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Examination of Factors Affecting the Shear Strength of Granulated Blast Furnace Slag

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Abstract

Blast furnace slag (BFS) is an alternative material used in various civil engineering functions, such as stabilization of problematic soils, ready mixed concrete production, road and foundation construction and fill material. In this study the geotechnical index properties and shear strength behaviour of Granulated Blast Furnace Slag (GBFS) were determined for fine, medium and coarse grained samples at loose, medium and dense densities. The sieve analysis was performed and GBFS was divided in three sections; coarse (4.75 mm - 2 mm), medium (2 – 0.425 mm) and fine grained (< 0.425 mm) samples. The consolidated drained direct shear tests were conducted with saturated samples at a shear rate of 0.20 mm/min. The test results have shown that GBFS had comparatively higher specific gravity than usual soils (3.0 – 3.4). GBFS was basic (pH >7) and non- plastic characteristic (NP). The maximum shear stress of the samples was obtained at 5% - 10% axial deformation range. The internal friction angle of fine, medium and coarse grained samples were with in the range of 14° - 33°, 27° - 42° and 46° - 50°, respectively. The highest internal friction angle for fine and medium grained samples were obtained for dense samples. Increment of density affects the internal friction angles of medium grained samples positively. However, no significant change in the internal friction angle of the coarse grained samples was observed. The cohesion of GBFS samples ranged between 7 and 39 kPa.
Keywords: Blast furnace slag, Density, Grain size, Index properties, Friction angle, Shear strength.

1. Introduction

The BFS is a by-product material of the production of pig iron, and it is a naturally cementitious substance [1, 2, 3]. It is versatile and alternative construction material used in the civil engineering applications. The BFS is a favourable material to be utilized in many areas of civil engineering; it is used in the processes of ready concrete production, road and foundation fill, ground improvement applications, controlling soil dispersion, stabilization of soils with low bearing capacities and liquefaction resistant agents [3 - 7].

Goodarzi and Salimi (2015) studied the treatment of a dispersive soil using granulated blast furnace slag (GBFS), they found out that with a recommended curing period of 7 days, an optimum GBFS content of (20-25%) could satisfactorily stabilize dispersive clays. GBFS application could overcome the soil dispersion problem; authors reported that by the addition of 30% amount of GBFS to the dispersed soil, the plasticity index declined from the initial plasticity index of 350% to 42% [1].

Cokca et al. (2008) conducted by a study on the stabilization of expansive clays using GBFS, they observed that by adding 25% of GBFS to expansive clay, it reduced the liquid limit by 29%, plasticity index by 25% and increased the shrinkage limit by 5%. Similar to Goodarzi and Salimi (2015) they came to a conclusion of that 20% of GBFS would be enough to reduce the swelling percentage in expansive clays down to 6% [3].

O'Kelly (2008) studied the geo-engineering properties of two samples of GBFS. Author stated that the GBFS was in a very dense state of dry densities of 13.4 kN/m^3 and 14.7 kN/m^3 corresponding to specific gravities (G_s) of 2.41 and 2.67, respectively. It was also measured a pH of 12, and conducted direct shear tests and defined the internal friction angle to be very high and largely unchanged between the values of 39º and 40º, irrespective of levels of densification. It was also recorded that crushing did not occur during shearing under vertical applied force of 400 kN/m^2, and the slag materials had a hydraulic conductivity of 1.8 - 3.4x10^{-3} m/s in the medium-dense and dense states. Overall, it was concluded that the slag material was readily suitable for highway embankment and pavement constructions [8].

The main purpose of this study is to examine the usability and suitability of geotechnical design properties of GBFS for civil engineering applications. For this reason, the particle size and unit weight effects on shear strength behaviour of GBFS were investigated. Firstly, geotechnical index properties of GBFS were determined;

such as maximum dry unit weight and optimum moisture content, Atterberg limits, specific gravity and pH values. Moreover, shear strength behaviour of GBFS was determined for dense, medium and loose densities and coarse, medium and fine particle size ranges.

