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Geotechnical Properties of Two Granulated Blast Furnace Slag Materials

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Abstract

Blast furnace slag, a co-product of iron manufacture, 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. The results of a series of geotechnical laboratory tests that were conducted on two granulated slag materials are presented. Both materials were classified as well-graded gravely sands comprising glassy, serrated angular grains. The specific gravity of solids of 2.41 and 2.67 differed on account of different proportions of air bubbles becoming trapped within the constituent grains after water quenching the molten slag materials from the blast furnaces. A very dense state, with maximum dry unit weights of 1.34 and 1.47 tonne/m^3, was readily achieved by compaction. When the peak shear strengths measured in shearbox tests were corrected for dilatency effects, the angle of internal friction of was found to have remained largely unchanged at 39–40 degrees over the of normal stress range 0–400 kPa. The slag materials were free draining with coefficient of permeability values in the range 1.8–3.4 x10^{-3} m/s.

Keywords: Blast furnace slag, Engineering properties, Geotechnical, Granulated

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INTRODUCTION

Blast furnace slag material, a co-product of iron manufacture, is produced in large quantities annually. The smelting process reduces the iron ore to molten iron when coke material is burned in the blast furnace at about 3,000°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. Typical mineralogical compositions of blast furnace slag are listed in Table 1.

Table 1. Typical compositions of blast furnace slag material [1].

Constituent	Weigth (%)
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

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

This paper presents the geotechnical properties of two granulated slag materials sourced from blast furnaces in Dunkirk (France) and Ghent (Belgium). The slag materials naturally cemented over a long period of time, Fig. 1. However, the geotechnical laboratory tests were conducted on the disaggregated materials yielding engineering properties that are representative of material recently stockpiles or placed onsite.

Fig. 1. Naturally Cemented Ghent Slag Material

PHYSICAL AND CHEMICAL PROPERTIES

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

Table 2. Some properties of the granulated slag materials.

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
Max dry unit weight (tonne/m^3)	1.34	1.47
Min dry unit weight (tonne/m^3)	1.09	1.18
Sulphate content (mg/l)	110	176
pH	12	12

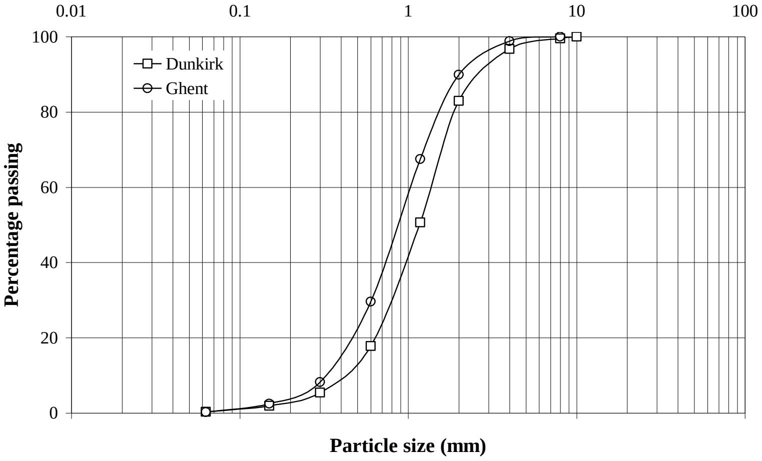


Fig. 2. Grading Curves

The specific gravity of 2.67 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 accounted for its lower specific gravity of solids value of 2.41. More internal void space had formed since greater proportions of air bubbles had become trapped within the constituent grains most likely due to a marginally slower rate of quenching the molten slag material.

The minimum dry unit weights of 1.09 and 1.18 tonne/m^3 were determined by pluviating the disaggregated, oven-dried material into a one-litre graduated cylinder such that the grains fell freely on an individual basis, thereby forming a grain structure in its loosest state. Distilled water was then added to the graduated cylinders and the saturated specimens were vibro-compacted using a mechanical shaker to form a grain structure in its densest state with maximum dry unit weights of 1.34 and 1.47 tonne/m^3, respectively. Although the grading curves and hence the limiting states of densification achieved for both materials were similar, the unit weights of the Dunkirk slag were marginally lower due to its lower specific gravity of solids.

