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Optimization of the Combined Effect of Lime and Ground Granulated Blast-furnace Slag on Clayey Soil

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Abstract

This work investigates the behavior of a silty clay stabilized with 3, 6, 9, and 12 % of ground granulated blast-furnace slag (GGBS), respectively, and 1 % of quicklime used as an activator. The influence of the composite (Quicklime - GGBS) on the immediate behavior of the silty clay is studied by examining the Atterberg limits, the maximum dry density, the optimum moisture content, and the immediate bearing index. The evolution, at different curing periods (1, 7, and 28 days), of the mechanical characteristics of the treated soil, namely unconfined compressive strength, cohesion, and internal angle of friction is also studied. The increase, up to a dosage of 9%, of the GGBS content, leads to an increase in the optimum moisture content, the immediate bearing index, the unconfined compressive strength, and shear strength parameters. Paradoxically, a decrease in the plasticity index and the maximum dry density was observed.

Keywords: optimization, silty clay, GGBS, quicklime, strength parameters

1 Introduction

Clay soils, as in the case of dams, embankments, and roads, are often the site of vertical and horizontal deformations which can generate serious problems of stability and settlement, leading to very important economic damages. In the United States, annual losses due to structural damage from expansive soils are estimated at $ 2.3 billion [1]. Keeping this global issue in mind and meeting the technical and economic needs, clay soil stabilization techniques are more than necessary. Stabilization of clay soils, through the addition of hydraulic binders such as cement [2], lime [3], and fly ash [4], is an old practice. However, in road geotechnics, the application of GGBS is so far not widely used. On the other hand, the use of GGBS as the main component of alkali-activated cement or as a partial replacement for Portland cement (PC) is widely used [5]. Today, the increasing demand for GGBS is due to economic and

technical reasons and environmental concerns associated with its production. A comparative study between the environmental impacts associated with the production of GGBS and those associated with the production of PC [6] showed that the production of one ton of GGBS at an energy consumption of 1300 MJ results in only 0.07 tons of CO_2 emissions while the production of one ton of PC results in 0.95 tons of CO_2 emissions and high energy consumption of 5000 MJ. GBBS, a co-product of the steel industry, is formed when molten blast-furnace slag is rapidly cooled by immersion in water. GGBS is available in large quantities worldwide. In Algeria, the annual production of slag is estimated at 500,000 tons [7]. In addition, global crude steel production reached 200 million tons in 2015, of which five million tons of slag were produced in France alone [7]. In the United States, steel industries generate 10-15 million tons of steel slag each year, while about 15-40 % of steel slag production is sent to slag disposal sites [8]. GGBS is chemically composed of four main oxides: lime (CaO), silica (SiO_2), alumina ($A1_2O_3$) and magnesia (MgO). GGBS contains the same major oxides as Portland cement (PC) which, in the presence of water, forms cementitious hydrates similar to those forming during the hydration of PC [9]. The GGBS rate of hydration is very slow compared to that of clinker of PC because, once the slag grains come into contact with water, low basicity and low permeability gelling layer, forms around the grains preventing the dissolution of the slowing down the hydration kinetics [10]. Hence, the addition of an appropriate activator is necessary to dissolve the layer covering the GGBS grains, thus accelerating the hydraulic setting. Chemical activation of GGBS is usually performed using either calcium activation [11] or alkaline activation [12] or PC activation [9] and finally sulfate activation [13]. Thus, some studies have shown that CaO has a better potential for GGBS activation than some activators [9]. The high CaO content in GGBS, added to the clayey soils and the presence of water and calcium activator, tigger quick hydration reactions resulting in the formation of a large quantity of calcium cations Ca^{+2} and hydroxyls (OH^-). The Ca^{+2} cations react with the surfaces of clay minerals through the process of cation exchange leading to the flocculation of the particles in the form of water-insensitive lumps that result geotechnically in the decrease of plasticity of the treated soil [14]. The calcium hydrates (C-S-H, C-A-H, and C-S-A-H), occurring over time, result from two different reaction mechanisms. The first is a direct result of the hydration reaction between GGBS grains and water, which leads to the appearance of primary cementitious products in the form of gels coating the lumps [15]. The second mechanism appears thanks to the pozzolanic reaction from where, thanks to a high level of PH that increases with the increase of hydroxyl ions concentration [16], silica (SiO_2) and alumina ($A1_2O_3$) contained in the clay particles, react with the excess of calcium brought by GGBS and the activator forming insoluble calcium hydrates that are responsible for the increase in strength [17, 18]. GGBS as a binder is well established in many soil mixing applications. The effects of GGBS on the swelling properties of lime-stabilized sulfate-bearing clay soils were the concern of several studies [19, 20]. These studies showed that partial substitution of GGBS with lime in sulphate bearing soils produced significant improvements in strength development and reduced the expansion. Celik and Nalbantoglu [19] reported that, in the presence of 6 % GGBS, the swell potential of the lime-treated soil with 10,000 ppm sulfate concentration decreased from 8 % to 1 %. The potential of using other binders as an alternative to lime with GGBS for the stabilization of expansive soils was also evaluated [17, 21]. Guda [21] revealed that GGBS with 2 % of cement as an activator can be used as cushioning material to minimize the heave of expansive soil. The use of lime-activated GGBS to stabilize acid sulfate soils (ASS)

