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# The development of an ecofriendly binder containing high volume of cement replacement by incorporating two by-product materials for the use in soil stabilization

**Key words:** soil stabilization, eco-friendly binder, ordinary Portland cement, ground granulated blast furnace slag, cement kiln dust, cement replacement

## Introduction

The use of cement, in the treatment of weak soils, induces chemical reactions that improve the geomechnical properties of the treated soils significantly. Hence it has been widely used for soil stabilization. It can be utilized for the stabilization of any type of soil apart from those with pH values less that 5.3 or organic contents of more than 2% (Saride, Puppala & Chikyala, 2013; Ma, Chen & Chen, 2016). The demand for ordinary Portland cement (OPC) is increasing on a daily bases because of the industrialization and urbanization. Consequently, the cement industry has grown significantly in recent years. It has been reported by van Ruijven et al. (2016) that the global cement production is predicted to grow annually by 5%. However, the OPC manufacturing have several environmental issues particularly the carbon dioxide ($CO_2$) emission and intensive energy consumption (Jafer, Atherton, Sadique, Ruddock & Loffill, 2018a).

Worldwide nowadays, the global warming as well as the climate changes represent a major concern to the mankind. These phenomenon are related to the green-house gases produced by different sectors of industry which their increased emissions adversely impacting the environment. The carbon dioxide represents one of the main gases contributing to the harmful gasses, being normally emitted by the process of incineration from various industrial factories (Hermawan, Marzuki, Abduh & Driejana, 2015). Meanwhile, the manufacturing of cement is a major sector of industry contributing to the emission of carbon dioxide, with a global $CO_2$ emission of 7–9% (Zainab, Zainab, Jafer, Dulaimi & Atherton, 2018). Hence, to minimize the environmental influences of cement, researches have investigated the possibilities of utilizing new materials as alternative to cement. These materials substitute cement partially or totally to make binders used in various construction sectors such as mortars, concrete and soil stabilization (Jafer, Atherton, Ruddock & Loffill, 2017; Jafer, Atherton, Sadique, Ruddock & Loffill, 2018b; Majdi et al., 2020).

Supplementary cementitous materials (SCMs) are the named given to these materials that are wastes or by-products incorporated partially as cement substituents. Supplementary cementitous materials have been utilized since approximate 300 years before century in Roma when volcanic ash was incorporated with lime in building roads (Aïtcin, 2016). Supplementary cementitous materials either induce pozzolanic activity due to having a significant amount of silica such as palm oil fly ash (POFA), rice husk ash (RHA), and fly ash (FA) (Aprianti, 2017), or possess considerable contents of calcium oxide to work like cement while being blended with water such as ground granulated blast furnace slag (GGBFS), sewage sludge ash (SSA) and cement kiln dust (CKD) (Majdi et al., 2020).

Ground granulated blast furnace slag (GGBFS) is a by-product produced from the manufacturing processes of iron industry. In terms of the chemical compositions, GGBFS has chemical oxides such as lime, aluminates and silicates similar to those available in the Portland cement but in different proportions (Oner & Akyuz, 2007). It was reported that most of mineral phases of GGBFS are in the glass phases making them easy to react with water during the hydration process (Zhao, Wang, Yan, Zhao & Zhang, 2016). Despite of that GGBFS was highly utilized in soil stabilization. It was confirmed by previous research that GGBFS in its own have low cementitous reactivity. Hence, lime or OPC are mixed with GGBFS in order to accelerate the hydration of GGBFS via activation that involves supplying enough alkalinity (Higgins, 2005).

Cement kiln dust (CKD) is produced as a by-product during cement manufacturing retrained in the incineration gasses transferred via the kiln. The chemical composition of CKD consists primary of non-calcined and calcined raw and feed materials used in the processes of cement manufacturing in addition to fine clinker and rich alkali compositions (Kunal, Siddique & Rajor, 2014). In spite of the fact that the CKD resulted from cement industry has been lowered subs-considered due to the utilization of new advanced methods in cement manufacture, the discard of CKD is a considerable issues in term of environmental and economic aspects in cement industry (Wild, Kinuthia, Robinson & Humphreys, 1996).

