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Geo-engineering properties of granulated blast furnace slag

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ABSTRACT: Blast furnace slag material is a co-product of the iron manufacturing process. The slag material is formed when the lime in the flux chemically combines with the silica and alumina of the iron ore and coke ash. Granulated blast furnace slag is the non-metallic, sand-like material that is produced when the molten slag is rapidly cooled by water quenching. This paper presents the results of a series of geotechnical laboratory tests that were conducted on two granulated blast furnace slag materials. Both materials were classified as well-graded gravely sands that comprised glassy, serrated angular grains. The specific gravity of solids values of 2.41 and 2.67, which were measured for the two slag materials, differed on account of the different proportions of air bubbles that had become trapped within the constituent grains on water quenching the molten slag materials shortly after being tapped from the blast furnaces. A very dense state (maximum dry densities of 1.34 and 1.47 tonne/m^3) was readily achieved by compaction. When the peak shear stresses measured in shearbox tests had been corrected for dilatency effects, the angle of internal friction value was found to have remained largely unchanged at between 39 and 40 degrees over the applied normal stress range of 0 to 400 kN/m^2. Both blast furnace slag materials were free draining with measured hydraulic conductivity values in the range of 1.8–3.4 x10^{-3} m/s in the medium dense to dense states.

1 INTRODUCTION

Blast furnace slag material, a co-product of the iron manufacturing process, is produced in large quantities annually. The smelting process reduces the iron ore to molten iron when coke material is burned in a blast furnace at a temperature of about 3,000^{o}C. The slag material forms when the lime in the flux (limestone or dolomite) chemically combines with the silica and alumina of the iron ore and coke ash. Table 1 lists typical mineralogical compositions of blast furnace slag material.

The engineering properties of the slag material are largely determined by the rate at which the molten slag material (tapped periodically from the blast furnace) is cooled. Granulated slag is the non-metallic, glassy, sand-like material that is produced when the molten slag is rapidly quenched by immersion in water. Other factors that influence the engineering properties include the method of iron production; the chemical composition of the different input materials and the temperature of the molten slag just prior to water quenching. The molten slag can be cooled at a slower rate using either steam or ambient air, although this gives rise to greater void space within the constituent grains. The granulated slag material has been used in the construction of highway embankments and pavements; as a backfill material, and soil-cement. In the powdered state, the slag material has been used as a supplementary cementatious material in Portland cement concrete.

Constituent	**Weight (%)**
Lime (CaO)	32 – 45
Magnesium oxide (MgO)	5 – 15
Silica (SiO_2)	32 – 42
Alumina (Al_2O_3)	7 – 16
Sulphur (S)	1 – 2
Iron oxide (FeO, Fe_2O_3)	0.1 – 1.5
Maganese oxide (MnO)	0.2 – 1.0

Table 1. Typical compositions of blast furnace slag (Lewis, 1982).

This paper presents the geo-engineering properties of two blast furnace granulated slag materials, which were sourced from blast furnaces in Dunkirk (France) and Ghent (Belgium). The slag materials were found to naturally cement during storage over a long period of time, Fig. 1. However, the geotechnical laboratory tests were conducted on the disaggregated materials so that the measured engineering properties are representative of slag material that has been recently stockpiled or placed onsite. Aging (natural cementation) will increase the shear strength of the slag material, thereby increasing the factor of safety on bearing capacity type failure and slope instability in the longer term.

Figure 1. Naturally cemented slag material.

2 PHYSICAL AND CHEMICAL PROPERTIES

Grading curves for the Dunkirk and Ghent slag materials are shown in Fig. 2. Both materials were greyish white, well-graded gravely sands that comprised serrated, angular grains. The natural water content of the stockpiled materials was between about 9 and 12%. Some physical and chemical properties of the materials are listed in Table 2.

Property	**Dunkirk**	**Ghent**
Effective size (D_{10}) (mm)	0.42	0.32
Coefficient of uniformity	3.3	3.1
Coefficient of curvature	1.1	1.1
Specific gravity of solids	2.41	2.67
Maximum void ratio	1.22	1.26
Minimum void ratio	0.80	0.82
Maximum dry density (tonne/m^3)	1.34	1.47
Minimum dry density (tonne/m^3)	1.09	1.18
Sulphate content (mg/l)	110	176
pH	12	12

Table 2. Some properties of the granulated slag materials.

