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Experimental feasibility study of stabilization and solidification of arsenic-contaminated soil with alkali-activated slag cement

Étude expérimentale de faisabilité de la stabilisation et de la solidification d'un sol contaminé par l'arsenic avec du ciment de laitier activé par les alcalis

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ABSTRACT: Heavy metals in soils are to be found everywhere in the world. Therefore, contaminated soil with heavy metals has been an issue of concern these days. The present research aims to accomplish an experimental study of stabilization and solidification (S/S) of arsenic-contaminated soil with alkali activated slag cement. As a result, using environmentally friendly materials such as ground granulated blast furnace slag (GGBFS) as waste and recyclable material instead of Portland cement for soil stabilization can reduce the volume of greenhouse gases such as carbon dioxide. This paper deals with the effect of binder contents, curing age, curing condition on unconfined compressive strength (UCS) and toxicity characteristic leaching procedure (TCLP) tests. Furthermore, field emission scanning electron microscopy (FE-SEM) and X-ray diffraction (XRD) experiments were performed to analyze the characteristics of the binder and to explore the S/S mechanism. Based on the obtained results, it is observed that increasing the slag content to 20 wt.% yields a significant increase in UCS. The UCS of the soil has been increased from 80 kPa to about 20 MPa, also the leaching arsenic concentration of the soil has been reduced by about 90%.

RÉSUMÉ: Les métaux lourds dans les sols se trouvent partout dans le monde. Par conséquent, le sol contaminé par des métaux lourds a été un sujet de préoccupation ces jours-ci. La présente recherche vise à réaliser une étude expérimentale de la stabilisation et de la solidification (S/S) d'un sol contaminé par l'arsenic avec du ciment de laitier activé par les alcalis. En conséquence, l'utilisation de matériaux respectueux de l'environnement tels que le GGBFS comme déchets et matériaux recyclables au lieu du ciment Portland pour la stabilisation des sols peut réduire le volume de gaz à effet de serre tels que le dioxyde de carbone. Cet article traite de l'effet du contenu du liant, de l'âge de durcissement, de l'état de durcissement sur la résistance à la compression non confinée (UCS) et des tests de la procédure de lixiviation caractéristique de toxicité (TCLP). De plus, des expériences FE-SEM et XRD ont été réalisées pour analyser les caractéristiques du liant et explorer le mécanisme S/S. Sur la base des résultats obtenus, il est observé que l'augmentation de la teneur en scories à 20 % en poids entraîne une augmentation significative de l'UCS. L'UCS du sol a été augmentée de 80 kPa à environ 20 MPa, de même que la concentration d'arsenic de lixiviation du sol a été réduite d'environ 90%.

KEYWORDS: Stabilization/solidification, Leachability, Alkali-activated slag cement, Contaminated soil, Arsenic.

1 INTRODUCTION

Soil contamination has been an essential concern in geoenvironmental issues because it has potentially harmful effects on living organisms and may alter soil behavior (Zou et al., 2020). Arsenic (As) is a metalloid toxic to plants, animals, microorganisms, and humans (Li et al., 2017). As pollution from human activities such as mining and pesticide use often draws more attention to its remediation, natural sources of As are increasingly known as potentially long-term threats to human health (Li et al., 2017).

There are several technologies for the remediation of contaminated soils. Recently, stabilization/solidification method has emerged as a low cost, versatility and low-risk strategy for controlling contaminated soils. In this approach, heavy metals in contaminated soils are generally immobilized by physical siege and chemical reactions with the hydration products of binders (Wang et al., 2015). Ordinary Portland cement (OPC) is the most appropriate material for chemical stabilization of contaminated soils (Shariatmadari et al., 2020).

Global warming and climate change, mainly due to the emissions of carbon dioxide (CO_2), one of the most serious problems that have sparked enormous concern for international community (Chen et al., 2019). Extensive CO_2 emissions have created a series of environmental issues, such as global warming and climate change. The OPC production causes a CO_2 emission of about 0.7–1.1 tons per ton of OPC (Ghadir & Ranjbar, 2018). Therefore, it is necessary to replace conventional soil stabilizers, including OPC, with low-carbon footprint binders (Hataf et al., 2018). This has prompted increased research to investigate more environmentally friendly and sustainable binders for stabilization/solidification (S/S) applications.

In recent years, many researches have been conducted to introduce alkali activated cement as a substitute for OPC. Extensive studies show that alkali activated material (AAM) can present higher compressive strength, lower permeability, and greater resistance to sulfate attack, acid corrosion, and ion permeability than OPC (Thomas et al., 2018). AAM are synthetic alkali alumino-silicates produced when combining a solid alumina-silicate (pozzolanic or industrial by-product) with a highly concentrated aqueous alkali hydroxide or silicate solution. Ground granulated blast furnace slag (GGBFS) as an industrial by-product can produce cementitious hydrates (Portlandite) through the pozzolanic reaction which in turn accelerates cement hydration reactions (Nedunuri et al., 2020). Replacing OPC with other cementitious materials such as GGBFS not only reduces carbon footprint but also declines the production rate and landfilling costs of industrial by-products (García-Lodeiro et al., 2012).