Based on the literatures, there is a limited number of researches investigated the effect of cement replacement using binary blending of GGBFS and CKD on the performance of the produced binders, particularly for the use in fine grained soil stabilization. In this research, GGBFS and CKD were incorporated as replacements to the conventional binder (OPC). Hence, the OPC was replaced at different levels: 15, 30, 45, 60 and 75%. The Atterberg limits, compaction parameters, and unconfined compressive strength (*UCS*) tests were employed to evaluate the produced mixtures and compare to the reference mixture (soil – 100% OPC binder). To understand the improvement gained in different soil geotechnical properties, the scanning electron microscopy (SEM) technique was utilized by examining the microstructure of the paste of the most logical mixture that exhibited a closed performance to the reference binder.

## Materials and methods

### Soil samples

The soil samples were obtained from the main campus of University of Babylon, Babylon, Iraq. They were collected from a depth of about 0.5 m below natural ground surface. The particle size distribution curve obtained from carrying out both sieve and hydrometer analysis is shown in Figure 1. This curve shows that the main fraction of the soil is clay while; the silt falls in the second order. Table 1 recapitulates some geotechnical properties of the soil, while the soil micrograph image obtained from the SEM test. It appeared as flocks and platy shape particles reflecting the existance of clay minerals.

TABLE 1. Some geotechnical properties of the soil

| Property | Unit | Value |
|---|---|---|
| Liquid limit (*LL*) | % | 42 |
| Plastic limit (*PL*) | % | 21.5 |
| Plasticity index (*PI*) | – | 20.5 |
| Sand | % | 11 |
| Silt | % | 41 |
| Clay | % | 48 |
| Specific gravity ($G_s$) | – | 2.66 |
| Maximum dry density (*MDD*) | $Mg \cdot m^{-3}$ | 1.61 |
| Optimum moisture content (*OMC*) | % | 21.5 |
| Unconfined compressive strength (*UCS*) | kPa | 144 |

### Binder materials

The materials used to produce the binders were: OPC which was obtained from a local factory located in Babylon

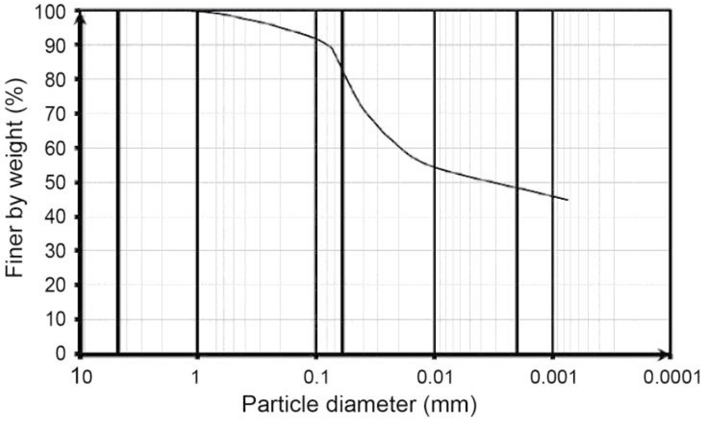

FIGURE 1. Grain size distribution curve for obtained soil

Province, Iraq, ground granulated blast furnace slag (GGBFS); supplied from Hanson Heidelberg Cement Group, Skuthorpe, UK, and cement kiln dust (CKD) which was provided by local cement factory.

The chemical compositions of the candidate materials are listed in Table 2. These compositions were obtained by conducting X-ray fluorescence (XRF) analysis using Shimadzu's EDX-720 Energy Dispersive X-Ray Fluorescence Spectrometer. It is important to observe that the percentages of calcium oxide CaO in GGBFS and CKD were more than 42% and 57% respectively, which are considerable values for the desired objective. On the other hand, the content of silica oxide ($SiO_2$) available in the composition of GGBFS was high enough to be an alternative pozzolanic source of the replaced cement. In the same view, the source of alumina ($Al_2O_3$) provided by GGBFS and CKD surpassed that available in cement.

