SUSTAINABLE STABILIZATION OF SOIL UTILISING GROUND GRANULATED BLASTFURNACE SLAG (GGBS): A LITERATURE REVIEW

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ABSTRACT

This paper describes the sustainable soil stabilization method utilising Ground Granulated Blastfurnace Slag (GGBS), an industrial by-products from steel manufacturer. It examines the chemical composition and properties of GGBS and describes in detail the reactions and mechanisms that occur when modification and stabilization processes are carried out. The effects in incorporating GGBS to soil stabilization on the engineering behavior of soil are a/so discussed.

Keywords: Soil stabilization, granulated blastfurnace slag, industrial waste by-products, Soil engineering behavior

Introduction

Soil stabilization may be defined as the alteration of the properties of an existing soil to meet the specified engineering requirements. The main properties that may require to be altered by stabilization are: (a) *Strength-* to increase the strength and thus stability and bearing capacity; (b) *Volume stability -* to control the swell-shrink characteristics caused by moisture changes; (c) *Durability -* to increase the resistance to erosion, by weathering or traffic usage, and (d) *Permeability -* to reduce permeability and hence the passage of water through the stabilized soil (Sherwood, 1993).

Soil stabilization is widely used in road construction to improve sub-bases and sub-grades, for railroad and airport construction, for embankments, as soil exchange in unstable slopes, as backfill for bridge abutments and retaining walls, as canal linings, for improvement of soil beneath foundation slabs and for lime piles.

Ground granulated blastfurnace slag (ggbs)

Blastfurnace slag is produced from iron blast furnaces as a by-product of the iron making industry. It results from the fusion of a limestone flux with ash from coke and the siliceous and aluminous residue remaining after the reduction and separation of the iron from the ore. Iron blastfurnace slag, consists essentially of silicates and alumino-silicates of lime and other bases (Lee, 1974) with potential cementitious reactivity. Molten blastfurnace slag has a temperature of $1,300°C — 1,600°C$ and is chilled very rapidly to prevent crystallization. The granulated material produced is known as granulated blastfurnace slag. It is a latently hydraulic product that can be activated with lime, alkalis or Portland cement to give hydraulic properties (Gupta and Seehra, 1989). The latent hydraulic properties of blastfurnace slag were discovered in Germany in 1862 (Bijen, 1996). The latent hydraulicity means that

once activated, the slag reacts with water to give cementitious products. In the United Kingdom, this potential of blastfurnace slag was first realized in Scotland in 1914 when granulated blastfurnace slag was ground with Portland cement. In slag manufacture, the granules or pellets are ground into a fine powder similar in fineness to PC (specific surface 320- 380 m2/kg) and with specific gravity in the range 2.85-2.94 (PC is 3.15).

Ground granulated blastfurnace slag (GGBS), can be incorporated in cementitious materials to modify and improve certain properties in order to conserve non-renewable natural resources and to utilize industrial by-products (Nixon and Gaze, 1981). The possibility of recycling or processing materials to use as partial replacements for cement in concrete, or to stabilize soils, has great economic benefits in all areas of the construction industry (Wild and Tasong, 1999).

Although GGBS is cementitious on its own, the process is very slow unless there is activation. It is a hydraulic material and therefore if hydrated at elevated temperature and for a long time requires no additives other than water for hydration and hardening to take place (Song *et a!.,* 2000; of North East Slag Cement Ltd. Data sheet Nov. 1997, and others). Higgins (1998) observed that GGBS on its own has only mild cementitious properties and in conventional concrete, it is used in combination with Portland cement whose alkalinity provides the catalyst to activate the cementitious properties of the GGBS. He also reported that lime (calcium hydroxide) could provide the necessary alkali for activation. The use of GGBS is well established in many cement applications where it provides enhanced durability, high resistance to chloride penetration, resistance to sulfate attack and protection against alkali silica reaction (ASR). Its use in soil stabilization is however still a novel process in the UK although it has been used in South Africa. The well- established sulfate-resisting properties imparted to cements by blending them with GGBS suggests that by blending lime with GGBS, the latter may impart similar sulfate-resisting properties to lime-stabilized clay (Wild *et a!,* 1996). In both hydrated PC and mixtures of sulfate-containing clay mixes and PC, the phases present are similar — ettringite, C-S-H, C-A-H and C-A-S-H gels. As PC hydration products are practically the same as those of slag-Portland cement blends, it is likely that those of lime-slag- clay are also similar or at least comparable with those of cement-slag blends (Smolczyk, 1980, Regourd, 1980, Kinuthia, 1997).