The sulphate contents and pH values of the slag leachates were measured using a Merck® sulphate test-kit and an electrometric method after the slag specimens had been allowed to soaked in distilled water for a period of 24 hours. The high pH of 12 measured for both slag leachates arose due to their high lime and magnesia contents.

COMPACTION

Figure 3 shows compacted unit weight versus water content data for the slag materials determined using standard Proctor compaction tests. The dry unit weights of about 1.3 and 1.4 tonne/m^3 obtained for the Dunkirk and Ghent slag materials, respectively, were consisted with the values determined by vibro-compaction (Table 2) indicating a very dense state of compaction can be readily achieved onsite.

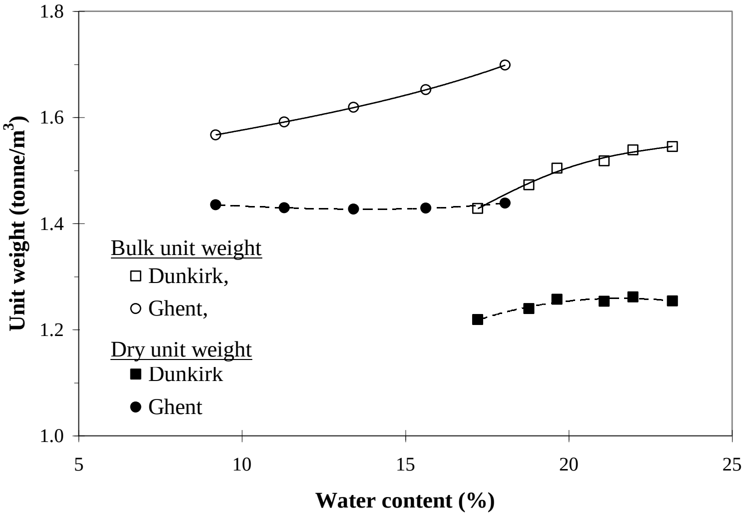


Fig. 3. Compacted Unit Weight Versus Water Content

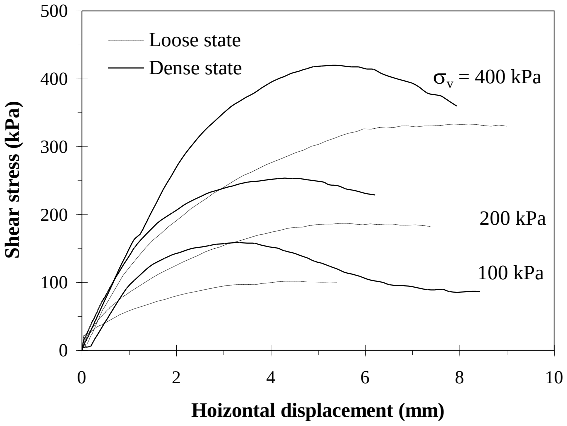
SHEAR STRENGTH

Shear Strength Measurement

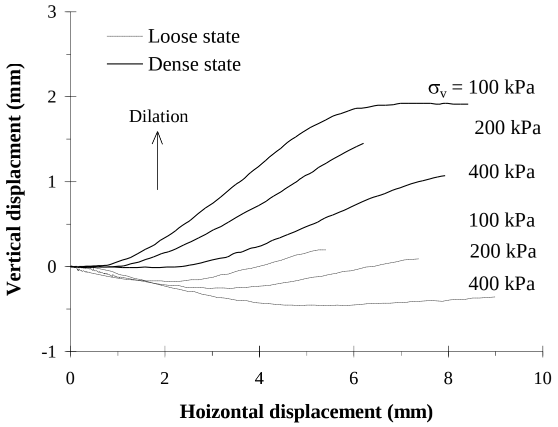
The shear strength parameters for the disaggregated slag materials were determined from shearbox tests on sets of dry, very loose and very dense specimens. The ranges of values measured for the stress parameters are consistent with those of the most common case for geotechnical stability calculations where the slag materials have been recently stockpiled or placed onsite. The shear resistance of the undisturbed material progressively increases due to natural cementation of fine slag dust at the grain contacts. Sieve analysis was carried out on the specimens at the end of the shearbox tests and the grading curves were compared with those plotted in Fig. 2 to determine whether crushing of the individual grains had occurred over the range of applied normal stresses. California Bearing Ratio penetration tests, used to determine the suitability of materials as subbase or subgrade in highway construction, were also carried out on the densified slag materials.