Figure 2 presents the SEM images of binder materials along with virgin soil in their powder states. The EDX Oxford Inca x-act detector and FEI SEM models Inspect S instrument was employed for SEM imaging using voltages acceleration of 5–20 kV. For utmost image clarity, a sputter cater was used to coat the specimen by palladium thin layer. It can be seen that the GGBFS appeared as irregular shapes, while CKD shows agglomerated particles. An instrument used laser particle size analyzer was employed to disclose the gradation of binder materials. The grain size distribution curves of OPC and the replacement materials used are illustrated in Figure 3. It can be perceived that GGBFS is finer than the OPC which gave an opportunity to make the chemical reaction faster and more reactive.

TABLE 2. The major chemical compositions of the candidate materials

| Item | OPC | GGBFS | CKD |
|---|---|---|---|
| CaO [%] | 65.89 | 42.27 | 57.23 |
| $SiO_2$ [%] | 24.71 | 41.29 | 16.52 |
| $Al_2O_3$ [%] | 1.71 | 5.14 | 4.2 |
| $Fe_2O_3$ [%] | 1.61 | – | 3.8 |
| MgO [%] | 1.32 | 4.06 | 0.8 |
| $Na_2O$ [%] | 1.36 | 3.13 | 0.23 |
| $K_2O$ [%] | 0.83 | 0.72 | 6.72 |
| $SO_3$ [%] | 2.54 | 1.29 | 4.31 |
| $TiO_2$ [%] | – | 1.01 | 0.21 |
| pH [-] | 12.93 | 11.65 | 12.75 |

## Laboratory program

The laboratory program involved three main stages: The untreated soil classification experiments in addition, the unconfined compression test (*UCS*) were carried out in the first stage. The second stage included the process of preparing the specimens of the soil treated with different binder mixtures contained OPC, GGBFS, and CKD with different proportions as illustarted in Table 3. At this stage, Atterberg limits, compaction parameters, and *UCS* test were conducted. In all complementary mixtures, the strategy of replacement comprised using GGBFS of two folds of CKD so that the total replacement began with 15% from the total OPC. Then, the 15% was increased to be 30, 45, 60 and 75%.

Tests of Atterberg limits were made according to standard BS 1377-2:1990 (British Standard Institution [BSI], 1990a). The adopted procedure of standard Proctor compaction test matched with