The utilization of GGBS in soil stabilization is a relatively new phenomenon in the UK. The introduction of GGBS into a clay-lime hydration system modifies the clay-lime reaction products (Wild *et* a/., 1998). GGBS provides additional alumina, calcia, siiica and magnesia to the system, depending on the type and amount of GGBS (Smolczyk, 1980). Since the principle reactants introduced by GGBS are also present in the clay-lime system as well as in PC-GGBS blends, the strength of hydrated clay- lime GGBS mixtures is likely to be governed by the same factors observed in hydrated PC-GGBS blends. These factors include water content and curing environment, the properties of the C-S-H gel, such as its amount, porosity and permeability, the fineness and composition of all reactants involved, the efficiency of mixing, the temperature and the curing period. GGBS also introduces extra and more freely available alumina and silica, due to its high reactivity in the presence of lime, thus enhancing strength by contributing silicates and aluminates. The lime in the clay-lime mix will provide the required alkaline environment for GGBS activation and hydration, whilst also modifying the clay (Wild *et al.,* 1998).

Chemical Composition and Properties of ggbs

GGBS Activation And Its Hydration Products

GGBS can be activated in different ways, but the most common is chemical activation. In chemical activation, an activator is required and/or an alkaline medium. Several activators have been suggested to activate GGBS. Calcium hydroxide, calcium sulfate, standard PC, sodium hydroxide, sodium carbonate, sodium sulfate and sodium silicate are the most commonly used activators (Gjorv, 1989). Wu *et al.,* (1990) suggested that sodium hydroxide, sodium sulfate and potassium aluminium sulfate could be used as activators for GGBS and could help in breaking the Si-O and Al-O bondings. Wild and Tasong (1990) used lime as an activator in their study into the influence of GGBS in the sulfate-resistance of lime-stabilized kaolinite. They observed that the optimum lime/GGBS ratio was 1:5 to activate the GGBS, and to prevent attack caused by excess sulfate solution. They also observed that the lime-activated GGBS hydration reaction was quicker than the pozzolanic reaction of lime with clay. Due to its high alumina and silica content, the main reaction products of GGBS activated by lime are C-A-S-H gel and hydrotalcite-type phases containing magnesium.

However, the most commonly used activator for GGBS is PC. The reaction of PC with GGBS and water is complex. Water hydration of PC produces mainly calcium hydroxide (Ca(OH)2) and C-S-H gel. In the hydration of blended PC, although minor amounts of alkalis are released, GGBS is mainly activated by the hydration product Ca(OH)2 (Hakkinen, 1993; Bijen, 1996). Therefore, lime in the form of Ca(OH)2 may be added either as an additive or released from PC hydration. GGBS, due to its high alumina and silica content, produces slightly different hydrates from those formed when using standard PC. The main reaction products of GGBS hydration are calcium silicate hydrate, calcium aluminate hydrate and a small amount of calcium hydroxide (Higgins *et al.,* 1998).

Douglas *et aI.,* (1991) observed that 3% by weight of hydrated lime could retard the setting time of alkali-activated GGBS concrete. Maphee *et al.,* (1989) found that the GGBS hydraulic reactions were slower than the hydration of PC and had a "pore- the lime-clay blocking" effect which led to a greater ultimate strength and lower permeability, clay-lime together with the reduced Ca(OH)2 and other improved binding and absorptive reaction is ti effects, enhanced the resistance of GGBS concrete to sulfate attack.

Calcium sulfate is not only a successful activator but also plays an important role known to cc as a reactant (Daimon, 1980; Taylor, 1990). A reactant participates significantly in the produce C-A reaction process while an activator creates an appropriate environment for the reaction process without necessarily playing a significant role in the reaction (Ouf 2001).

