also to verify the expansion prediction equation, volume expansion tests were conducted on slag samples with and without surcharges.

The ASTM standard test method was adopted in the laboratory testing. The diameter of the testing mould is 15.24 cm, the area is 182.4 cm^2 and the height of the section containing materials is 12.8 cm. Steel slag samples were tested in the mould under conditions with and without 4560 g (25 g/cm^2) surcharges. The slag

Table 2
Volume change of free lime–water system.

Equation of reaction	Molecular weight	Specific gravity	Absolute volume of the system (cm^3)		Absolute volume of the solid phase (cm^3)		Absolute volume change (%)	
			Before reaction	After reaction	Before reaction	After reaction	System	Solid phase
CaO +	56.08	3.34						
H_2O	18.02	1.00						
=								
$Ca(OH)_2$	74.10	2.23	34.81	33.23	16.79	33.23	−4.54	97.92
Water needed for the reaction					0.321			

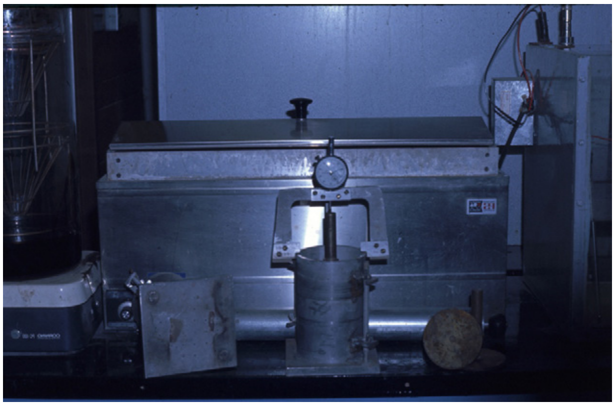


Fig. 2. View of the volume expansion test equipment according to ASTM D4792.

samples were soaked in water bath at 74 ± 3 °C. Figs. 2 and 3 give the view of the volume expansion testing.

Samples were initially selected for the expansion test to qualitatively verify if any differences of volume expansion exist. Two parallel tests, with and without surcharges, for each sample with nominal particle size of 20 mm (16–20 mm) were carried out.

Fig. 3. Parallel volume expansion test.

Table 3
Properties of steel slag samples for the comparison of volume expansion test.

	BOS slag 1	BOS slag 2	BOS slag 3
Free lime content (F-CaO, %)	1.84	0.34	1.27
Specific gravity of steel slag (γ_s, g/cm^3)	2.980	3.075	3.160
Estimated volume expansion based on Eq. (4) (%)	2.08	0.39	1.52

4.2. Test results

Three samples were initially selected, i.e., BOF slag 1, BOF slag 2 and BOF slag 3 which are air-cooled BOF slags from different sources. The properties of the three slag samples and the estimated volume expansion are presented in Table 3.

The volume expansion test results with and without surcharges are shown in Table 4.

From the results in Tables 3 and 4, it can be seen that (i) differences do exist between the surcharged and non-surcharged samples; (ii) the differences, or differentials, K_{25}, which means under 25 g/cm^2 surcharge, are from 7% to 13%; (iii) the lower limits happened when the expansion rate became stable, i.e., in the later testing days, (iv) the estimated Eq. (4) is fairly reliable for estimating the major expansion which occurs during the first 1–2 weeks of hydration. Fig. 4 presents the expansion test results of the three BOF slag samples with and without surcharge (7–13% differences).

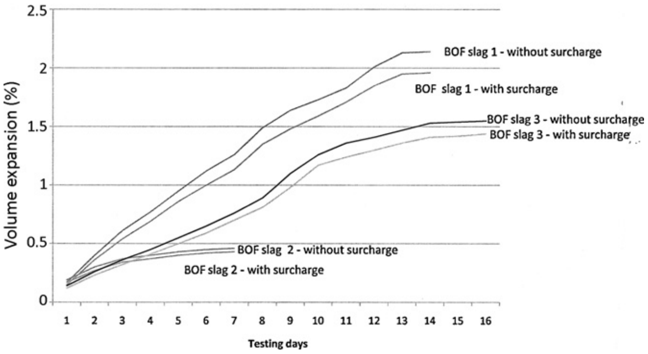


Fig. 4. Volume expansion results for three BOF slags with and without surcharge.

Table 4
Volume expansion test results.