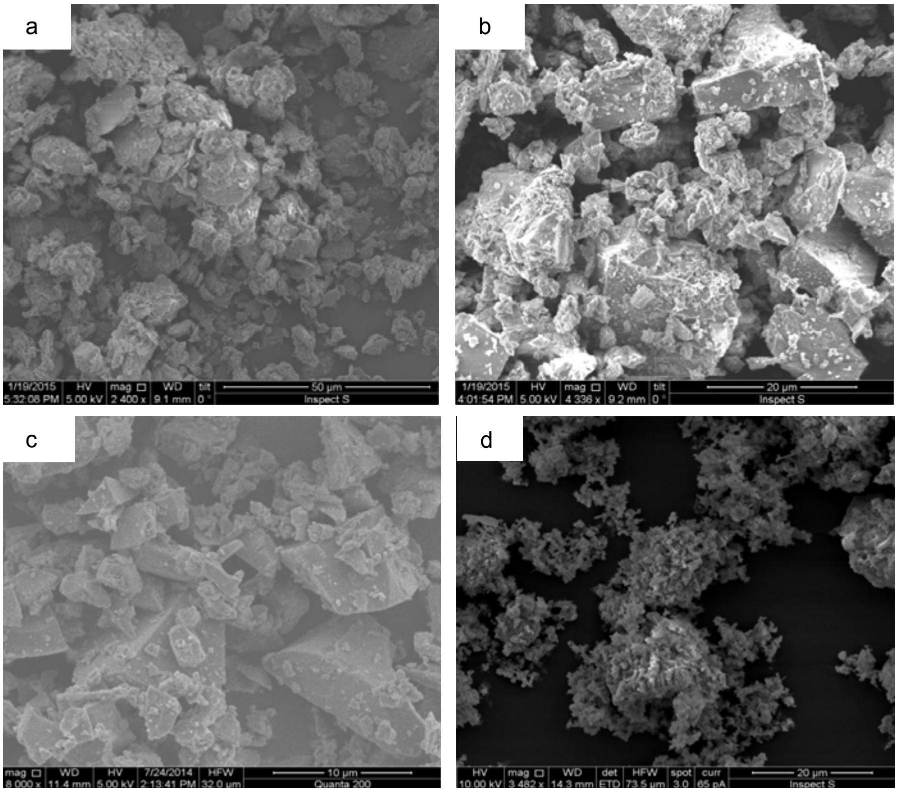

FIGURE 2. SEM magnification of (a) virgin soil, (b) OPC, (c) GGBFS and (d) CKD

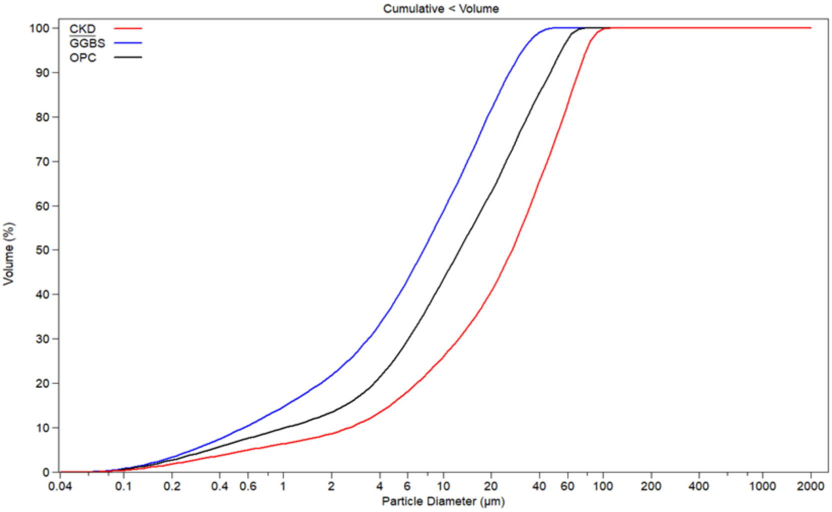

FIGURE 3. Gradations of GGBSF, CKD and OPC

TABLE 3. Mixing procedure adopted in this project

| No | Replacement [%] | Mix. ID | Percentages by the total binder [%] | | |
|---|---|---|---|---|---|
| | | | OPC | GGBFS | CKD |
| 1 | 0 | US | 0 | 0 | 0 |
| 2 | 0 | RF | 100 | 0 | 0 |
| 3 | 15 | OGC1 | 85 | 10 | 5 |
| 4 | 30 | OGC2 | 70 | 20 | 10 |
| 5 | 45 | OGC3 | 55 | 30 | 15 |
| 6 | 60 | OGC4 | 40 | 40 | 20 |
| 7 | 75 | OGC5 | 25 | 50 | 25 |

standard BS 1377-4 (BSI, 1990b). Strain controlled triaxial testing machine with zero lateral stress ($\sigma_3$) was employed to performed *UCS* in which the standard BS 1377-7 (BSI, 1990c) was adopted for *UCS* test. The samples prepared for this test were made at densities and moisture contents corresponding to maximum dry density and optimum moisture content obtained for each mixture. All specimens were prepared with dimensions of 38 and 76 mm in diameter and height respectivily, then wrapped by polyethylene plastic film to maintain the moisture of soil sample while stored during the curing time.

At the third stage, and to identify some mechanisms of treatment along chemical reactions took place over curing periods, a series of scanning electron magnification analyses, for specimens of the most promising binder, after each curing time was performed. Same apparatus and procedure mentioned in section 2.3 were used for this purpose.