To understand how the addition of GGBS alters the soil properties, GGBS mixtures is hydration should be studied in some detail. The effectiveness of GGBS hydration factor depends on many factors. These are the chemical composition of the GGBS, alkali permeability concentration of the reacting system, glass content and fineness of GGBS, and environment temperature during the early stages of the hydration process (Kinuthia, 1997). The strength in initial reaction during GGBS hydration produces coatings of alumino-silicate products GGBS mixes on the surfaces of GGBS grains within a few minutes of exposure to water. These and silica surface layers are impermeable to water, inhibiting further hydration reactions (Daimon, 1980). Therefore, GGBS used on its own shows only minimal hydration. Caijun and Wild a Day (1993) studied the hydration of a Canadian GGBS and found that when GGBS contact with water, an Si-Al-O rich layer formed on the GGBS particle surfaces. This layer may absorb H' resulting in an increase in OH and pH of the solution but leads to a re this is insufficient to break the Si-O and Al-O bonds to allow formation of C-S-H, C-A-H or C-A-S-H components. They also found that only a small

amount of C-S-H sufficient to was formed after 150 days of moist curing. For this reason therefore, utilization of GGBS is based on its activation.

When PC hydrates, the principal hydration products are calcium hydroxide (CH) and calcium-silicate-hydrate (C-S-H) gel, whereas GGBS hydration products using an alkali are mainly C-S-H and hydrotalcite type phase containing gypsum (Wild *et al.,* 1998; Tasong *et al.,* 1999). Song *et al.,* (2000) reported the formation of the hydrotalcite type phase in higher pH pastes along with C-S-H. They also observed that the pH of the mixing solution may affect the nature of C-S-H and its Ca-Si ratio. Talling (1989) using XRD, studied lime-alkali-activated GGBS. He identified the presence of C4AH3 as well as the formation of C-S-H. In addition to C-S-H and C-A-H, ettringite is also a principal hydration product in Portland cement and in GGBS-Portland cement blends. The formation of Ca(OH)2 during OPC hydration produces an alkaline environment suitable for the dissolution of Al_2O_3 and SiO_2. These are liberated from the GGBS and/or any other sources in the reacting system such as clay or Portland cement. In the presence of $Ca(OH)_2$, $CaSO_4$ reacts with A1203 to form ettringite ($C3A_3CaSO_4 32H_2O$).

The microstructural features in the GGBS/activator mixture comprise a poorly limit, thus crystallized hydrated layer on the grain surfaces (Daimon, 1980; Richardson *et al.,* ratio. 1994). The hydration products of GGBS are found to be more crystalline than the in kaolinite hydration products of Portland cement, and so add density to cement paste (Smolczyk, 1980; Taylor, 1990).

Clay-Lime-GGBS Reactions

The introduction of GGBS into the lime-clay hydration will undoubtedly modify the lime-clay reaction products. The clay-lime-GGBS reaction is different from the clay-lime reaction in that there are two competing reactions rather than one. The first reaction is the hydration of GGBS activated by lime to produce C-A-S-H gel and hydrotalcite type phases containing magnesium (Meng *et al*., 1998). This reaction is known to consume lime. The second reaction is the typical clay-lime reaction to produce C-A-S-H and calcium aluminates and alumino-silicates. In contrast to the pozzolanic reaction of clay with lime, which is slow, the slag hydration activated by lime is much quicker (Tasong and Wild, 1999). The strength of clay-lime GGBS mixtures is governed by the same factors observed in GGBS-OPC blend hydration. These factors include properties of the C-S-H gel such as its amount, porosity, permeability and structure. The lime-clay mix provides the required alkaline environment for GGBS activation and hydration. Thus, the observed increases in strength in GGBS-Portland cement blends are also likely to take place in lime-clay GGBS mixes since the GGBS will introduce extra and more freely available alumina and silica thereby enhancing the formation of the strength contributing silicate and aluminate hydrates, compared to the clay-lime system.

Wild *et al*., (1999) suggested that the total binder content (GGBS and lime) would be determined by the required engineering properties. The partial replacement of lime by GGBS enhances strength and using a GGBS-Lime system instead of lime only leads to a reduction in total binder content. However, the degree of lime replacement should not exceed a certain percentage, in order to keep a minimum lime content sufficient to fully activate the GGBS (Wild *et a!.,* 1999).

Effects of GGBS on the Engineering Behaviour of Soil

Effects of GGBS on the Consistency (Atterberg) Limit

Akinmurusu (1991) studied the effect of adding GGBS on the consistency, compaction characteristics and strength of lateritic soil. The slag content varied from O% to 15% by dry soil weight. He observed a decrease in both liquid and plastic limit and an increase in plasticity index with increasing GGBS addition.