Testing days	BOF slag 1			BOF slag 2			BOF slag 3		
	Volume expansion (%)		Differential in expansion (%, K_{25})	Volume expansion (%)		Differential in expansion (%, K_{25})	Volume expansion (%)		Differential in expansion (%, K_{25})
	Surcharge	Non-surcharge		Surcharge	Non-surcharge		Surcharge	Non-surcharge	
1	0.15	0.17	13.0	0.17	0.19	11.2	0.12	0.14	16.6
2	0.36	0.40	11.1	0.27	0.30	11.1	0.23	0.26	13.0
3	0.54	0.61	13.0	0.34	0.37	8.8	0.32	0.36	12.5
4	0.69	0.77	12.0	0.37	0.40	8.1	0.41	0.45	9.8
5	0.86	0.95	10.0	0.40	0.43	7.5	0.50	0.55	10.0
6	1.00	1.12	12.0	0.42	0.45	7.1	0.59	0.65	10.2
7	1.13	1.26	11.5	0.43	0.46	7.0	0.70	0.76	8.6
8	1.35	1.49	10.4				0.81	0.89	9.9
9	1.48	1.64	10.8				0.98	1.10	12.2
10	1.59	1.73	8.8				1.17	1.26	7.7
11	1.71	1.83	7.0				1.24	1.36	9.7
12	1.85	2.01	8.6				1.30	1.41	8.5
13	1.95	2.13	9.0				1.36	1.47	11.0
14	1.96	2.14	8.0				1.41	1.53	8.5
15							1.42	1.54	8.5
16							1.44	1.55	7.6

Table 5
Densities and free lime content of steel slag samples.

Sample number	BOF 2-1	BOF 2-2	BOF 2-3	BOF 2-4	BOF 2-5	BOF 2-6
γ_o	2.346	2.278	2.149	2.307	2.189	2.243
γ_s	3.361	3.271	2.886	3.189	2.990	3.261
F (%)	2.7	3.5	3.3	3.1	2.4	3.4

The differences caused by the 25 g/cm^2 surcharge are important to set up the usability criterion. Yet, the lower limits of the differences should be used in the usability criterion as it will place the criterion in the safe side.

To further quantitatively verify the lower differentials, six steel slag samples with 20 mm nominal size (16-20 mm) were selected to run 12 parallel tests with and without surcharges. The densities and free lime contents of the steel slag samples are shown in Table 5. AASHTO T 85 testing method—specific gravity and absorption of coarse aggregate were used for determination of γ_o and γ_s. Volumetric analysis method was used in determination of free lime content. The lower limits of differentials after the volume expansion become stable are shown in Table 6.

Results have shown that the maximum expansion value ranged from 0.56% to 2.55% (Table 5). Comparing two parallel tests of each sample, it was found that expansion values of the slag samples with surcharge are lower by 7.7–10.9% in average than those of the samples without surcharges. This difference is called differential in expansion and expressed as K_{25}.

5. Usability criteria for steel slag use as granular material

From the volume expansion tests, it can be seen the lowest differentials caused by the surcharge are 7–8%. That means if the estimated expansion, Eq. (4) is less than 7–8% of an estimated voids content (7.5% is taken below) and the materials is acted upon by a 25 g/cm^2 surcharge, actual expansion volume of the steel slag will not occur. In other words, if

$$E_s < 7.5\%(1 - D) \qquad (5)$$

or

$$0.38 \times \gamma_s F < 7.5\% \left(1 - \frac{\gamma_o}{\gamma_s}\right) \ (25\,\mathrm{g/cm^2}\ \text{surcharge}) \qquad (6)$$

Apparent volume expansion of the granular material will not occur. In Eq. (5) the unit of left side is volume change (%); the unit of right side is percentage of volume that can take the expansion of slag.

Eq. (6) can be rewritten in the form shown as follows:

$$F < \frac{0.075(\gamma_s - \gamma_o)}{0.38\gamma_s^2} \times 100 \qquad (7)$$

It states if free lime content in the steel slag is less than the right-hand term, the steel slag will not expand macroscopically, or the expansion resulting from free lime can be ‘absorbed’ by the void volume of steel slag itself under a pressure of 25 g/cm^2. In other words, overall expansion will not occur if this condition is met. It simply provides a convenient estimation for a given steel slag with a known content of free lime content and physical properties. Eq. (7) has been developed experimentally for steel slag under the condition that the steel slag material exerted a pressure 25 g/cm^2 above in the pavement structure. Fig. 5 shows asphalt pavement structure layers which include hot mix asphalt layers, normally 100–300 mm (4–12 in.) thick; granular base and subbase layers. Fig. 6 gives the view of the granular base and/or subbase layers under the ‘surcharge’ of hot-max asphalt layers. It is assumed that the thickness is larger than 100 mm (4 in.) and the surcharge is larger than 25 g/cm^2 condition.