2. Materials and Methods
2.1 Materials

Depending on the method used to cool molten slag, different kinds of slag material are produced. These products include air-cooled blast furnace slag (ACBFS), expanded or foamed slag, pelletized slag, and granulated blast furnace slag (GBFS). The GBFS is the non-metallic, sand-like material that is produced when the molten slag is rapidly cooled by water quenching [2]. It is cooled by quenching a large amount of water to be produced in the granule structure it maintains to be later used in various geotechnical engineering areas. The GBFS has a dark grey colour and comes in different sizes and shapes, a mixture of large and small particles with angular and rounded shapes. Moreover, since it is a sub product of pig iron production and comes in bulks, it is a considerably hard material (Figure 1).

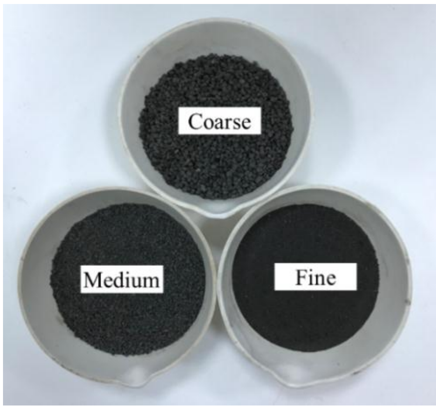

Figure 1. GBFS samples.

The GBFS used in this study, was obtained from Özerdem Demir Industry Incorporated Company in Aliağa, İzmir, Turkey.

2.2 Methods

Geotechnical index properties of GBFS material, such as Atterberg limits, specific gravity, maximum dry unit weight and optimum moisture content were determined according to ASTM and British standards, these tests were performed two times to check the repeatability [10 -13]. Firstly, sieve analysis was conducted to determine the particle size distribution of a representative sample of GBFS [9]. The particle size distribution analysis was conducted for raw (undivided) GBFS sample and it was found that it contains 4% fine-grained particle. The GBFS was divided into three sections; the particle size of the coarse-grained sample ranged from 4.75 to 2 mm. The particle size of the medium grain sample was 2 - 0.425 mm and the fine-grained sample contains particles less than 0.425 mm.

The specific gravities of the GBFS samples were determined with distilled water, pycnometer and vacuum pump [10]. The liquid limit was determined with fall cone method defined [11]. In this method, the moisture content corresponding to 20 mm penetration is defined as the liquid limit of the GBFS sample. It was determined that GBFS was non-plastic (NP) material and plasticity index were determined [12]. The maximum dry unit weight and optimum moisture content of GBFS sample was determined with compaction using Standard Proctor energy [13].

In order to determine shear strength parameters of GBFS, consolidated drained direct shear tests were performed [14]. The GBFS samples were tested for 3 different particle ranges (fine, medium, coarse) and 3 densities (loose, medium, dense). Furthermore, to achieve the required densities, the different compaction procedures were applied depending on blow numbers. Loose, medium and dense samples were mixed with water at 50% liquid limit, 25, 50 and 70 blows were applied to each of the three layers. The engineering characteristics, symbols and unit weights of samples have shown in Table1.

Table 1. Characteristic and symbols of test samples.

No	Grain size	Density	Symbol	Unit weight (kN/m^3)
1	Fine	Loose	FL	23.0
2		Medium	FM	25.0
3		Dense	FD	27.0
4	Medium	Loose	ML	21.0
5		Medium	MM	22.5
6		Dense	MD	24.0
7	Coarse	Loose	CL	19.0
8		Medium	CM	21.0
9		Dense	CD	23.0

The direct shear tests were conducted with fully automatic computer system which enables to record shear force, vertical and horizontal displacements. The GBFS samples were tested in saturated condition at three different normal stresses of 49 kPa, 98 kPa and 196 kPa, respectively. In order to prevent generation of excess pore water pressure, test samples were sheared at a speed of 0.20 mm/min. The shear stress (τ) - axial strain (ε_a) and shear stress (τ) - normal stress (σ) graphs were drawn to determine the shear strength parameters and examine the engineering behaviour of GBFS.