Shearbox Tests

Direct shear tests were conducted on sets of very loose and very dense specimens using a 60-mm square by 20-mm deep shearbox. The test material was oven dried and passed the 2 mm sieve size. Very loose specimens were prepared by rapidly pouring the materials into the shearbox from a small height. Very dense specimens were prepared by vibro-compacting the materials under a small surcharge provided by the shearbox loading pad to achieve the maximum dry unit weights. The 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 for the materials both before and after shearbox testing confirmed that crushing of the individual grains had not occurred over this stress range. The shear stress and vertical displacement versus horizontal displacement responses for the Dunkirk and Ghent slag materials are shown in Figs. 4 and 5, respectively.



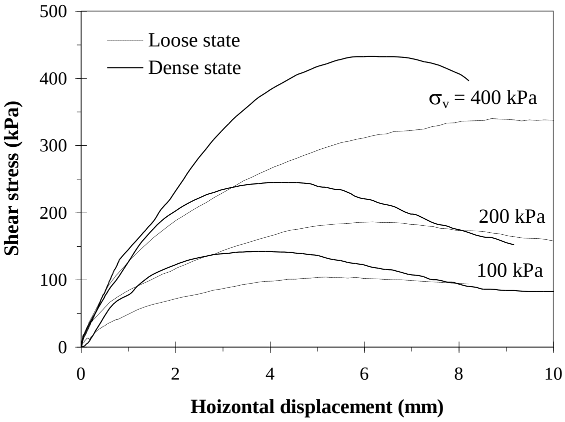
(a) Shear Stress–Horizontal Displacement



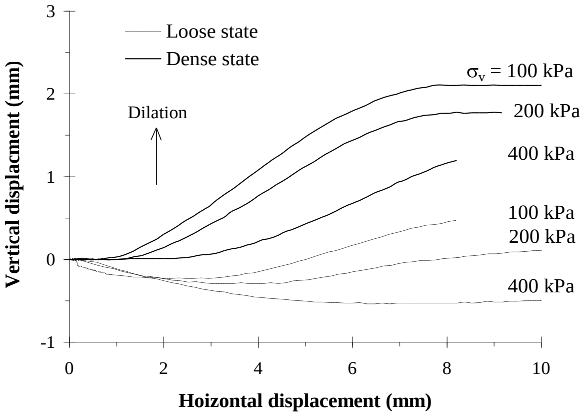
(b) Vertical Displacement–Horizontal Displacement

Fig. 4. Shearbox Data for Dunkirk Slag

The sets of very dense specimens experienced marked dilatency. The measured peak shear strength was corrected for dilatency effects [2] and the Mohr failure envelops are plotted in Fig. 6. The failure envelope for the very dense slag specimens was curved, as is generally the case for dense sands. The angle of internal friction of the very loose and very dense specimens remained largely unchanged at 39–40 degrees over the stress range and was consistent with the values reported for gravely sands by Head [3].