Table 6
Volume expansion results.

Sample number	Surcharge	Non-surcharge	Differential in expansion (%, K_{25})
BOF 2-1	1.85	2.01	8.6
BOF 2-2	2.30	2.55	10.9
BOF 2-3	0.56	0.62	10.7
BOF 2-4	1.35	1.49	10.4
BOF 2-5	1.95	2.10	7.7
BOF 2-6	1.96	2.16	10.2

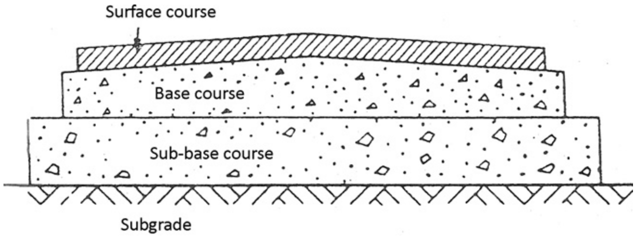


Fig. 5. View of pavement structure.

5.1. Modification of the criterion

Literature has reported that the measured free lime content comes from two sources: residual free lime and precipitated lime from the molten steel slag [15]. The volume expansion of steel slag is contributed by the content of residual free lime. When the measured total free lime is less than 4%, it contains 2% precipitated lime; if the measured total free lime is larger than 4%, it contains 2.8% precipitated lime [19]. Thus, the final modified criterion can be rewritten as follows in two parts:

When measured free lime is ≤4%, the allowable free lime content, i.e.,

$$F_{all} < 2.0\% + \frac{K_{25}(\gamma_s - \gamma_o)}{0.38\gamma_s^2} \times 100 \qquad (8)$$

When measured free lime is >4%, the allowable free lime content, i.e.,

$$F_{all} < 2.8\% + \frac{K_{25}(\gamma_s - \gamma_o)}{0.38\gamma_s^2} \times 100 \qquad (9)$$

Here F_{all} is the allowable (or maximum) free lime content for a given steel slag that is evaluated for possible use as a granular material with a condition that above the steel slag there is a struc-

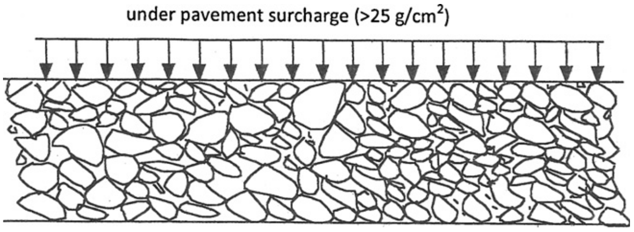


Fig. 6. Steel slag as a base or subbase in the pavement structure, the surface course is general thicker than 10 cm (4 in.) meet the condition by the criteria.

ture layer(s) thicker than 10 cm upper layer(s), or a surcharge larger than 25 g/cm^2 within the pavement structure.

6. Discussion

The testing equipment with surcharge is considered to be a simulation of road base or subbase granular materials. The 25 g/cm^2 surcharge is equivalent to a minimum 10 cm thick (4 in.) concrete or hot mix asphalt pavement on top of steel slag granular base course on subbase course. From the test results of the six samples, it is calculated that the allowable free lime contents for the samples to be safely used as a granular base or subbase is in the range of 3.7–3.9%, under the condition of 25 g/cm^2 constraint force, i.e., 10 cm thick upper layer of pavement structure.

Literatures provide the free lime limits for steel slag use as a granular material to date. Some data based on road construction suggested the limit should be about 4% [2,20]. Others have suggested the limit of 4% can be extended [21,22]. However, it is noted that (i) the recommendation came from field visual observation only; (ii) the suggested limits are for asphalt concrete aggregate, granular materials, or cementing materials applications. The criteria developed can be used for steel slag, or other nonferrous slag, producers or users to evaluate the potential usability of their products in highway construction.

7. Conclusion

The ultimate maximum volume expansion of steel slag can be estimated and predicted by the theoretical expansion equation. The calculation of volume expansion based on free lime is convenient and reliable for use to evaluate the usability of steel slag. The calculated volume expansion can also be used as quality control measures during slag processing or evaluation criterion for a given slag proposed for an engineering application(s).

The differences of volume expansion exist due to the porous nature of granular material and the external constraint force. In other words, certain percentage of the volume expansion takes up the void volume and makes the entire bulk steel slag sample do not show apparent expansion. The lowest difference, which is most meaningful for the development of usability criteria, happened in the later hydration days, which is approximately 7%, is not related to the free lime content. For steel slag, and other nonferrous volume expansion-prone slags, when used as unbound granular material, apparent volume expansion should be taken into consideration. For the use of steel slag as an aggregate in rigid matrix, portland cement concrete for instance, expansion force, rather than volume expansion rate should be used in development of the usability criterion.