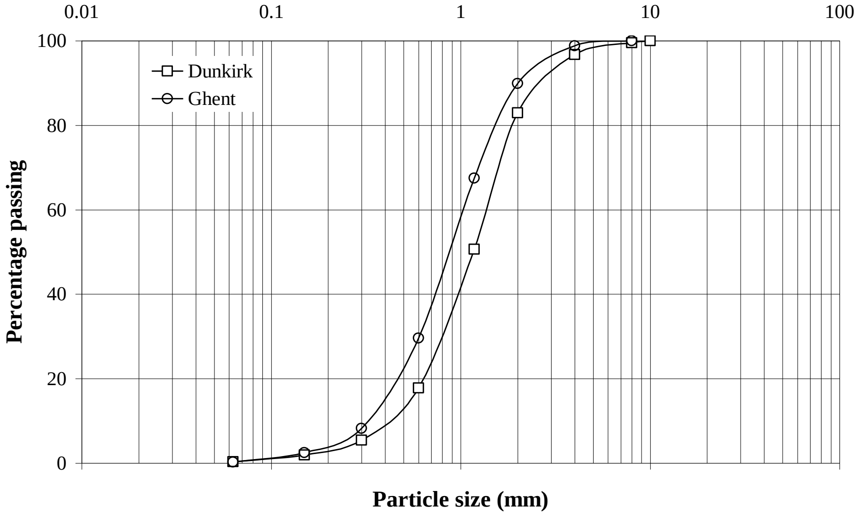


Figure 2. Particle size distribution of slag materials.

The specific gravity of solids value of 2.67 measured for the Ghent slag is identical to that of quartz sand. Some of the constituent grains of the Dunkirk slag had a pumice-like structure, which would account for its slightly lower specific gravity of solids value of 2.41. The Dunkirk slag had more internal void space, with greater proportions of air bubbles trapped within its constituent grains, and most likely occurred due to a marginally slower rate of water quenching for the molten Dunkirk slag material.

Although the grading curves, and hence the limiting states of densification that can be achieved for both materials were similar, the density values for the Dunkirk slag (lower specific gravity of solids) were marginally lower than that of the Ghent slag. The minimum dry density values of 1.09 and 1.18 tonne/m^3 were measured for the Dunkirk and Ghent slag materials, respectively, by pluviating the disaggregated, oven-dried material into a one-litre graduated cylinder, such that the constituent grains fell freely on an individual basis, thereby forming a grain structure in its loosest state. Distilled water was then added to the slag material in the graduated cylinder and the saturated specimen was vibro-compacted using a mechanical shaker in order to obtain a grain structure in its densest state. Maximum dry density values of 1.34 and 1.47 tonne/m^3 were measured for the Dunkirk and Ghent slag materials, respectively.

Saturated test specimens of the slag material were allowed to soak in distilled water for a period of 24 hours following which the sulphate content and pH values of the slag leachate were measured using a Merck® sulphate test-kit and an electrometric method, respectively. The high pH value of 12 measured for the leachate was due to the high lime and magnesia contents of the slag materials.

3 DENSIFICATION

Figure 3 shows the density versus water content relationships measured under standard Proctor compactive effort for the two slag materials. The dry density values of about 1.3 and 1.4 tonne/m^3 that were measured for the Dunkirk and Ghent slag materials, respectively, were consisted with the values determined by vibro-compaction (Table 2), and indicates that a very dense state can be readily achieved onsite.