## Results and discussion

### Atterberg limits

The results obtained from Atterberg limits test for the virgin soil (US) were 42, 21.5 and 20.5% for *LL*, *PL*, and *PI* respectively. Since the *PI* is greater than 17, US is considered as a high plasticity soil. The results experienced some increase in *LL* and *PL* in the case of RF specimen whereas, a noticeable reduction in *PI* was obtained, and the *PI* was lowered towered 13.8%. These results agreed with the previous studies (Al-Zoubi, 2008; Jafer et al., 2018b) where the increments in *LL* and *PL* were justified by the increase in the water demand necessary for the cement hydration. Table 4 shows the results of Atterberg limits of primary and complementary mixtures. In the view of this table, it can be inferred that partially replacement of OPC by GGBFS and CKD induced slightly increases in the values of both *LL* and *PL* for all mixtures tested in this study. On

TABLE 4. Results of Atterberg limits

| No | Mix ID | *LL* | *PL* | *PI* |
|---|---|---|---|---|
| 1 | US | 42 | 21.5 | 20.5 |
| 2 | RF | 46.8 | 33 | 13.8 |
| 3 | OGC1 | 46 | 32 | 14 |
| 4 | OGC2 | 46.3 | 32.7 | 13.6 |
| 5 | OGC3 | 47 | 33.6 | 13.4 |
| 6 | OGC4 | 47.6 | 34 | 13.6 |
| 7 | OGC5 | 48.4 | 35.2 | 13.2 |

the other hands, *PI* values were seeing to slightly increase in the case of OGC1 and then little decrease for the other mixtures when compared with those of RF. It should be noted that the binder OGC5 indicated the lowest value of *PI* (13.2) among all other mixtures.

## Compaction parameters

Regarding the results of compaction, the *MDD* and *OMC* for US were 1.61 gm·cm$^{-3}$ and 20.5% respectively. Due to adding OPC in the case of RF mixture, a reduction took place in the value of *MDD* to be 1.52 gm·cm$^{-3}$. Furthermore, a considerable growth in the value of *OMC* can be observed for RF specimen which became 27%. The reduction in *MDD* is due to flocculation and agglomeration in clay particles to make them coarser leading to increase the void ratio (Hayano, Dong & Morikawa, 2013). Moreover, the formation and crystallization of cementitious gel after a series of chemical reactions between soil minerals and OPC components formed needle structures which were in turn forms rough texture. This texture characterized by void ratio greater than that in US and less density (Hayano et al., 2013). Figure 4 presents the change in *MDD* and *OMC* for all studied mixtures. The results of compaction tests also indicated an increase in the *MDD* accompanied with a reduction in the *OMC* after the inclusion of GGBFS and CKD particularly with the use of OGC1. This could be attributed to the reduction in the water demand due to the decrease occurred in the active lime after the cement replacement as well as the high fineness of GGBFS replaced the OPC in the aforementioned

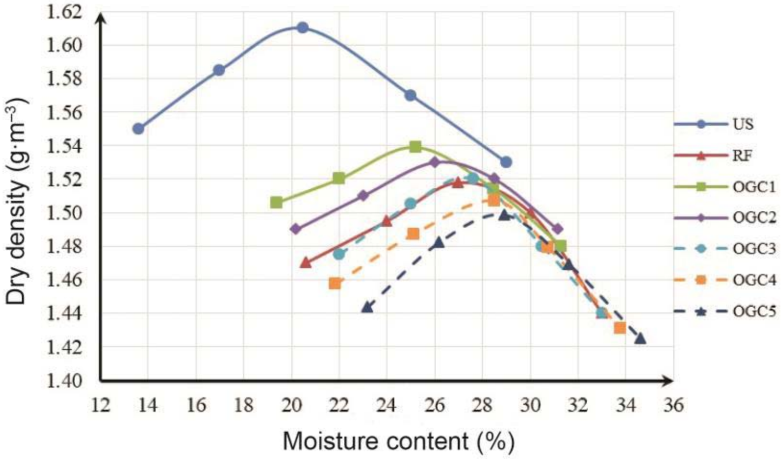

FIGURE 4. Dry densities – moisture contents for US, RF, and all complementary mixtures

binder (Eyo, Ng'ambi & Abbey, 2020). However, the values of *MMD* then decreased and *OMC* increased with the continuous increase the portion of cement replacement in the used binder as shown in Figure 4.