containing pyrite is another application [22, 23, 24, 25]. The effect of pyrite (FeS_2) content on the strength behavior of EngClay (an artificial clay prepared by mixing 85 % kaolin and 15 % bentonite) using lime activated GGBS was investigated [24, 25]. The results indicated that the negative effect of pyrite (FeS_2) could be reduced in acid sulfate soils (ASS) by using lime-activated GGBS and the formation of thaumasite-ettringite, a deleterious mineral, is deemed to be responsible for the degradation of strength in treated ASS. Lime-GGBS stabilized clay was also used to reduce the harmful effect of flooding in road structures and embankments [15, 26, 27]. They suggested that in roads and embankments, built on floodplains, GGBS reduced the water absorption and increased the formation of the CSH gel matrix responsible for the improvement of densification, strength, and durability. To reduce the use of PC in soft-clay stabilization, many studies investigated the efficiency of Lime-GGBS, Carbide Slag (CS)-GGBS and Alkali-GGBS compared with that of PC [18, 28]. Yi et al [18] found that the UCS after 90- a day cure, with a lime/GGBS ratio of 0.10, was 1.7 times that of PC stabilized marine soft-clay. Recently, the effectiveness of the GGBS using different types of activators in treating petroleum hydrocarbons and heavy metals contaminated soils was the subject of some studies [29, 30, 31, 32]. These studies showed that GGBS activated by different binders (Lime, PC, MgO, CaS_{O4}, fly ash) would reduce the leachability of contaminants and enhance the physical and mechanical properties in contaminated soils using stabilization / solidification technology. The objective of this research is to promote the use of GGBS, a by-product of the steel industry, in the field of civil engineering and public works which will reduce the use of traditional binders such as cement and lime. In this research, the stabilization of silty clay using a composite (lime and GGBS) will be investigated.

2 Materials Used

The soil studied in this work comes from Laghdir deposit, located about 30 km east of Skikda (Algeria), and used to build a section of the East-West highway. According to the GTR (A French guide for road earthworks, backfills and subgrade layers), the soil taken from a depth of about 2 m is a silty clay (SC) characterized by high plasticity which, at medium and low water contents, becomes highly coherent , sticky, and slippery. The plasticity index (PI) and the activity coefficient of the studied soil are respectively 30.18 % and 0.75. Based on these results, and according to Skempton's correlation [33] and Mitchell [34] between the type of clay mineral and the activity coefficient, and according to the activity classification of Skempton [33], the predominant mineral in the studied clay is mainly composed of illite as the normal active clay mineral. The GGBS is a greenish-grey color. It was kindly provided by the El Hadjar steel complex of Annaba (Algeria). It was ground with a ball mill to increase the specific surface and thus increase the hydraulic power of the slag. The value of the basicity index (BI) being superior to the unit (BI = 1.22 > 1), the GGBS used is thus basic [35]. The physico-chemical properties of soil, GGBS and the activator namely quicklime from the SODEPAC plant in Saida (Algeria), are presented in Table 1. Figure 1 shows the particle size curve of the studied soil.