GGBFS can be activated in an alkaline environment and achieved high initial strength (Hu et al., 2019). Alkali activated slag binder demonstrated a good potential of bonding with both natural and recycled aggregate, which leads to higher peak compressive stress and strain of specimens as compared to OPC ones (Hu et al., 2019). Besides, unconfined compressive strength (UCS) of alkali activated GGBFS-stabilized soil after 90 days was reported 1.7 times more than that of the OPC-stabilized soil

(Yi et al., 2015). For the same percentage of binder content, the activated GGBFS-stabilized soil illustrated 600% mechanical strength improvement compared to the OPC treated specimens in a short-term curing time of 28 days (Singhi et al., 2017). In addition to the effects of curing age and condition, it has been reported that increasing the binder to soil ratio improves the compressive strength of stabilized soils (Leong et al., 2018).

Apart from the type of binders, time is an important factor that determines the efficiency of remediating contaminated lands. In most short-term cases (<10 years) of S/S, due to the in-progress hydration, contaminants emissions are likely to decrease over time (Kogbara et al., 2013). Previous studies on the leaching performance of S/S treated site soils at 0.2, 2.4, 5 and 17 years, indicated that slightly higher concentrations of heavy metals were washed in 5 years after treatment compared with those in 0.2 and 17 years using a TCLP test, and the hydration process of treated samples did not complete at 5 years but fully completed at 17 years (Preetham & Nayak, 2019).

The aim of this study is to experimental investigation of stabilization/solidification of arsenic-contaminated soil with alkali activated slag cement. In the present research, the effect of curing condition, curing time, binder content have been studied. Two parameters, namely, unconfined compressive strength (UCS) and leaching behavior, were investigated to evaluate the effect of the alkali activated slag binder on Arsenic-contaminated soil solidification. In addition, X-ray diffraction (XRD) and field emission scanning electron microscopy (FE-SEM) were performed to further analyze the characteristics of binders and to examine the solidification mechanisms.

2 MATERIALS AND METHODS

2.1 *Materials*

2.1.1 *Soil characterization*

The arsenic-contaminated soil used in this study was collected from the residential area of Mes-Sarcheshmeh town of Kerman-Iran. Analysis of soil particle size has shown that as-received soil has 93.2 wt.% of sand (23.9 wt.% of coarse sand, 36.4 wt.% of medium sand and 32.9 wt.% of fine sand), 6.79 wt.% of silt, and 0.01 wt.% of clay, according to the ASTM D422. The engineering characteristics of soil such as Atterberg plastic and liquid limits, specific gravity, were determined based on the ASTM D4318 and ASTM D854, respectively. Maximum dry unit weight and optimum moisture content of the soil were measured using the standard Proctor compaction test, according to the ASTM D698. The basic properties of soil are given in Table 1.

Table 1. Basic properties of soil.

Property	Quantity
Liquid limit (%)	21.5
Plastic limit (%)	18.5
Plastic Index (%)	3.0
Particle specific gravity, G_s	2.75
Optimum moisture content (%)	16.0
Maximum dry unit weight (kN/m³)	17.8
Coefficient of uniformity, C_u	10.0
Coefficient of curvature, C_c	1.04
USCS[a]	SW-SM

[a] Unified soil classification system

2.1.2 *Binder characterization*

The ground granulated blast-furnace slag (GGBFS) used in this study has been collected from Zobahan factory located in Isfahan-Iran. The ordinary Portland cement type II has been obtained from Tehran Cement Company. The particle-size distribution curves of the GGBFS and OPC can be observed in Fig. 1. The X-ray fluorescence (XRF) is used to determine the oxide composition of GGBFS and OPC, as listed in Table 2.

The alkaline activator solution (AA) and distilled water were used to stabilize the soil using GGBFS and OPC, respectively. The alkaline activator solution used in this study is a combination of sodium hydroxide solution (SH) and sodium silicate solution (SS). The sodium hydroxide solution was made from sodium hydroxide granulated with a density of 2.13 g/cm³ (20 °C) with an assay percentage above 95% and also, the sodium silicate solution used has a purity of 47% with a ratio of 2.4 (33.18 wt.% of SiO_2, 13.82 wt.% of Na_2O and 53 wt.% of H_2O) and a density of 1.56 g/cm³ (20 °C).

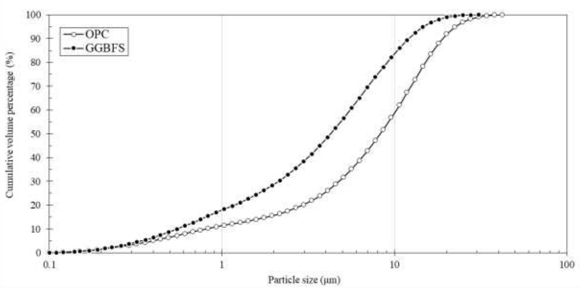


Figure 1. Particle-size distribution curves of the GGBFS and OPC

Table 2. Chemical composition of GGBFS and OPC.