3. Results and Discussion
3.1 Geotechnical Index Properties

The specific gravity, pH, Atterberg limits and compaction tests were performed and obtained values are summarized in Table 2. The test results proven that GBFS was a non-plastic and alkaline material. The coarse, medium and fine grained GBFS samples had much higher specific gravities than usual soil sample (Gs ≅ 2.7).

Table 2. Engineering properties of GBFS.

GBFS	G_s	pH	LL (%)	PL (%)	w_{opt} (%)	γ_{dmax} (kN/m^3)
Fine	3.43	9.8	34.1	NP	32.0	25.0
Medium	3.14	9.9	34.1	NP	22.7	23.4
Coarse	3.06	10.2	34.1	NP	10.1	21.2

The compaction curves of fine, medium and coarse grained samples are shown in Figure 2. The unit weight of direct shear test samples prepared at medium density were equal to the maximum dry unit weight. The unit weight of the samples prepared at dense density is greater than the maximum dry unit volume weight. In order to draw reasonable compaction curve, some incompatible points were eliminated.

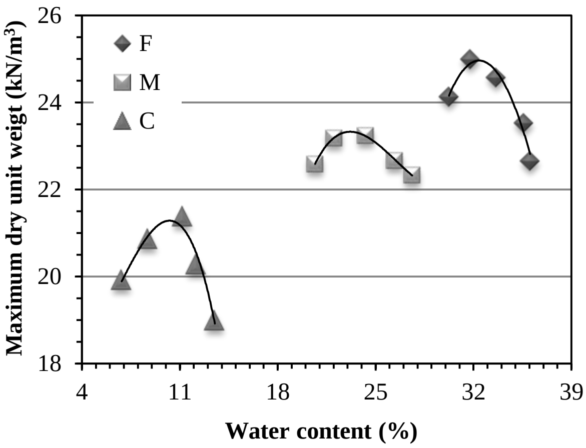

Figure 2. Compaction curves of GBFS samples.

3.2 Shear Strength Behavior of GBFS

3.2.1 Normal stress effect on shear strength

The direct shear test results have clearly shown that coarse grained GBFS sample has the higher shear stress values than medium and fine grained for dense, medium and loose densities. Figure 3 shows the axial strain (ε_a - τ) shear stress relations for fine (F), medium (M) and coarse (C) grained samples which prepared dense density at 196 kPa normal stress (σ). The average (dense, medium and loose densities) shear stress of coarse grained samples under normal stress of 196 kPa is 1.7 times higher than medium grained samples and 2.7 times higher than fine grained samples (τ_C =243 > τ_M = 141 > τ_F = 91 kPa). The coarse grained sample was more angular and rougher than medium and fine grained samples. Angularity and surface roughness positively affect the shear strength. Therefore, the shear stress of the coarse-grained sample under the similar density and normal stress was greater than the medium and fine grains. ε_a - τ curves showed that after the samples reached their maximum shear stress, while the axial stress value increased, the shear stresses remained constant.

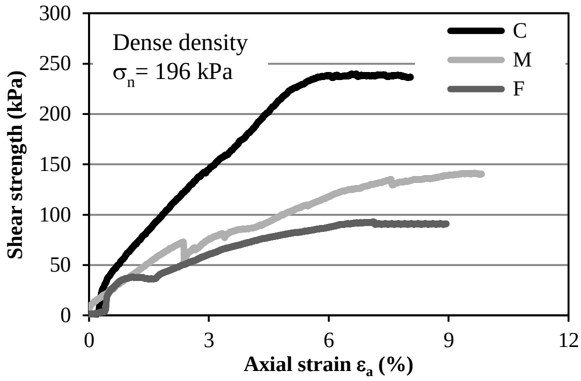

Figure 3. ε_a - τ relation of FD – MD - CD samples at σ=196 kPa.