Table 1: Materials properties used in the study

Materials Properties	**Value**		
	Soil	**GGBS**	**Quicklime**
GTR Classification guide	SC	/	/

Percent passing 80 µm sieve (%)	50	98	95
Specific surface Blaine (cm^2 / g)	/	4100	/
Basicity index	/	1.22	/
The product A.C (A is the Al_2O_3 content and C is the CaO content)	/	439.91	/
Natural moisture content (%)	19.55	/	/
Methylene blue value (cm^3)	7.01	/	/
Liquid limit (%)	56.54	/	/
Plastic Limit (%)	26.36	/	/
Plasticity index (%)	30.18	/	/
Consistency index	1.22	/	/
Optimum moisture content (%)	17.55	/	/
Maximum dry density (g / cm^3)	1.69	/	/
Immediate bearing index (%)	3	/	/
Organic matter (%)	1.80	/	/
Activity	0.75	/	/
CaO (%)	4.79	45.92	> 83.5
AL_2O_3 (%)	17.72	9.58	< 1.5
Fe_2O_3 (%)	6.80	5.45	< 0.5
SiO_2 (%)	51.65	37.58	< 2.5

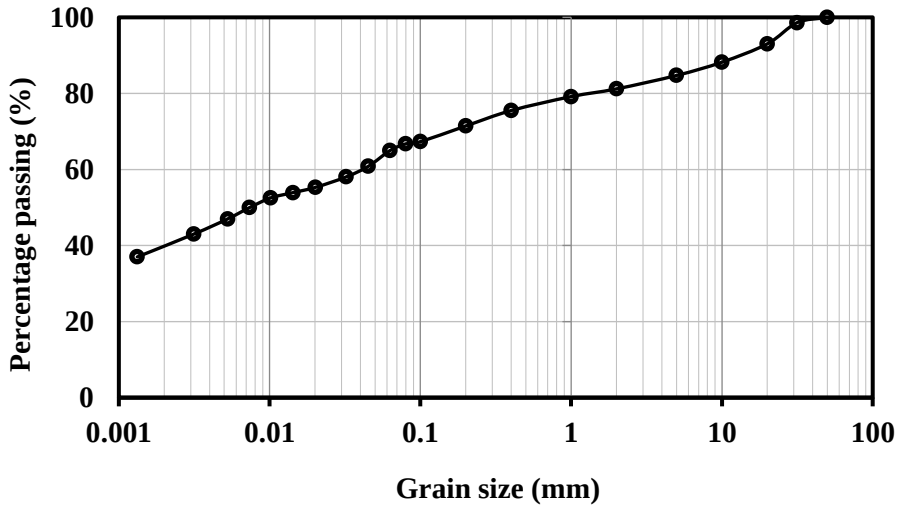

Figure 1: Grain-size curve of soil used

3 Testing Program and Sample Preparation

Several series of physico-chemical, mechanical and identification tests were carried out in accordance with French standards (AFNOR), at the university laboratory (see Figure 2, 3). The behavior of the treated soil, at different curing periods (0, 1, 7 and 28 days) was investigated using the following tests: - Atterberg limits [36] - Standard Proctor [37] - California Bearing Ratio (CBR) [38] - Unconfined compressive [39] - Direct shear [40]. After drying the samples at 105° C, passing materials are mixed with 3, 6, 9 and 12 % GGBS and 1 % quicklime, used as an activator (Table 2). In order to perform CBR, unconfined compressive

and direct shear tests, the composite samples (Quicklime - GGBS - Soil) are wetted to an optimum moisture content (OMC) determined by a standard Proctor compaction test. The treated samples are compacted in molds 101 mm in diameter and 117 mm in height [37]. For direct shear tests, specimens 60 mm x 60 mm in section and 30 mm in height are carried out under vertical loads of 50, 100, and 150 kPa. The drying of the specimens for the unconfined compressive and direct shear tests was carried out in the laboratory (average humidity of 65 % and a temperature of 20° C ± 2° C).

Table 2: Formulations of the samples

Tests	**Sieve ⌀ (mm)**	**Mass of the sample (g)**	**GGBS (%)**	**Quick lime (%)**	**Specimen (⌀, h, L, ℓ) (mm)**	**Curing time (days)**
Atterberg limits	0.4	200	0, 3, 6, 9 and 12	1	/	0
Compaction	20	2500	0, 3, 6, 9 and 12	1	⌀ = 101 ; h= 117	0
CBR	20	5500	0, 3, 6, 9 and 12	1	⌀ = 152 ; h= 152	0
Unconfined compressive	20	2500	0, 3, 6, 9 and 12	1	⌀ = 101 ; h= 117	1, 7 and 28
Direct shear	2	400	0, 3, 6, 9 and 12	1	ℓ = 60 ; L= 60 ; h = 30	1, 7 and 28