Component	CaO	SiO_2	Al_2O_3	MgO	TiO_2	MnO
GGBFS [wt.%]	37.9	35.9	10.3	8.9	1.9	1.5
OPC [wt.%]	61.4	18.4	5.2	2.7	0.3	0.1
Component	SO_3	Fe_2O_3	K_2O	Na_2O	SrO	P_2O_5
GGBFS [wt.%]	0.9	0.6	0.4	0.3	0.2	-
OPC [wt.%]	4.1	3.6	0.8	1.6	0.1	-

2.2 *Methods*

2.2.1 *Specimen preparation*

The alkaline activator solution was prepared through a two-step method. First, granule sodium hydroxide was dissolved in distilled water and the prepared NaOH solution was allowed to cool down before it is used. Then, aqueous sodium silicate was added to NaOH solution and stirred for 5 min to prepare the alkaline activator solution. Contaminated soil and GGBFS were mixed with alkaline activator solution and water (excess water was added to reach optimum moisture content of the soil) to investigate the effects of curing condition, binder content, and curing age on unconfined compressive strength and leachability of As. Specimens were prepared using cylindrical molds with an inner diameter of 38 mm and a height/diameter ratio of 2.0.

The specimens were cured at two conditions of ambient temperature (AT) in which the specimens were sealed in the plastic bags with a relative humidity of 80 ± 2 % and temperature of 22 ± 2 ºC, and the curing condition of hot water bath (HW) with a nearly constant relative humidity of 95 ± 2 % and temperature of 40 ± 2 ºC. The ratio of alkaline activator (AA) to GGBFS was fixed at 0.4, the ratio of SS to SH was 1.5 and $NaOH_{(aq)}$ concentration was 14 M. The binder content of stabilized specimens varied from 5 to 20 wt.% (to dry soil) of GGBFS or OPC. All tests were conducted after 7 and 28 days of curing. The identical samples have been prepared for toxicity characteristic leaching procedure (TCLP) tests.

2.1.2 *Unconfined compressive strength*

The unconfined compressive strength (UCS) of the specimens was determined by ASTM D1633-84. The average UCS of three replicates after failure was obtained by uniaxial device (ELE Company, England) which was operated at speed of 1 mm/ min.

2.1.3 *Leachability*

Different leaching methods are used to evaluate the solidification efficiency according to the specific objectives. In all leaching experiments, the goal is to extract the desired contaminant from the solid matrix using an extraction fluid. The difference between these methods in the ratio of extracted liquid to solids, the surface of solids, the type of extracted liquid, pH of extraction fluid, contact time, rotation rate, extraction fluid replacement number, leaching bottle and temperature. In this study, the amount of leaching and arsenic concentration of specimen was performed using toxicity characteristic leaching procedure (TCLP) test based on USA EPA method 1311.

According to this experiment, the largest diameter of a solid particle should be less than 95 mm, and the weight ratio of the extracted liquid (including distilled water and acetic acid) to the solids is 20:1. In this method, the extraction fluid has a pH of 2.88 ± 0.05. The bottle that contains the extracted liquid and soil rotated at a speed of 30 rpm for 18 hours. It is then sampled and filtered, using the ICP-OES (Varian Inc., USA) device to determine the arsenic concentration in the specimen.

2.1.4 *Microstructural characterization*

The microstructural characterization of the specimens were performed using field emission scanning electron microscopy (FE-SEM) and X-ray diffraction (XRD). In the FE-SEM analysis, imaging, surface morphology, and chemical characterization were measured on the Nova Nano SEM 450 (FEI co., USA) using resolution accuracy of 1.4 nm. In the XRD test, the patterns were measured on the Ultima IV (Rigaku co., Japan) using Cu Kα radiation (Kα = 1.54 Å). The device also operated at a voltage of 40 kV and a current of 30 mA with a step size of 0.02 degree and a scanning rate of 0.05 degree/sec in the 2θ range of 10–80 deg.

3 RESULTS AND DISCUSSION

3.1 *Maximum dry unit weight*

The effect of adding GGBFS on the maximum dry unit weight and optimum moisture content of the soil was investigated, Fig. 2. The standard Proctor compaction tests were performed on both stabilized and untreated soil. The optimum moisture content was found to decrease while the maximum dry unit weight increased with increasing slag content. Maximum dry unit weight increases till 40% replacement, beyond which maximum dry unit weight declined (Preetham & Nayak, 2019). As can be seen in Fig. 2, the highest maximum dry unit weight and the lowest optimum moisture content of the sample with 20 wt.% of GGBFS. Optimum moisture content reduced because of the replacement of soil with that of GGBFS, which has lower water holding capacity than the study soil.