Wild *et al.,* (1996) studied the effect of adding lime, and GGBS activated by lime on kaolinite clay. They observed that the addition of small amounts of lime to kaolinite produced a marked increase in the plastic limit. The liquid limit may increase or decrease but in such a way that there is a decrease in the plasticity index with increasing lime percentage. The addition of GGBS and lime to kaolinite alters the Atterberg limits giving a small reduction in the liquid limit and a marked decrease in plastic limit, thus producing an increase in plasticity index with a decrease in lime-GGBS ratio. They also observed that these trends were maintained when gypsum was present in kaolinite, but gypsum has the ability to produce slightly higher liquid limits and plasticity indexes.

Effects of GGBS on the Compaction Characteristics of Soils

Wild *et al.,* (1996) found that the addition of lime to kaolinite dramatically decreased the maximum dry density and increased the optimum moisture content. However, a decrease in lime-GGBS ratio produced a slight increase in maximum dry density and a slight and non-systematic variation in the optimum moisture content. The presence of gypsum gives a slight increase in maximum dry density and optimum moisture content.

Akinmusuru (1991) observed that the addition of GGBS to soil increased the maximum dry density up to 10% GGBS addition, above which the MDD decreased. This could be due to an increase of fine powder in the mixture leading to a decrease in the proportion of the coarse material thus making it difficult to attain good compaction.

Effects of GGBS on the Strength of Soils

The strength gain using GGBS activated by lime has been investigated by many researchers. Gupta and Seehra (1989) in their studies, found that lime-GGBS soil stabilized mixes with and without the addition of gypsum, or containing partial replacement of GGBS by fly ash produced high unconfined compressive strength (UCS) and California Bearing Ratio (CBR) in comparison to plain soil. They concluded that partial replacement of GGBS with fly ash further increased the UCS. Akinmusuru (1991) studied the effect of adding GGBS on shear strength parameters. He stated that the CBR increased with an increase in GGBS percentage up to 10% GGBS content, and then started to decrease.

Wild *et al*., (1998) studied the influence of GGBS and gypsum on kaolinite and Kimmeridge Clay when stabilized with lime. They found that a partial substitution of lime with GGBS produced improved strength for both kaolinite and Kimmeridge Clay. In the case of kaolinite, the effects were more significant in the presence of gypsum. After 28 days, the most significant strength enhancement was at high lime GGBS ratio, and was due to the contribution of gypsum to the longer-term kaolinitelime-gypsum reaction. In the absence of gypsum, the most significant strength enhancement was at low lime-GGBS ratio, due to lime-activated GGBS hydration. The greatest short-term strength enhancement was for low lime-GGBS mixture with gypsum, due to the accelerating effect of gypsum on the lime-activated

GGBS hydration. They also found that there was no effect on the *7* and 28 day strength of kaolinite clay when GGBS alone was added. Higgins *et al*., (1998) observed that the optimum lime:GGBS ratio to achieve maximum UCS was 1:5 for kaolinite clay and about 2:3 for Kimmeridge Clay.

Effects of GGBS on the Swelling Potential of Soils

Higgins *et al.,* (1998) studied the effect of GGBS on the strength and swelling properties of lime-stabilized kaolinite in the presence of sulfate. They found that kaolinite clay containing gypsum and stabilized with lime produced large expansion when saturated with water. The addition of GGBS to the clay-lime-gypsum system resulted in great reduction in expansion. In their laboratory investigation and full scale trial, they demonstrated that lime-GGBS combinations could be successfully used for soil stabilization in the presence of sulfate to prevent swelling. They also found that the partial substitution of lime by GGBS could significantly reduce swelling and heave in the presence of sulfates. Wild *et al.,* (1999) stated that to eliminate problems of sulfate expansion, 60% to 80% of lime for stabilization was replaced by GGBS.

Higgins and Kennedy (1999) carried out a full site trial using GGBS and lime on a temporary diversion to carry the A421 Tingewick Bypass traffic. The soil on this site comprised of sulfate-containing boulder clay. GGBS activated by lime was used in particular sections and lime and cement in other sections. The temporary diversion performed well over a full year. No swelling problems were observed in the sections which were treated with GGBS activated by lime while expansion was detected in the sections which were treated with lime and cement without using GGBS.

Conclusion

The substitution for conventional stabilization methods with this innovative by-product from steel manufacturer, GGBS has numerous benefits. The soil's engineering properties, including consistency limits, compaction characteristics, strength development and swelling resistance are generally improved when additions of GGBS, activated by relatively small amount of lime, are incorporated in the soil. Within this context of growing environmental awareness by both industry and its clients, GGBS has to be the preferred choice when competing with conventional additives such as lime and cement.

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