The criteria developed can be used as guidance for the use of steel slag as a granular material. It can also be used for other nonferrous slags. For nonferrous slags, or slags with different physical properties, it is important to conduct a laboratory testing to identify the volume expansion differentials, i.e., K_{25}, which may need to substitute the factor in Eqs. (8) and (9), before use the criteria.

In most cases, volume expansion rate of steel slag granular base materials are smaller than the void content. This is partially because of the porosity and honeycomb shaped surfaced property. Further wok should be done to find the relationships between various physical characteristics of slag aggregate and the volume differentials, or the differentials based on different surcharges.

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References

[1] E. Tsakiridis, G.D. Papadimitrious, S. Tsivilis, et al., Utilization of steel slag for portland cement clinker production, J. Hazard. Mater. 152 (2) (2008) 805–811.

[2] C. Shi, Steel slag—its production, processing, characteristics, and cementitious properties, ASCE J. Mater. Civil Eng. 16 (3) (2004) 230–236.

[3] W Shen, M. Zhou, W. Ma, et al., Investigation on the application steel slag-fly ash-phosphogypsum solidified material as road base material, J. Hazard. Mater. 164 (1) (2009) 99–104.

[4] P. Suer, J. Lindqvist, M. Arm, et al., Reproducing ten years of road ageing—accelerated carbonation and leaching of EAF steel slag, Sci. Total Environ. 407 (2009) 511–518.

[5] H. Motz, J. Geiseler, Products of steel slags an opportunity to save natural resources, Waste Manage. 21 (2001) 285–293.

[6] P. Ahmedzade, B. Sengoz, Evaluation of steel slag coarse aggregate in hot mix asphalt, J. Hazard. Mater. 165 (2009) 300–305.

[7] Y. Xue, S. Wu, H. Hou, et al., Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture, J. Hazard. Mater. B138 (2006) 261–268.

[8] Y. Huang, R. Bird, O. Heidrich, A review of the use of recycled solid waste materials in asphalt pavements, Resour. Conserv. Recy. 52 (2007) 58–73.

[9] American Society for Testing and Materials, Standard test method for potential expansion of aggregates from hydration reactions, ASTM D 4792-00, Reapproved 2006.

[10] G. Wang, J. Emery, Technology of slag utilization in highway construction, in: Annual Conference of Transportation Association of Canada, Quebec City, Quebec, 2004.

[11] US Federal Environment Protection Agency, Use of Recycled Industrial Materials in Roadways, available at http://www.epa.gov/osw/conserve/rrr/imr/pdfs/roadways.pdf (accessed on April 30, 2010).

[12] US Geological Survey, Industrial Solid Wastes, available at http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/790400.pdf (accessed on April 12, 2010).

[13] G. Wang, Determination of expansion force of steel slag coarse aggregate, J. Const. Mater. 24 (2010) 1961–1966.

[14] G. Zhu, S. Sun, Should speed up the utilization of iron and steel slag, China Steel (1) (2007) 23–27.

[15] R. Sersale, V. Amicarelli, G. Frigione, et al., A study on the utilization of an Italian steel slag, in: Proc. 8th International Congress on the Chemistry of Cement, Rio de Janeiro, Brazil, 1986, pp. 194–198.

[16] D. Montgomery, G. Wang, Engineering uses of slag—a by-product material, in: Proceedings of the International Conference on Environmental Management, Geo-Water & Engineering Aspects, NSW, Australia, 1993.

[17] M. Thomson, Why is types hydrated lime special? in: International Building Lime Symposium, Orlando, Florida, 2005.

[18] F. Lea, Chemistry of Cement and Concrete, 4th ed., Chemical Publishing Company, Inc., 2004.

[19] J. Geiseler, Use of steel works slag in Europe Waste Manage. 6 (1–3) (1996).

[20] Y. Wang, D. Lin, The steel slag blended cement, Silic. Ind. 6 (1986) 121–126.

[21] US Federal Highway Administration, Recycled materials in highway environment, available at http://www.tfhrc.gov/hnr20/recycle (accessed on May 2, 2010).

[22] J. Piret, Upgrading of LD slag: general aspects of the problem and achievements in the road building industry, Translation from French by Hamilton, EC for BHP Central Research Laboratories, Translation No. CRL/T 8122, 1977, 13 pp.