Figure 2: General view of the soil mechanics laboratory



Figure 3: Simple compression device

4 Results and Discussion

4.1 The Limits of Atterberg

Figure 4 shows that the increase in GGBS content leads to a change of the consistency of the silty clay. This change results in an increase in the plastic limit (PL) and a slight increase in the liquid limit (LL) inducing hence, a reduction of the plasticity index (PI) is observed. For 3 % GGBS content, a decrease of 17 % in PI is observed. For higher dosages, i.e., 6 and 9 %, reductions in PI of 27 and 41 % are respectively observed. Despite the large reductions in PI, 10 % with 6 % GGBS and 24 % with 9 % of GGBS, compared to the 17 % reduction in PI with 3 % GGBS content (Table 3) and, for economic reasons, a dosage of 3 % is considered as the optimum GGBS value. Nevertheless, the importance of the effect of 3 % of GGBS on IBI (Immediate Bearing Index) must be further looked over.
In its natural state, the liquid limit (LL) of the silty clay is 56.5 % and increases to 60.1 % for 12 % GGBS content. This small variation in LL may be explained by the increase in the specific surface of the silty clay due to the addition of GGBS powders. This phenomenon leads to an increase in the cation exchange capacity which increases the water adsorption capacity. The immediate changes occurring after the addition of GGBS to the soil could be explained by the hydration process of quicklime contained in GGBS and the quicklime used as a basic activator. This process would give rise to calcium Ca^{+2} cations responsible for bonding clay mineral layers called the flocculation phenomenon [41]. Flocculation, occurring after mixing, leads to the appearance of water-insensitive lumps [42].

It can be seen in Figure 4 that from 9 % GGBS onwards, no significant variation of the Atterberg limits is observed. This could probably be explained by the fact that the soil has reached its optimal lime fixation point defined by the condition: PH = 12.4 corresponds to a solution saturated with lime [43].

The addition of 9 % GGBS would therefore be more than sufficient to improve the short-term consistency of the silty clay.

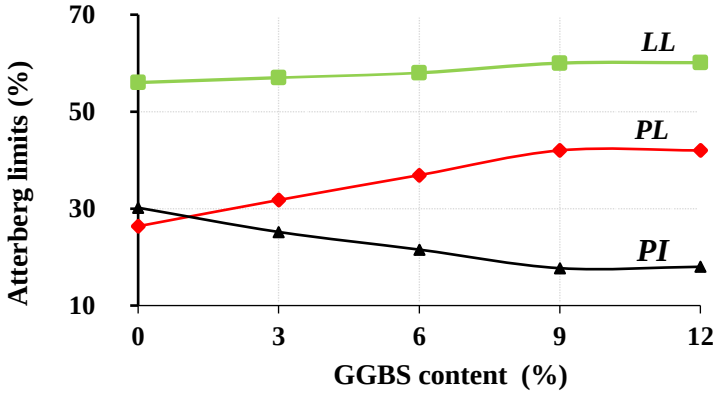

Figure 4: Effect of GGBS content on Atterberg limits

Table 3: Rate of decrease in PI for different increments of GGBS

GGBS (%)	Rate of decrease of PI (%)
0 to 3	17
0 to 6	27
0 to 9	41
3 to 6	10
3 to 9	24

4.2 Compaction Test

The compaction curve of the soil in its natural state, figure 5, shows a significant concavity, which may be due to the high sensitivity of the soil to water. On the other hand, the increase of GGBS (3, 6, 9, and 12 %) induces a progressive reduction of the soil's sensitivity to water, which results in flattening the compaction curves of the composites to a gradual decrease in slope. Furthermore, it is observed that the compaction curves of the GGBS treated specimens are located below and shifted to the right of the Proctor curve of the untreated soil. Thus, the GGBS treatment may reduce the maximum dry density (MDD) and increases the optimum moisture content (OMC). It can also be observed, in Figure 5, that an increase in the dosage of GGBS (3, 6, 9, and 12 %) induces a reduction in the MDD (3.5, 8, 11 and 12 % respectively). These reductions may be due to the following phenomenon:

- The granulometric modification, by the flocculation of the particles due to the immediate action of the quicklime contained in the GGBS and the activator, allows the lumps to occupy a larger space leading thus to an increase in the volume of the soil structure.
- The low density of GGBS also contributes to the reduction of the MDD of the composite (Quicklime - GGBS - Soil).