Figure 4 shows the axial strain - shear stress relation of medium grain sized GBFS sample at medium density (M). ε_a - τ curves presented that the specimens reached the maximum shear stress values before reaching 10% axial stress. The test result indicates that show that peak shear (failure point) was not observed and shear stress remained constant when the axial strain increased.

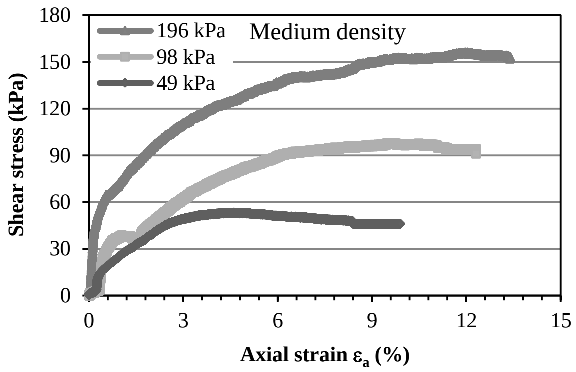

Figure 4. ε_a - τ relation of MM sample.

When the axial strain - shear stress graphs of GBFS samples were examined, it was seen that peak shear stress point equals to ultimate shear stress point and the samples reached these values at 5% - 10% axial strain range.

3.2.2 Particle size effect on shear strength

The Mohr-Coulomb failure envelopes were drawn using the maximum shear stresses and corresponding normal stresses of each sample. Figure 5 shows the failure envelopes of fine, medium and coarse grained samples prepared by the same compaction procedure (loose).

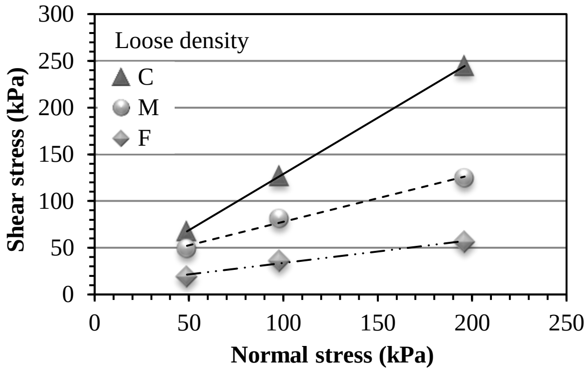

Figure 5. Failure envelopes of CL – ML – FL samples.

The lowest internal friction angle belongs to the fine grained loose prepared sample (ϕ_{FL} = 14°). Considering that the samples are prepared under the same conditions, it has determined that grain size is the highly effective factor on the internal friction angle. In addition to this, internal friction angle of coarse grained sample has almost 2 times higher than medium grained loosely prepared sample (ϕ_{CL} = 50° > ϕ_{ML} = 27°).

Similar results have been observed on fine, medium and coarse grained samples prepared at the medium density (Figure 6). A considerable increase was observed in the internal friction angle of the fine grained sample prepared at medium density (ϕ_{FM} = 23° > ϕ_{FL} = 14°).

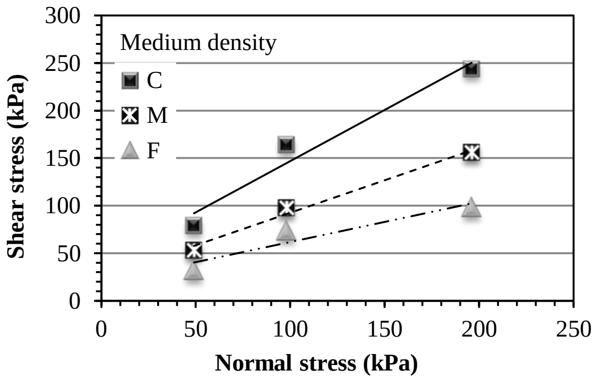

Figure 6. Failure envelopes of CM – MM – FM samples.