(a) Shear Stress–Horizontal Displacement



(b) Vertical Displacement–Horizontal Displacement

Fig. 5. Shearbox Data for Ghent Slag

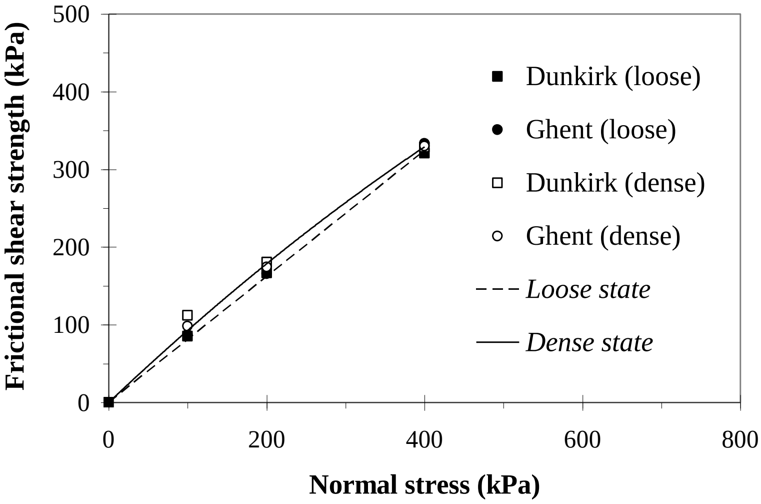


Fig. 6. Mohr Failure Envelopes for Frictional Shear Strength

California Bearing Ratio Penetration Tests

The California Bearing Ratio (CBR) penetration tests were performed on damp, slag specimens that had been standard Proctor compacted to achieve the maximum dry unit weights. The loads that were applied to the CBR piston in order to penetrate the specimen ends at a rate of 1.0 mm/min are shown in Fig. 7. The corrected CBR values corresponding to penetrations of 2.5 and 5.0 mm at the top and bottom ends of the specimens are listed in Table 3.

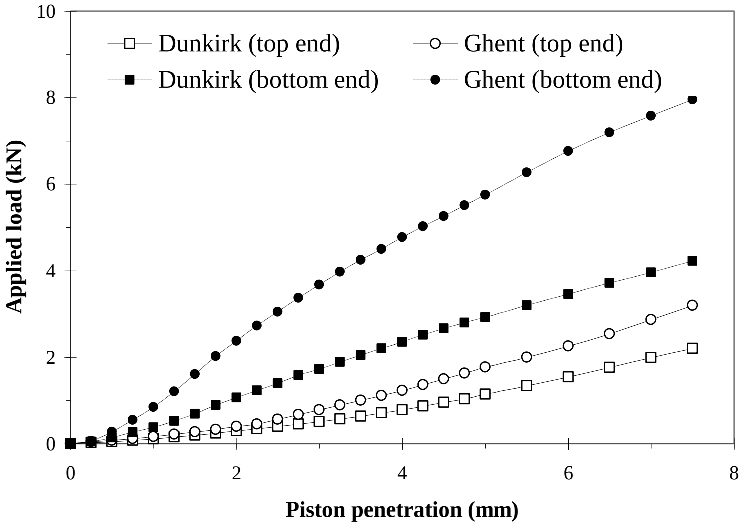


Fig. 7. Applied Load Versus Piston Penetration from CBR Tests

Table 3. Corrected CBR values.

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

The CBR values for the bottom end were consistently higher since the level of densification achieved was highest at this part of the specimen arising from the compaction method. The CBR values of 16 and 31 % for the Dunkirk and Ghent slag materials, respectively, are typical of gravely sands [3] and indicate that both materials are readily suited for use in the pavement construction, from the subgrade level right up to the surfacing layer.

PERMEABILITY

Constant head permeability tests were conducted on saturated, medium-dense to dense slag specimens using a 75 mm diameter permeameter cell at ambient laboratory temperature of 20°C. The coefficient of permeability of the Dunkirk and Ghent slag materials were 3.4×10^{-3} and 1.8×10^{-3} m/s, respectively, typical of sand and sand-gravel mixtures [3].

SUMMARY AND CONCLUSIONS

The geotechnical properties of two granulated, blast furnace slag materials were studied. The materials were classified as well-graded, gravely sands comprising glassy, serrated angular grains. The specific gravity of solids were 2.41 and 2.67, with the lower value arising on account of greater proportions of air bubbles becoming trapped in the constituent grains on water quenching the molten slag materials from the blast furnaces. The pH of 12 for the leachates were high on account of the high lime and magnesia contents. A very dense state, with dry unit weights of 1.34 and 1.47 tonne/m^3, was readily achieved by vibro or standard Proctor compaction. When the peak shear strengths measured in shearbox tests were corrected for dilatency effects, the angle of internal friction of the very loose and very dense specimens was found to have remained largely unchanged at 39–40 degrees. Crushing of the grains did not occur over the applied stress range of 0–400 kPa considered in the shearbox tests. The slag materials were free draining with coefficient of permeability values of 1.8–3.4 x10^{-3} m/s in the medium-dense to dense states. California Bearing Ratios of 16 and 31 % indicated that both materials are readily suited for pavement construction.

Acknowledgements

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