## Results of *UCS* test

Figure 5 illustrates the outcomes of unconfined compressive strength tests. Based on the obtained results, the strength of US specimens was 144 kN·m$^{-2}$. As per the *UCS* test results, the strength of treated soil after cement replacement experienced significant growth compared with the RF strength. The partial replacement of OPC using 2 : 1 mixing proportions of GGBFS and CKD succeed in generating the cementitious gel which plays the main role of strength evolution. This inference is clarified from Figure 5, where *UCS* developed generally in the same trend over curing time for the mixtures OGC1, OGC2, and OGC3. However, the strength gain demonstrated lower trends in the OGC4 and OGC5 mixtures. This significant growth in the strength can be attributed to the formation of cementitious gel which bonded soil particles together in one side and crystallized more and more over time on the other side (Pourakbar, Asadi, Huat & Fasihnikoutalab, 2015; Eyo et al., 2020). These two mechanisms make the soil strength developed over curing period.

Moreover, the strength of the first three mixtures gained at rate higher than that of the other mixtures particularly at the short and medium term curing periods. Where, the *UCS* reached values between 1,300 and 1,281 kN·m$^{-2}$ at the age of 28 days. At the long term curing, the results hovered from 1,376 to 1,350 kN·m$^{-2}$ at age of 90 days which almost closed to that of RF. But the results showed noticeable reduction particularly in the case OGC5 for all curing periods compared with RF strength. This is may be due to the OPC as activator became not enough for chemical reaction of GGBFS and CKD and in turns induced

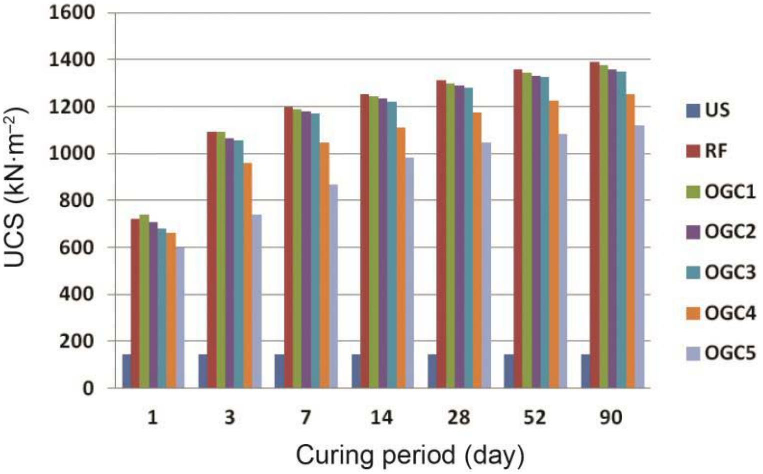

FIGURE 5. Strength developments over curing periods for all mixtures

low creation of cementitious gel (Rahman, Abo-El-Enein, Aboul-Fetouh & Shehata, 2016; Shubbar et al., 2020).

These results of *UCS* indicated that the OPC can be replaced up to 45% by GGBFS and CKD (2 : 1) and got almost same results of strength of the soil – 100% OPC mixture. However, the replacement of OPC with 60% using the combination of GGBFS and CKD (OGC4) indicated accepted results to improve most of the geotechnical properties of the stabilized soil in this study in comparison to those gained from using the binder 100% OPC. The proper percentages of calcium oxide, alumina, and silica included in the chemical composition of GGBFS and CKD gave appropriateness to partial exchange the OPC.