The increase from loose to medium density resulted in a 27% increase in the internal friction of the medium grained sample (ϕ_{MM} = 34 ° > ϕ_{ML} = 27°). On the other hand, a small reduction was observed on the internal friction angle of the coarse grained sample (ϕ_{CM} = 47°< ϕ_{CL} = 50°).

3.2.3 Compaction density effect on shear strength

In order to examine density effect on internal friction angle of GBFS, test samples were prepared at loose, medium and dense densities by specified compaction procedures. Figure 7 indicates the failure envelopes of fine grained samples prepared at loose, medium and dense state. The test results have demonstrated that as the sample density increased, the internal friction angle increased. The higher compaction energy made a tighter test sample and decreased the void ratio, increased the internal friction angle.

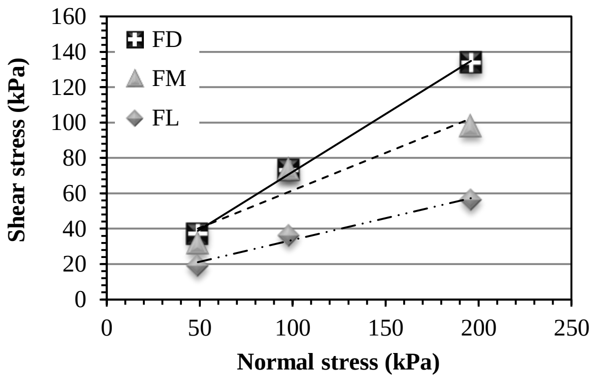

Figure 7. Failure envelopes of FD – FM – FL samples.

Figure 8 shows that the highest internal friction angle for fine grained soils belongs to FD and then follows FM and FL, respectively (ϕ_{FD} =33 ° > ϕ_{FM} = 23° > ϕ_{FL} = 14°). A higher internal friction angle difference was observed between the FL and FM samples compared to the FM and FD samples. The direct shear test results have shown that the particle size is one of the most effective parameters on the internal friction angle.

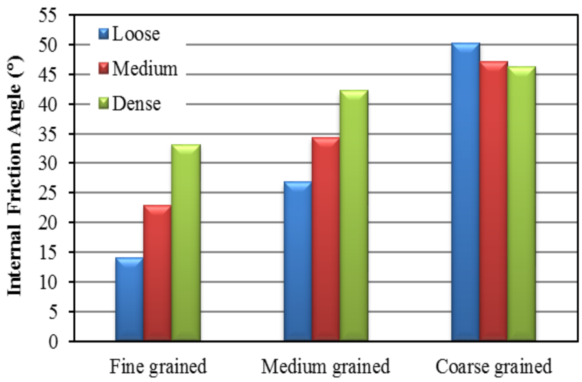

Figure 8. Internal friction angles of GBFS samples.

The coarse grained samples have the higher internal friction angles than the medium and fine grained samples prepared at loose, medium and dense densities. Increment of density plays a more effective role in fine grained samples compared to medium and coarse grained samples. Increment of density affects the internal friction angles of fine and medium grained samples positively. However, no significant change in the internal friction angle of the coarse grained samples was observed. This situation can be explained by the particle crushing caused by the high compaction energy applied. At the end of the direct shear test, the coarse grained samples were dried and sieved, indicating that the amount of fine content increased.

The shear strength parameters of GBFS samples were summarized in Table 3.

Table 3. Results of direct shear tests on GBFS.