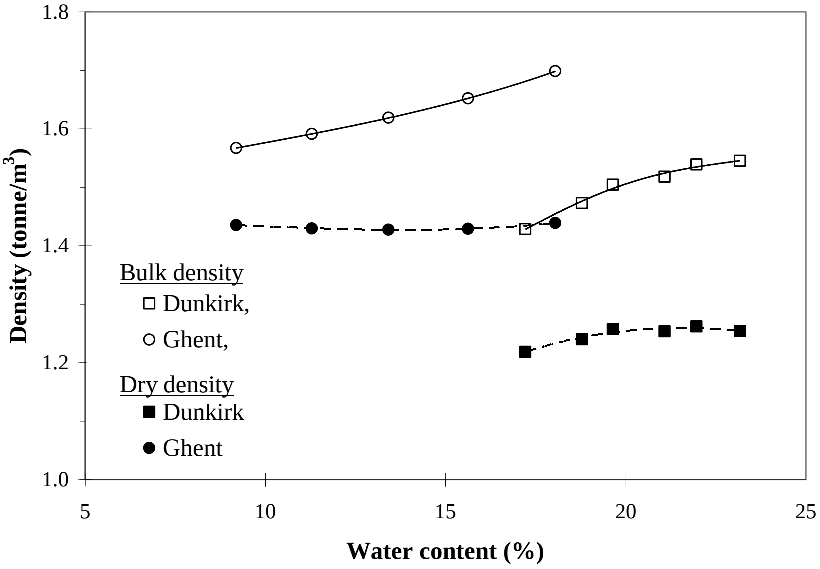


Figure 3. Density versus water content for standard Proctor compactive effort.

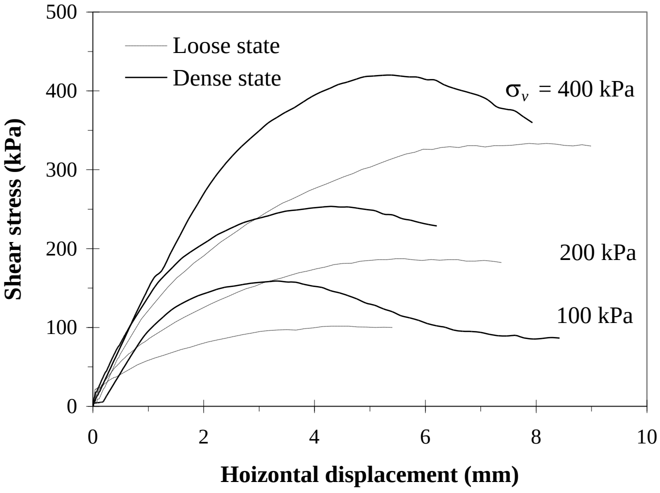
4 SHEAR STRENGTH

4.1 *Shear strength measurement*

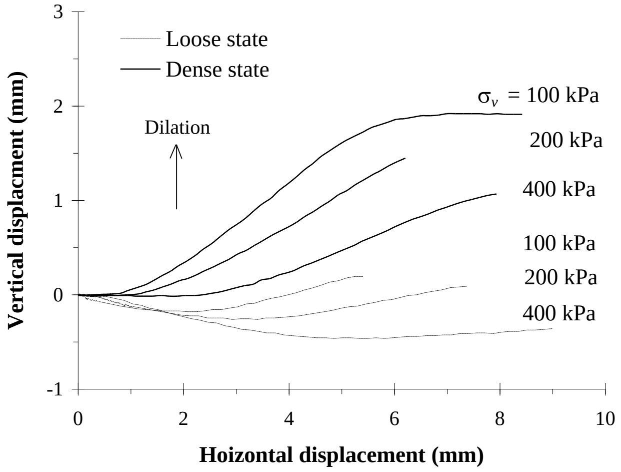
The values of the shear strength parameters were determined from shearbox tests conducted on sets of dry specimens of the disaggregated slag materials. These measured values are consistent with the most critical condition for geotechnical stability in which the slag materials have been recently stockpiled or placed onsite. The shear resistance of the undisturbed slag material will progressively increase due to the natural cementation of the fine slag dust that occurs at the grain contacts. A sieve analysis was also carried out on the shearbox specimens at the end of the shearbox tests, and these grading curves were compared with those plotted in Fig. 2 in order to determine whether crushing of the individual slag grains had occurred over the range of normal stresses applied. Finally, California Bearing Ratio penetration tests, which are used to determine the suitability of materials as sub-base or subgrade in highway construction, were carried out on the densified slag materials.

4.2 *Shearbox tests*

Shearbox tests were conducted on sets of very loose and very dense specimens using a 60-mm square by 20-mm deep shearbox. The slag material was dried in an oven at a temperature of 105°C, and sieved to pass the 2.0 mm sieve size. Specimens were prepared in the very loose state by rapidly pouring the slag material into the shearbox from the small height. Very dense specimens were prepared by vibro-compacting the material under a small surcharge provided by the shearbox top-loading platen. Both sets of specimens were sheared at a rate of 0.6 mm/min under applied normal stresses of 100, 200 and 400 kN/m^2. A comparison of the grading curves determined for the slag materials both before and after shearbox testing confirmed that no significant crushing of the individual slag grains had occurred over this range of applied stresses. The shear stress and vertical displacement versus horizontal displacement responses measured for the Dunkirk and Ghent slag materials are shown in Figs. 4 and 5, respectively.