### SEM analysis results

Figure 6 presents the results of microscopic analysis and images of SEM of 45% replacement mixture (OGC3) after 6 periods of curing; 1, 3, 7, 28, 52, and 90 days. The analysis pursued the products of chemical reaction results over the mentioned curing periods. The reaction in the short term (in the first day up to 7 days) produced a texture of needle like shape which belongs to ettringite material. Hexagonal shape particles can be detected in the mentioned ages of reaction which were Portlandite production (CH). In addition, at 3 and 7 days of curing, calcium silicate hydrate (C-S-H) can be observed which is the essential cementitious gel responsible for binding the soil particles to each other and strengthen the whole mass of soil. The formation of these materials reflects the reactivity of the proposed materials (CKD and GGBSF) to produce the desired cement characteristics (Sadique, Al-Nageim, Atherton, Seton & Dempster, 2013). At the medium age of curing, the Ettringite and CH disappeared under SEM microscope which revealed that they were consumed in chemical reactions at this age to produce more C-S-H gel to be the only materials covered the scene. Similar findings were reported by Jha and Sivapullaiah (2015) and Shubbar et al. (2020). Finally, the long term aging (52 and 90 days of curing) showed that the C-S-H gel began to get high crystallization so that it became solid and very dense matrix. The formation of this dense crystal matrix explains the gain of compressive strength of soil – cement mixture along the curing periods.

## Conclusions

In view of previous results, the following conclusions can be extracted:

- The plasticity index decreased significantly when adding 9.0% OPC compared with untreated soil. Cement replacement using GGBFS and CKD as waste materials can give relatively same reduction in plasticity of soil.
- A reduction in maximum dry density and increment in optimum moisture content were experienced in the treated soil by OPC and similar trend of results was found in the mixtures where replacement was made.
- The outcomes of strength evolution showed that the strength of OGC1, OGC2, and OGC3 mixtures gained at a rate higher than that of OGC4 and OGC5 particularly at the short and medium term of curing periods.