On the other hand, for 3, 6, 9 and 12 % of GGBS content (Figure 5), the OMC is 18.7, 19.9, 21.1 and 21.2 % respectively. These increases could be justified by the increase in the specific surface of the soil due to the addition of GGBS powders and therefore, in an increase in the water adsorption capacity.

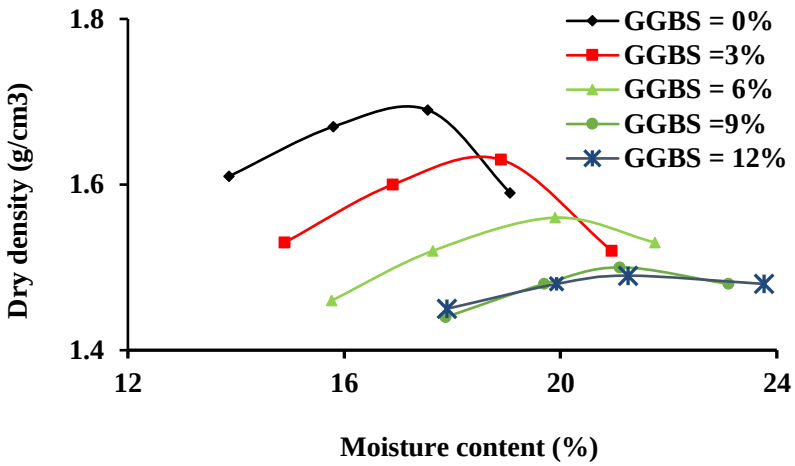

Figure 5: Effect of GGBS content on dry density

4.3 California Bearing Ratio (CBR) Test

To assess the ability of the treated soil to withstand the movements of road works construction machinery, CBR tests were performed to determine the immediate bearing index (IBI). It can be seen in Figure 6 that the IBI = 3 % of the untreated soil is lower compared to those of the treated soil samples whose increase in GGBS content (3, 6, 9 and 12 %) induced a significant increase in immediate bearing indexes (13, 21, 31 and 33 %, respectively). For a GGBS dosage of 3 %, the soil shows an IBI of 13, which satisfies the GTS [44] following criteria: - 5 < IBI < 10 for embankments; -IBI > 10 for platforms.
Hence, a GGBS content, even lower than 3 %, could ensure proper implementation of the backfill, which governed the choice of 3 % of GGBS in the formulation of the soil-GGBS-Quicklime composite. The increase in soil bearing capacity is mainly due to immediate chemical reactions, including cation exchange and flocculation, which result in a reorganization and a better distribution of the particles.

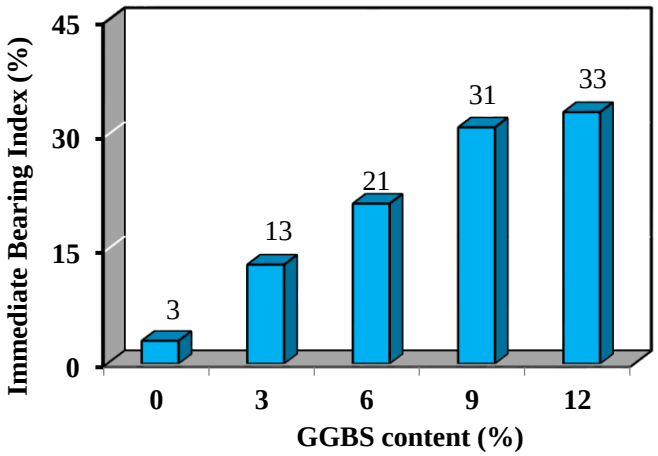

Figure 6: Evolution of the immediate bearing index as a function of GGBS content

4.4 Unconfined Compressive Test

Up to 9 % GGBS content, the unconfined compressive strength (UCS) increases progressively with the maturation of the soil-quicklime-GGBS composite (Figure 7). The addition of 3 % GGBS induces an increase in UCS of 113 % and 255 % at 7 and 28 days respectively. For 9 % GGBS content, increases in UCS of 86 % at 7 days and 280 % at 28 days are observed. However, for 3 % GGBS content and 28 days of age, the traffic criterion (According to GTS [44]), is verified: UCS = 1.09 ≥ 1 MPa. Once again, the latter result justifies the choice of 3 % of GGBS. Increasing the dosage of GGBS from 9 % to 12 %, for different curing periods, does not provide any additional strength gain, which may mean that the silty clay has probably reached its lime fixation point. The gain in UCS of the GGBS treated soil samples could be explained by the following chemical phenomena:

- The immediate actions of calcium (Ca^{+2} cations) allow the flocculation of the clay particles in the shape of water-insensitive lumps [41] favoring, the reorganization and redistribution of soil particles and therefore improving its mechanical strength.

- The hydraulic reaction of GGBS fines with water leads to the appearance of the first generation of calcium hydrates (CSH, CAH and CSAH) in the shape of gel coating the lumps. The latter favorises bonding between the lumps during compaction [15]. As the hardening of the gel takes place, a rigid shell forms [15]. This phenomenon could explain the increase in compressive strength at 7 and 28 days.

- We may consider that a pozzolanic reaction is originated by the PH increase of the medium, made possible by the hydroxide ions (OH^-) contained in the quicklime and GGBS [16]. A high PH level favorises the dissolution of silica and alumina in the clay particles. These particles in solution react with the excess calcium provided by the GGBS and the activator by forming insoluble calcium hydrates which in the presence of water form crystals, thus creating bonds of the same nature as those of the first generation [16, 17].The appearance of these types of second generation hydrates depends on the temperature, the PH of the medium and the nature of the clay minerals [43].

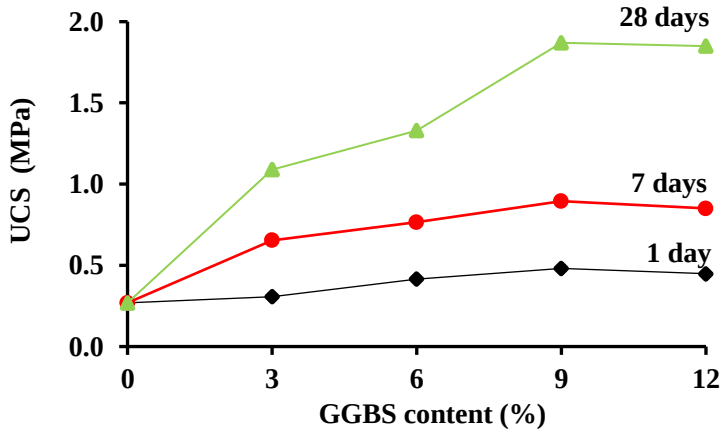

Figure 7: UCS versus GGBS for treated and untreated soil samples at different curing periods

4.5 Direct Shear Test

It can be seen in figure 8 that during the first week of cure, the increase in cohesion is slow to become faster till the 28th day. These variations over time may also be due to hydration and pozzolanic reactions [15, 17]. Regarding to the internal angle of friction (figure 9), an opposite tendency as that of the variation of the cohesion is observed. Indeed, the rate of increase of ø, during the first 7 days of treatment is fast to become slow till 28th days. This increase in the internal angle of friction would also be due to the phenomenon of flocculation responsible for the transformation of the silty clay into a lumpy structure. This reinforces the idea that the flocculation phenomenon, appearing approximately after two hours of treatment, is very significant. Nevertheless, this phenomenon begins to subside very quickly, becoming almost insignificant, after 7 and 28 days.

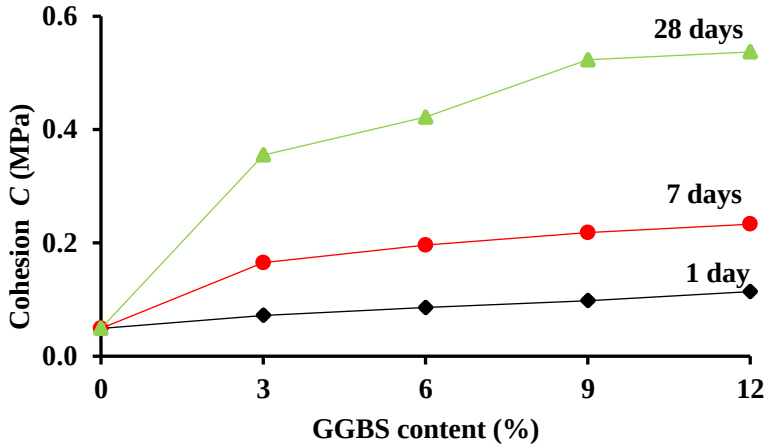

Figure 8: Cohesion versus GGBS for treated and untreated soil samples at different curing periods