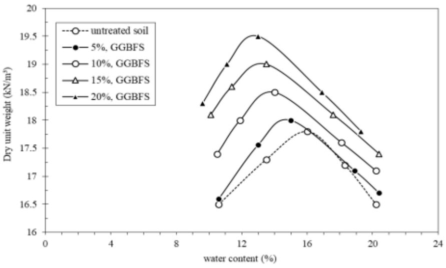


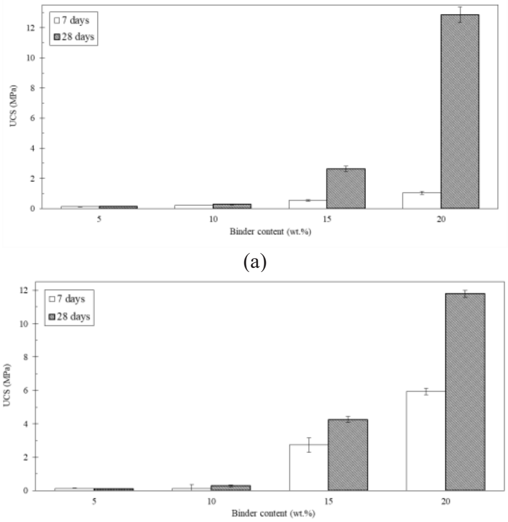
Figure 2. Optimum moisture content and dry unit weight of arsenic-contaminated soil specimens with different contents of GGBFS.

3.2 *Unconfined compressive strength*

3.2.1 *Effect of GGBFS content and curing age on UCS*

Fig. 3 displays that variation of UCS performance with the GGBFS content and curing age for samples cured at ambient temperature and hot water bath conditions. Other parameters including: alkaline activator solution (AA) to GGBFS ratio, sodium silicate solution (SS) to sodium hydroxide solution (SH) ratio and concentration of sodium hydroxide were fixed at 0.4, 1.5 and 14 molar, respectively. For GGBFS content and curing age, 5 to 20 wt.% (to dry soil) and 7 to 28 days of age were considered, respectively. In general, increasing the content of binder and increasing the curing time led to an increment in unconfined compressive strength of specimens. This is mainly due to a higher binder content that results in more amount of hydration products, which, in turn, accelerates the gain of compressive strength for the samples. Noteworthy, hydration products generated from alkali activated reaction is considered to be the major binding phase in the hardened alkali activated slag (Jiang et al., 2019). The UCS of samples was found to increase with increasing binder content as well as a longer curing age. In general, the compressive strength has been increased with an increase of age and binder dosage (Zhang et al., 2018).

Fig. 3 illustrates that as the content of GGBFS increases, the UCS indicated an upward trend, while this increment was sharp in UCS with increasing GGBFS from 15 to 20 wt.%. At all percentages of GGBFS, at a lower curing age, the almost UCS in the hot water bath condition was higher than the ambient temperature condition, which could be due to higher temperatures and humidity that accelerated hydration reactions. The elevated temperature enhances early-age (3-day) compressive strength of samples. However, higher activation reaction under elevated temperatures is found to remarkably exhibit the strength beyond 3 days curing, resulting lower strength than samples cured at lower temperatures. Samples subjected to expose curing has a higher 3-day UCS than sealed curing sample, but with a negligible rate of gain in the compressive strength (Jiang et al., 2019). However, over time and with almost complete hydration of the samples, the UCS at ambient temperature has reached slightly higher than the hot water bath conditions due to the high humidity in the hot water bath and the absorption of excess water by the samples after their hydration reactions which reduces the concentration of OH^- of the alkaline activator solution. When the content of water has been increased, the alkaline activator and the concentration of OH^- decreased, and the activation of GGBFS weakened. Previous studies have confirmed that the increase in liquid/solid ratio increases the porosity and reduces the mechanical strength (Zhang et al., 2018). Also, as shown in Fig. 3, with increasing curing age, the UCS has been increased significantly.



(a)

(b)

Figure 3. Unconfined compressive strength of stabilized soil specimens with different binder contents, curing duration, and curing conditions: a) ambient temperature curing, b) hot water bath curing.

3.2.2 *Effect of GGBFS and OPC content on UCS*

In this section, to evaluate the effect of binder type and its content, other parameters such as curing age, ratio of AA to GGBFS, ratio of SS to SH, and concentration of NaOH was fixed at 28 days, 0.4, 1.5 and 14 molar, respectively. Content of 5 to 30 wt.% were considered for the binder content. Samples were cured at ambient temperature and hot water bath condition. The effect of the content and type of binder on the UCS is given in Fig. 4. The results of this study display that in 5 and 10 wt.% of binder, there is a significant difference between UCS of OPC stabilized samples and alkali activated slag. In other words, OPC stabilized specimens has shown much higher UCS. This difference is negligible until 15 wt.%, but the strength of OPC samples is still higher. However, from 20 wt.%, there has been a sharp increase in the UCS of alkali activated slag-stabilized samples, which is why these samples have a much higher strength than OPC-stabilized samples, and this difference in strength has gradually increased. Stabilized soil by activated GGBFS demonstrated higher UCS values than stabilized OPC samples (Rafiean et al., 2020). Also, in relation to the untreated sample, the results of this study indicated that after 28 days, the sample cured at hot water bath conditions was unstable and it was not possible to perform the UCS test, but the sample cured at ambient temperature conditions after 28 days the UCS was 80 kPa.