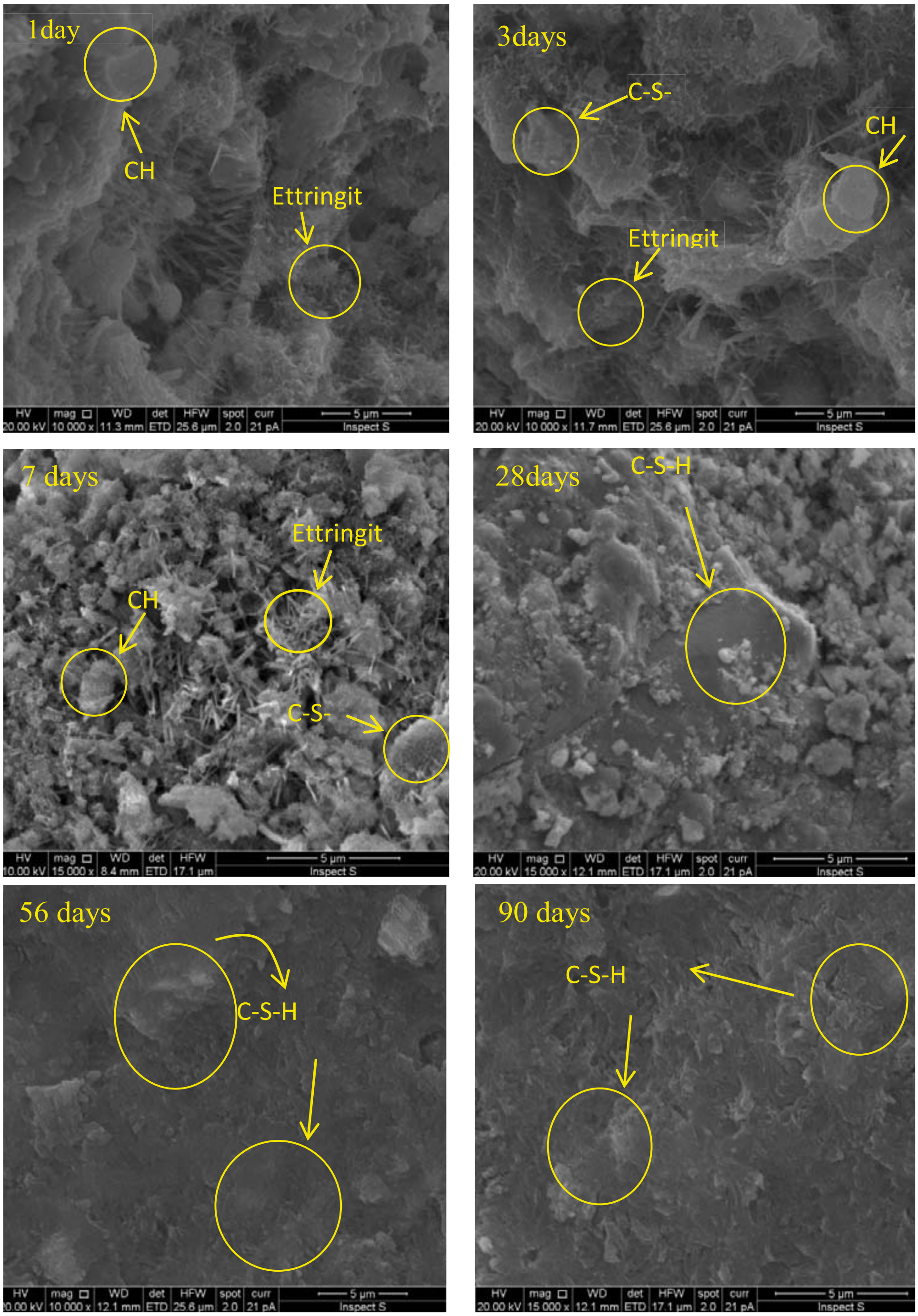

FIGURE 6. SEM microphotographs of binder paste containing 45% cement replacement

Furthermore, the first three mixtures got strength values close to that of RF specimen even in the long term curing.

- The SEM microscopic analysis results of 45% replacement binder showed that formation of needle like shape of Ettringite production and plate like shape of Portlandite formation at the short term curing (1–7 days). The formation of calcium silicate hydrate (C-S-H) can be observed at this age as well. At the medium and long term curing time, the images of SEM presented the only C-S-H formation and absence of CH and Etringite reflected dramatic changes in the microstructure of the hydrated paste of the tested binder along the time of curing. Moreover SEM images indicated that the C-S--H got more and more crystallisation over time.
- Finally, the outcomes of this study revealed that GGBFS and CKD can comfortably be used for cement replacement at levels between 45 and 60% with grantee results close to those that could be obtained from the conventional binder; cement.

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## Summary

**The development of an ecofriendly binder containing high volume of cement replacement by incorporating two by-product materials for the use in soil stabilization.** The development of an ecofriendly binder containing high volume of cement replacement by incorporating two waste materials for the use in soil stabilization. This paper investigates the possibility of replacing ordinary Portland cement (OPC) by two waste and by-product materials for the use of a silty clay soil stabilization purpose. The soil was treated by 9.0% OPC where this mixture was used as a reference for all tests. Two by-product materials: ground granulated blast furnace slag and cement kiln dust were used as replacement materials. Consistency limits, compaction and unconfined compression strength (*UCS*) tests were conducted. Scanning electron microscopy (SEM) analysis was carried out for the proposed binder to investigate the reaction of products over curing time. Seven curing periods were adopted for all mixtures; 1, 3, 7, 14, 28, 52, and 90 days. The results showed that the strength development over curing periods after cement replacement up to 45–60% was closed to those of the reference specimens. The microphotographs of SEM analysis showed that the formation of Ettringite and Portladite as well as to calcium silicate hydrate gel was obvious at curing periods longer than 7 days reflected that the replacing materials succeed to produce the main products necessary for binder formation.

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