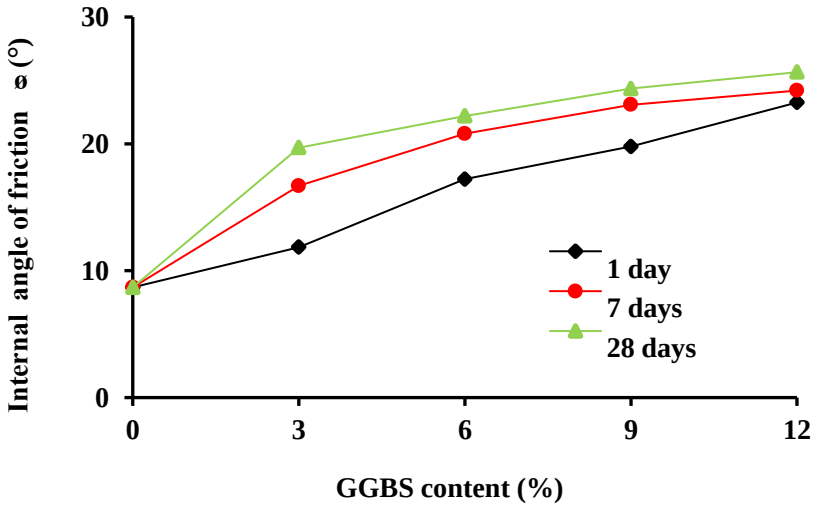

Figure 9: Internal angle of friction versus GGBS for treated and untreated soil samples at different curing periods

5 Conclusion

The use of large quantities of GGBS in the field of construction, will contribute to solving economic and environmental problems related to its storage such as well as the contamination of the water table. The use of GGBS as a hydraulic binder in the stabilization of silty clay would also reduce the use of traditional binders such as cement and lime. The aim of this work is to evaluate the hydraulic power of GGBS and highlight possible correlations between the chemical actions and the development of the physical and mechanical parameters of silty clay in road works and embankments. Several series of physico-chemical and mechanical tests were carried out and the following conclusions may be drawn:

- The addition of GGBS and quicklime to the silty clay generates immediate chemical reactions promoting the flocculation phenomenon which in turn creates lumpy structures. These observations could, possibly, be confirmed by physical and mechanical characterization tests such as the plasticity tests, the standard Proctor compaction test and the CBR test.
- For a variation of the GGBS content from 0 to 9 %, the plasticity index decreases while the consistency index of the composite (Quicklime - GGBS - Soil) increases.
- Due to the flocculation phenomenon, the granulometric modification allows the lumps to occupy a larger space, thus leading to an increase in the volume of the structure of the composite. Therefore, treatment of silty clay by adding GGBS reduces the maximum dry density and increases the optimum moisture content of the composite (Quicklime - GGBS – Soil).
- The increase of GGBS dosage leads to a significant increase in the immediate bearing index of the composite (Quiklime - GGBS - Soil), thus verifying the criterion of trafficability in the first day (IBI = 13) for a GGBS dosage of 3 %.
- Cementitious hydrates (C-S-H, C-A-H, and C-S-A-H), occurring over time, may result from two different reactions. The first one is the direct result of the hydration reaction between GGBS fines and water leading to the appearance of the first generation of calcium hydrates in shape of gel coated lumps. The second produces the second generation of calcium hydrates as a result of the pozzolanic reaction, between the clay minerals and the excess of calcium brought both by the GGBS and the activator. The development of cementitious hydrates is confirmed by the response of the following strength parameters:
- The UCS increases progressively with the age of maturation of the composite (Soil + 3 % GGBS + 1 % Quicklime), thus verifying the trafficability criterion (1MPa at 28 days).
- During the first week of cure, the variation in the cohesion of the composite (Quicklime - GGBS – Soil) is slow then faster till the 28th day.
- The variation in the angle of internal friction of the composite (Quicklime - GGBS – Soil) increases quite rapidly, especially during the first 7 days of curing, then more slowly tills the 28th day.

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