Also, in relation to the effect of the curing conditions of the stabilized samples after 28 days, according to the results of this study, it can be stated that the samples stabilized with OPC have higher UCS in all wt.% of binder values in hot water bath conditions than in ambient temperature conditions. However, the same result cannot be obtained for the samples stabilized with activated slag, but based on the results obtained in this research, it can be mentioned that in percentages less than 20 wt.%, the samples stabilized in the hot water bath conditions have higher UCS values, but the samples stabilized with more than 20 wt.% of GGBFS in ambient temperature conditions have achieved higher UCS. The results of this research showed that the highest UCS is related to the amount of 20% by weight of alkali activated slag in ambient temperature conditions

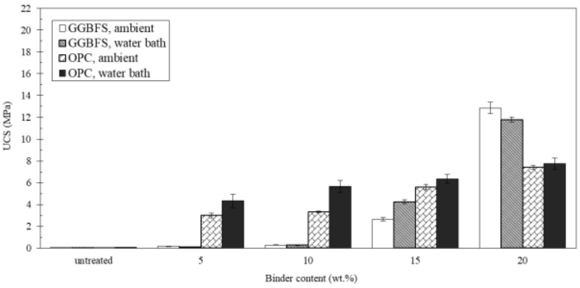


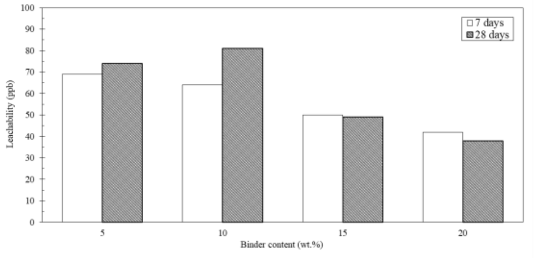
Figure 4. Unconfined compressive strength of stabilized soil specimens with different binder and curing conditions after 28 days.

3.3 *Leachability*

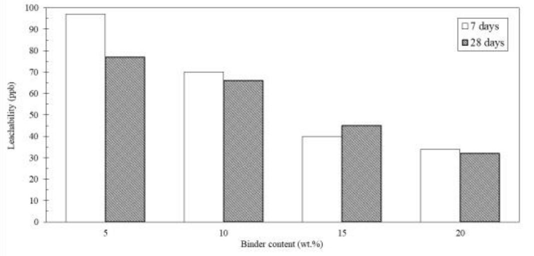
3.3.1 *Effect of GGBFS content and curing age on As leaching behavior*

In the main part of the leaching experiments, the effect of GGBFS content and curing age in both curing conditions of ambient temperature conditions and hot water bath have been investigated. In this section, other parameters including: the ratio of AA to GGBFS, the ratio of SS to SH and the concentration of NaOH were kept equal to 0.4, 1.5 and 14 molar, respectively, and for slag content and curing age, 5 to 20 wt.% and 7 to 28 days were considered, respectively. The effect of slag content and curing age on the concentration of leached As in ambient temperature conditions and hot water bath are presented in Figs. 5 (a) and (b), respectively. In general, with increasing the GGBFS content, the concentration of leached arsenic decreased according to the TCLP test. It can also be concluded from the results obtained in Fig. 5 that increasing curing age has a positive effect on reducing the concentration of leached As. However, there are low fluctuations in the results that can be attributed to the collection and use of contaminated natural soil from the study site.

In terms of the effect of the curing conditions of the samples, in almost all weight percentages of GGBFS and all ages of curing, almost similar results have been obtained in both conditions, but as with the results of UCS, early-age specimens cured in hot water bath conditions have less leaching than AT conditions, which can accelerate the hydration of the specimens due to higher temperatures and higher humidity in the HW condition but over time, as specimens are cured, the results are almost the same in both conditions. The results of this study demonstrated that the lowest concentration of leached As related to the content of 20 wt.% of slag in both curing conditions.



(a)



(b)

Figure 5. TCLP leached arsenic concentrations of stabilized soil specimens with different binder content, curing duration, and curing conditions: a) ambient temperature curing, b) hot water bath curing.

3.3.2 *Effect of binder type on As leaching behavior*

Fig. 6 demonstrates the concentration of leached As of samples stabilized by using a binder dosage of 5–20 wt.%. In this section, to investigate the effect of binder type (GGBFS and OPC) and its content on leached As concentration, other parameters such as curing age for both types of binder, constant and equal to 28 days and the ratio AA to GGBFS, the ratio of SS to SH and the concentration of NaOH was kept constant at 0.4, 1.5 and 14 molar, respectively, and for binder content, values of 5 to 30 wt.% were regarded, and finally untreated soil was regarded as a control sample. The samples were cured in two desired conditions in this study, namely the ambient temperature and hot water bath conditions.