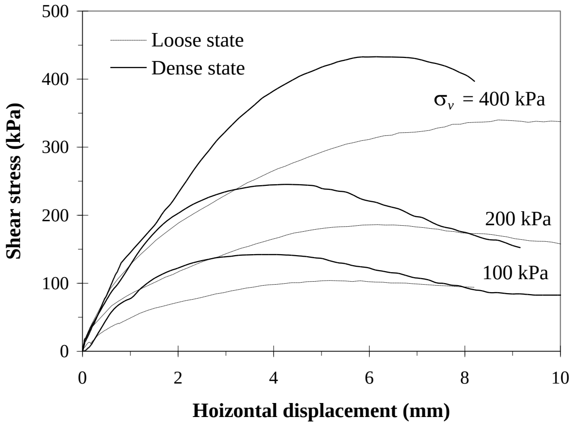
(a) Shear stress versus horizontal displacement.



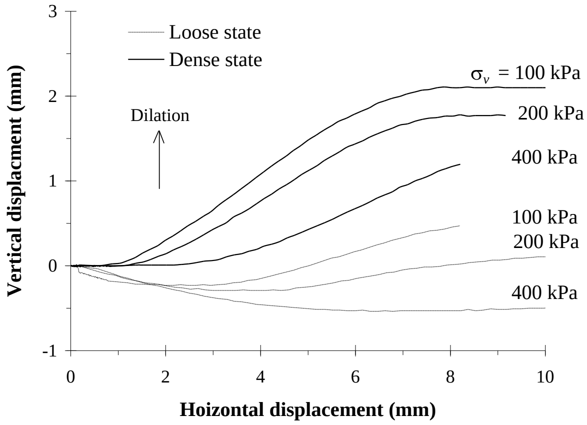
(b) Vertical displacement versus horizontal displacement.

Figure 4. Shearbox data for Dunkirk slag.

The peak shear stress values mobilised under the different normal stresses in the shearbox tests are plotted in Fig. 6. The very dense specimens experienced marked dilatency during shearing. Hence, the peak shear stress values were corrected for dilatency effects using the Bishop method (Bishop, 1971), and the resulting Mohr failure envelops are plotted in Fig. 7. The Mohr failure envelope for the very dense slag was slightly curved, as is generally the case for dense sand. The angle of internal friction value was between 39 and 40 degrees over the applied stress range (irrespective of the level of densification), which is consistent with the values reported for gravely sands by Head (1994).



(a) Shear stress versus horizontal displacement.



(b) Vertical displacement versus horizontal displacement.

Figure 5. Shearbox data for Ghent slag.

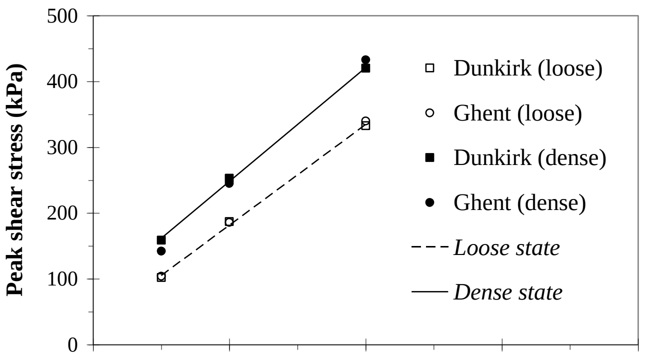


Figure 6. Peak shear stress related to normal stress from shearbox tests.

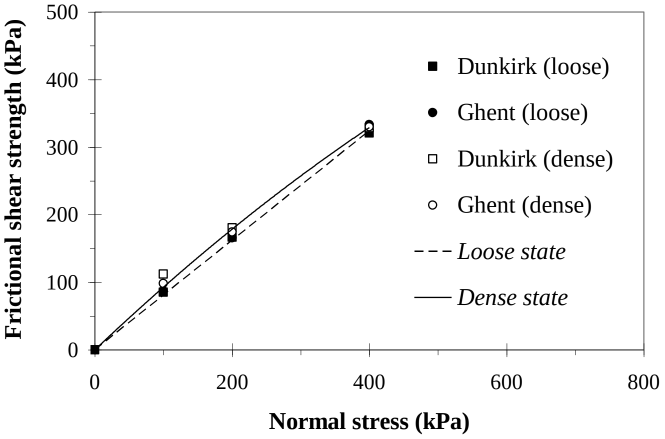


Figure 7. Mohr failure envelopes for frictional shear strength.