Grain	Density	Symbol	ϕ (°)	c (kN/m^2)
Fine	Loose	FL	14	9
	Medium	FM	23	19
	Dense	FD	33	7
Medium	Loose	ML	27	27
	Medium	MM	34	24
	Dense	MD	42	15
Coarse	Loose	CL	50	8
	Medium	CM	47	39
	Dense	CD	46	39

The internal friction angle of the fine grained samples is in a wide range (14° - 33°). On the contrary, internal friction angle of coarse grained samples gets value comparatively narrow spacing (46° - 50°). It is difficult to make a general assessment of cohesion. The highest cohesion value belongs to coarse grained samples prepared at medium and dense densities (c = 39 kPa).

4. Conclusion

In this study geotechnical engineering properties and shear strength behaviour of GBFS were examined for coarse, medium and fine grained samples prepared at dense, medium and loose densities.

It was determined that GBFS material had comparatively higher specific gravity than usual soil value. The GBFS was defined as a basic (pH >7) and non-plastic (NP) material. The average pH value of GBFS was determined as 10. The direct shear tests represented that the average shear stress of coarse grained samples under normal stress of 196 kPa was 1.7 times higher than medium grained samples and 2.7 times higher than fine grained samples.

Axial strain - shear stress graphs showed that peak shear (failure point) was not observed and shear stress tends to increase with axial strain. For fine and medium grained materials internal friction angles increased with increment of density. However, because of particle crushing similar result was not observed on coarse grained samples. The density increment played the more effective role on fine grained samples. With increasing density, the internal friction angle of the fine grained sample increased sharply. It is difficult to make a general assessment about the cohesion of GBFS samples. The coarse grained samples prepared at medium and dense densities had the highest cohesion value (c = 39 kPa).

References

1. Goodarzi, A, R, Salimi, M, Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag, *Applies Clay Science*, 2015, 108, 61-69.
2. O'Kelly, B, C, Geotechnical properties of two granulated blast furnace slag materials. *Third Symposium on Bridge and Infrastructure Research in Ireland*, Dublin, 12th–13th October, 2006, 1, 121-128.
3. Cokca, E, Veysel, Y, Stabilization of Expansive Clays Using Granulated Blast Furnace Slag (GBFS) and GBFS-Cement, *Geotechnical and Geological Engineering*, 2009, 27, 489-499.
4. Martin, P, E, Bobillon, G, Eisenlohr, L, Reuse of solid waste from the clearing of road basins and ditches in civil engineering: from characterization to ways of treatment. *Houille Blanche-Revue Internationale De L'Eau*, 2008, 17, 130-136.
5. Buddhdev, B, G, Varia, H, R, Feasibility Study on Application of Blast Furnace Slag in Pavement Concrete. *International Journal of Innovative Research in Science, Engineering and Technology*, 2014, 3, 3, 10795-10802.
6. Ekincioglu, O, Gurgun, A, P, Engin, Y, Tarhan, M, Kumbaracibas, S, Approaches for sustainable cement production – A case study from Turkey, *Energy and Buildings*, 2013, 66, 136-142.
7. Poh, H, Ghataora, G, Ghazireh, N, Soil Stabilization Using Basic Oxygen Steel Slag Fines. *J. Mater. Civ. Eng*., 2006, 18, 2, 229-240.
8. O'Kelly, B, C, Geo-engineering properties of granulated blast furnace slag, Proceedings, Innovative Geotechnical Engineering, *International Conference on Geotechnical Engineering*, Tunis, Tunisia, 24th–26th March, 1, 2008, 249 – 257.
9. ASTM D6913-04(2009)e1, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, *ASTM International, West Conshohocken*, PA, 2009.
10. ASTM D854-14, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, *ASTM International, West Conshohocken*, PA, 2014.
11. Methods of test for soils for civil engineering purposes, *British Standard Institution*, 2016, London, UK.
12. ASTM D4318-10e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, *ASTM International, West Conshohocken*, PA, 2010.
13. ASTM D698-12e2, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m^3)), *ASTM International, West Conshohocken*, PA, 2012.
14. ASTM 3080, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, *ASTM International, West Conshohocken*, PA, 2013.