The results of this study indicated that in general, with increasing the binder content, the concentration of leached arsenic decreases. In relation to the samples stabilized with OPC, from the same amount of 5 wt.% of OPC, the concentration of leached As decreases sharply, but with the increase of binder to 30 wt.%, it decreased at a very low rate. However, in the case of samples stabilizes with alkali activated slag at a relatively constant rate with increasing weight percentage of slag, the concentration of leached arsenic decreases. In all weight percentages of binder, samples stabilized with OPC illustrated less leaching in comparison to slag; however, in weight percentages above 20 wt.%, this difference is not very noticeable.

Also, the leached As concentration of the untreated sample was tested. As it can be seen in Fig. 6, the leached As concentration was determined by the ICP-OES test at 234 µg/lit, which stabilization of the sample with 20 and 30 wt.% of slag, this concentration has been decreased by about 90%, respectively, which is a appropriate result. Regarding the effect of the curing conditions of the samples, in almost all weight percentages of slag and OPC, similar results have been obtained in both conditions. The results of this research indicated that the lowest concentration of leached arsenic is pertinent to the sample stabilized with 30 wt.% of activated slag in hot water bath conditions.

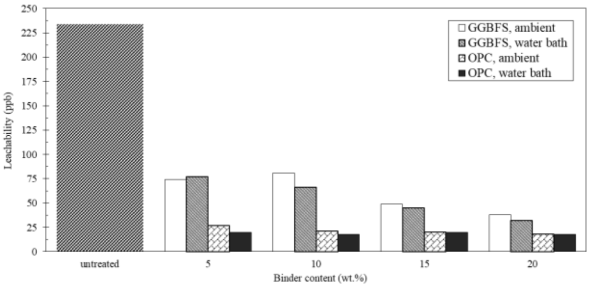


Figure 6. TCLP leached arsenic concentrations of stabilized soil specimens with different binder and curing conditions after 28 days

3.4 Microstructural characterization

3.4.1 *XRD analysis*

The XRD results of the studied samples are demonstrated in Fig. 7 As shown in section (a), the crystalline minerals quartz and calcite are visible, which are the main constituents of the soil under study. By adding alkaline activated slag to the soil, since the phases produced by geopolymers are mostly amorphous and semi-crystalline (Ji et al., 2020), the formation of abundant crystalline phases and many changes in soil structure seems unlikely. By adding GGBFS activated to the soil, Fig. 7 (b), amorphous calcium-aluminum silicate phases were formed in the structure at its angles of 30.3 and 60° of its semi-crystalline phases, and only the main peak and crystallinity of this phase were formed at an angle of 56.6°. This product and calcium silicate gel, which is the result of combining slag with alkaline activator solution, are the main products of geopolymer gel (Renaudin et al., 2009) and play a major role in increasing the strength of the sample. In the present study, by adding activated slag, it caused the formation of calcium aluminum silicate hydrate gel or CASH gel, which is the main factor in creating a strong structure and thus the ability to encapsulate arsenic pollutant. Fig. 7 (c) illustrates the XRD result of the sample cured under H.W. conditions containing 20 wt.% of GGBFS. In this case, like the sample cured under A.T. conditions, C-A-S-H gel is formed. Therefore, the main product of alkali activated GGBFS is the same in both curing conditions. In both conditions, the gel structure is well formed, based on the UCS results of the samples, the UCS range in both conditions is almost in the same range. Finally, in Fig. 7 (d), the sample result contains 20% by weight of OPC under A.T. conditions after 28 days of curing. As it can be observed from the figure, the product of cement hydration is C-S-H (calcium silicate hydrate), which is the main product of cement hydration reactions (Du et al., 2014), which was found at an angle of 32.2°. This is the main reason for the high compressive strength of the sample and the decrease in leached arsenic concentration. On the other hand, C-S-H gel is a strong gel in stabilization and solidification of heavy metals that has a high ability in stabilization, adsorption as well as physical encapsulation of heavy metals and metal-like contaminants (Li et al., 2019).

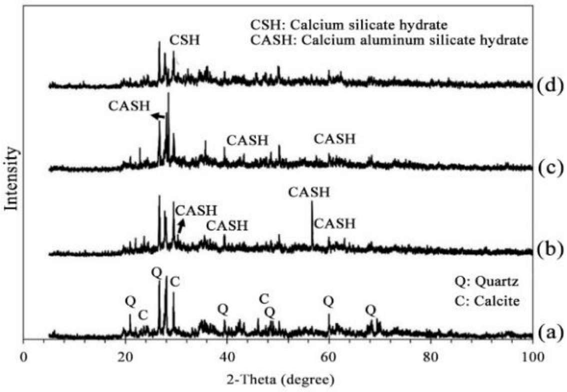


Figure 7. XRD patterns of stabilized samples after 28 days of curing: a) Untreated soil, b) Soil stabilized with 20 wt.% of GGBFS in ambient temperature conditions, c) Soil stabilized with 20 wt.% of GGBFS in hot water bath conditions, d) Soil stabilized with 20 wt.% of OPC in ambient temperature conditions.