4.3 *California Bearing Ratio tests*

The California Bearing Ratio (CBR) penetration tests were performed on damp slag material that had been standard Proctor compacted in a CBR mould to achieve the maximum dry density. Figure 8 shows the loads that were applied to the CBR piston to penetrate the ends of the specimen at a rate of 1.0 mm/min. The corrected CBR values corresponding to penetrations of 2.5 and 5.0 mm at both the top and bottom ends of the specimen are listed in Table 3.

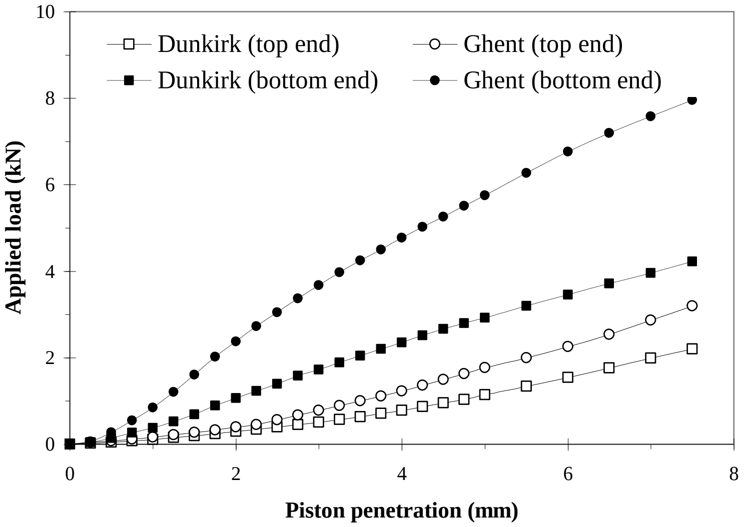


Figure 8. Applied load versus piston penetration from CBR tests.

The CBR values corresponding to the bottom end of the specimen were consistently higher since the compaction method produced the greatest level of densification at this end of the specimen. The measured CBR values of 16 and 31% for the Dunkirk and Ghent slag materials, respectively, are typical of gravely sands (Head, 1994), and indicate that both slag materials are readily suited for use in pavement construction from the subgrade level right up to the surfacing layer.

Penetration		CBR (%)	
		Dunkirk	Ghent
2.5 mm	top	3.0	4.2
	bottom	13.2	27.9
5.0 mm	top	5.8	8.8
	bottom	16.0	31.1

Table 3. Corrected CBR values.

5 PERMEABILITY

Constant head permeability tests were conducted on the saturated, medium-dense to dense slag materials using a 75-mm diameter permeameter cell at an ambient laboratory temperature of 20°C. The hydraulic conductivity values of the Dunkirk and Ghent slag materials were 3.4×10^{-3} and 1.8×10^{-3} m/s, respectively, which is typical of sand and sand-gravel mixtures (Head, 1994).

6 SUMMARY AND CONCLUSIONS

The geo-engineering properties of two granulated, blast furnace slag materials have been presented. The materials were classified as well-graded, gravely sands comprising glassy, serrated angular grains. The specific gravity of solids (G_s) values were 2.41 and 2.67, with the lower value explained by the greater proportion of air bubbles that had become trapped within the constituent grains on water quenching the molten slag material after it had been tapped from the blast furnace. The pH value of 12 measured for the leachate was high on account of the high lime and magnesia contents of the slag. A very dense state (dry densities of 1.34 and 1.47 tonne/m^3 corresponding to G_s = 2.41 and 2.67, respectively) was readily achieved by vibro or standard Proctor compaction.

When the peak shear stress values measured in the shearbox tests were corrected for dilatency effects, the angle of internal friction value remained largely unchanged at between 39 and 40 degrees, irrespective of the level of densification. Crushing of the constituent grains did not occur during shearing under vertical applied stresses of up to 400 kN/m^2. The slag materials were free draining, with hydraulic conductivity values of 1.8–3.4 $\times10^{-3}$ m/s measured for the material in the medium-dense to dense states. Overall, the slag materials are readily suited for highway embankment and pavement construction.

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