3.4.2 *FE-SEM analysis*

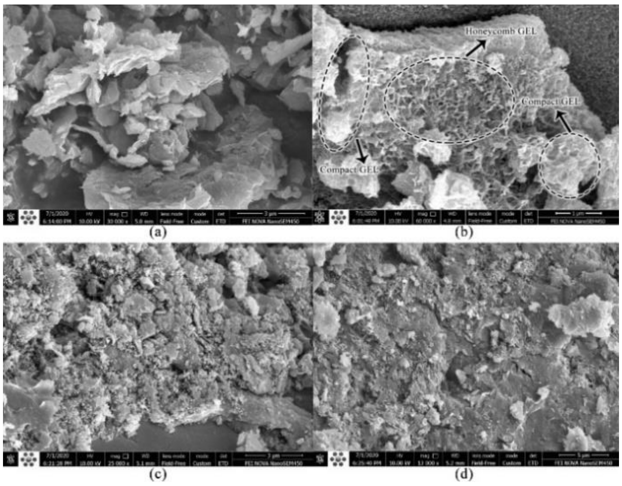


Figure 8. FE-SEM analysis of stabilized samples after 28 days of curing: a) Untreated soil, b) Soil stabilized with 20 wt.% of GGBFS in ambient temperature conditions, c) Soil stabilized with 20 wt.% of GGBFS in hot water bath conditions, d) Soil stabilized with 20 wt.% of OPC in ambient temperature conditions.

The FE-SEM image of a sample of arsenic-contaminated soil is displayed in Fig. 8 (a). In Fig. 8 (b), by adding alkaline activated slag, the structure becomes dense. C-A-S-H gel is the most important compound in the gel coating (Du et al., 2014) which is consistent with the XRD findings. In this form, the dense structure of the gel represents the strong C-A-S-H gel, which is the main factor of resistance, and also in some parts, the honeycomb-like structure of the gel is clearly visible (Du et al., 2014). Fig. 8 (c) illustrates the samples processed in the H.W.. C-A-S-H gel formation that is clearly visible as in the XRD results. In this sample, the gel has a very wide range and covers almost the entire surface of the sample. This factor causes low leaching of arsenic metal in this sample. In this case, the structure is dense and the main product of geopolymer hydration is well created, which indicates the creation of geopolymerization process in this curing condition. Fig. 8 (d) demonstrates the results of samples stabilized with OPC. The lattice products formed on the surface of the sample represent the C-S-H gel, which was also found in the XRD resulting from the addition of OPC to the soil. This product covers the soil surface and is located between large cavities (Palacios & Puertas, 2007). In the sample image, the formation of this gel and its excellent uniformity, which causes the density and uniformity of the structure, is clearly visible.

4 CONCLUSIONS

In this paper, a comprehensive laboratory test work has been conducted on contaminated soil to study the evolution of binder content, curing conditions, and curing time. Samples are tested to obtain their leachability and UCS development. Microstructural evolution of stabilized samples has been also investigated in this study by FE-SEM and XRD experiments.

Based on the results of the experimental tests performed, the following conclusions can be drawn:

- By increasing the weight percentage of alkali activated GGBFS to untreated soil, the UCS of the samples in both curing conditions, including ambient temperature conditions and hot water bath conditions, increased.
- The UCS of the specimens increases with age of curing. Initially, after 7 to 28 days, there was a significant change in the strength of all samples.
- Regarding the curing conditions of the samples, almost similar results were obtained. The only difference was with the 7-day-age samples, where stabilized samples in HW had higher values of UCS than samples in AT due to higher humidity and temperature of HW, which accelerates the hydration reactions of stabilized samples.
- In general, as the amount of alkali-activated slag has been increased, the concentration of leached arsenic in both curing conditions has been decreased. However, there are fluctuations in ICP-OES results due to the use of natural soil in the contaminated area where the amount of arsenic contaminants varies.
- Based on the results the effect of curing age on As leaching behavior, it can be stated that in both curing conditions, there is no specific trend that can be due to the small amount of leaching concentration and the use of contaminated soil in the area. However, in general, and especially in high amounts of slag, the concentration of leached arsenic has been decreased with increasing curing time.
- Regarding the effect of curing conditions on arsenic leaching behavior, relatively similar behavior has been occurred in both conditions, but in HW conditions, the concentration of leached arsenic in samples after 28 days is partially lower than the AT conditions.

5 REFERENCES

Chen, J., Shen, L., Shi, Q., Hong, J., & Ochoa, J. J. (2019). The effect of production structure on the total CO2 emissions intensity in the Chinese construction industry. *Journal of Cleaner Production*, *213*, 1087-1095.

Du, Y.-J., Jiang, N.-J., Liu, S.-Y., Jin, F., Singh, D. N., & Puppala, A. J. (2014). Engineering properties and microstructural characteristics of cement-stabilized zinc-contaminated kaolin. *Canadian Geotechnical Journal*, *51*(3), 289-302.

García-Lodeiro, I., Maltseva, O., Palomo, Á., & Fernández-Jiménez, A. (2012). Cimenturi hibride alcaline. Partea I: fundamente*/hybrid alkaline cements. Part I: fundamentals. *Revista Romana de Materiale*, *42*(4), 330.

Ghadir, P., & Ranjbar, N. (2018). Clayey soil stabilization using geopolymer and Portland cement. *Construction and Building Materials*, *188*, 361-371.

Hataf, N., Ghadir, P., & Ranjbar, N. (2018). Investigation of soil stabilization using chitosan biopolymer. *Journal of Cleaner Production*, *170*, 1493-1500.

Rafiean, A.H., Najafi Kani, E., & Haddad, A. (2020). Mechanical and durability properties of poorly graded sandy soil stabilized with activated slag. *Journal of Materials in Civil Engineering*, *32*(1), 04019324.

Hu, Y., Tang, Z., Li, W., Li, Y., & Tam, V. W. (2019). Physical-mechanical properties of fly ash/GGBFS geopolymer composites with recycled aggregates. *Construction and Building Materials*, *226*, 139-151.

Ji, Z., Su, L., & Pei, Y. (2020). Synthesis and toxic metals (Cd, Pb, and Zn) immobilization properties of drinking water treatment residuals and metakaolin-based geopolymers. *Materials Chemistry and Physics*, *242*, 122535.

Jiang, H., Qi, Z., Yilmaz, E., Han, J., Qiu, J., & Dong, C. (2019). Effectiveness of alkali-activated slag as alternative binder on workability and early age compressive strength of cemented paste backfills. *Construction and Building Materials*, *218*, 689-700.

Kogbara, R. B., Al-Tabbaa, A., Yi, Y., & Stegemann, J. A. (2013). Cement–fly ash stabilisation/solidification of contaminated soil: Performance properties and initiation of operating envelopes. *Applied Geochemistry*, *33*, 64-75.

Leong, H. Y., Ong, D. E. L., Sanjayan, J. G., & Nazari, A. (2018). Strength development of soil–fly ash geopolymer: assessment of soil, fly ash, alkali activators, and water. *Journal of Materials in Civil Engineering*, *30*(8), 04018171.

Li, J.-S., Wang, L., Tsang, D. C., Beiyuan, J., & Poon, C. S. (2017). Dynamic leaching behavior of geogenic As in soils after cement-based stabilization/solidification. *Environmental Science and Pollution Research*, *24*(36), 27822-27832.

Li, W., Ni, P., & Yi, Y. (2019). Comparison of reactive magnesia, quick lime, and ordinary Portland cement for stabilization/solidification of heavy metal-contaminated soils. *Science of The Total Environment*, *671*, 741-753.

Nedunuri, S. S. S. A., Sertse, S. G., & Muhammad, S. (2020). Microstructural study of Portland cement partially replaced with fly ash, ground granulated blast furnace slag and silica fume as determined by pozzolanic activity. *Construction and Building Materials*, *238*, 117561.

Palacios, M., & Puertas, F. (2007). Effect of shrinkage-reducing admixtures on the properties of alkali-activated slag mortars and pastes. *Cement and concrete research*, *37*(5), 691-702.

Preetham, H., & Nayak, S. (2019). Geotechnical investigations on marine clay stabilized using granulated blast furnace slag and cement. *International Journal of Geosynthetics and Ground Engineering*, *5*(4), 1-12.

Renaudin, G., Russias, J., Leroux, F., Frizon, F., & Cau-dit-Coumes, C. (2009). Structural characterization of C–S–H and C–A–S–H samples—part I: long-range order investigated by Rietveld analyses. *Journal of Solid State Chemistry*, *182*(12), 3312-3319.

Shariatmadari, N., Reza, M., Tasuji, A., Ghadir, P., & Javadi, A. A. (2020). Experimental study on the effect of chitosan biopolymer on sandy soil stabilization. E3S Web of Conferences,

Singhi, B., Laskar, A. I., & Ahmed, M. A. (2017). Mechanical behavior and sulfate resistance of alkali activated stabilized clayey soil. *Geotechnical and Geological Engineering*, *35*(5), 1907-1920.

Thomas, R., Ariyachandra, E., Lezama, D., & Peethamparan, S. (2018). Comparison of chloride permeability methods for Alkali-Activated concrete. *Construction and Building Materials*, *165*, 104-111.

Wang, F., Wang, H., & Al-Tabbaa, A. (2015). Time-dependent performance of soil mix technology stabilized/solidified contaminated site soils. *Journal of hazardous materials*, *286*, 503-508.

Yi, Y., Gu, L., & Liu, S. (2015). Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag. *Applied Clay Science*, *103*, 71-76.

Zhang, P., Zheng, Y., Wang, K., & Zhang, J. (2018). A review on properties of fresh and hardened geopolymer mortar. *Composites Part B: Engineering*, *152*, 79-95.

Zou, H., Liu, S., Cai, G., & Puppala, A. J. (2020). Probabilistic identification of contaminated soils using resistivity piezocone penetration tests. *Acta Geotechnica*, *15*(3), 761-779.