

Time-dependent physicochemical characteristics of Malaysian residual soil stabilized with magnesium chloride solution

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Abstract The effects of non-traditional additives on the geotechnical properties of tropical soils have been the subject of investigation in recent years. This study investigates the strength development and micro-structural characteristics of tropical residual soil stabilized with magnesium chloride ($MgCl_2$) solution. Unconfined compression strength (UCS) and standard direct shear tests were used to assess the strength and shear properties of the stabilized soil. In addition, the micro-structural characteristics of untreated and stabilized soil were discussed using various spectroscopic and microscopic techniques such as X-ray diffractometry (XRD), energy-dispersive X-ray spectrometry (EDAX), field emission scanning electron microscopy (FESEM), Fourier transform infrared spectroscopy (FTIR) and Brunauer, Emmett and Teller (BET) surface area analysis. From the engineering point of view, the results indicated that the strength of $MgCl_2$ -stabilized soil improved noticeably. The degree of improvement was approximately two times stronger than natural soil after a 7-day curing period. The results also concluded the use of 5 % of $MgCl_2$ by dry weight of soil as the optimum amount for stabilization of the selected soil. In addition, the micro-structural study revealed that the stabilization process modified the porous network of the soil. The pores of the soils had

been filled by the newly formed crystalline compounds known as magnesium aluminate hydrate (M-A-H).

Keywords Residual soil · Non-traditional additive · Magnesium chloride ($MgCl_2$) solution · UCS · FESEM · FTIR

Introduction

High-quality soils as material for geotechnical engineering construction are rare in many parts of the world, and more often than not, engineers are forced to seek alternatives to reach the stipulated requirements. In addition, the gradual increase in population as well as rapid development in the construction industry in recent years has made it more urgent than ever to gain the knowledge and information needed to improve existing soil for geotechnical engineering purposes.

Soil stabilization is the process of improving the physical and engineering properties of soil to obtain some predetermined targets. It operates in various ways such as mechanical, biological, physical, chemical and electrical (Marto et al. 2014). Nowadays, among the different methods of soil improvement, the use of chemical additives for soil stabilization in order to increase soil strength parameters and loading capacity is attracting more attention. Engineers in the construction industry and particularly in the geotechnical sector use chemical soil stabilization techniques in many ways, such as for road construction, slope stabilization and erosion control, foundation and embankment treatment and improving the coastline for construction. This popularity is due to their low cost and convenience, particularly in geotechnical projects that require a high volume of soil (Latifi et al. 2014; Katz et al. 2007).

It should be noted that each type of chemical additive has a different mechanism and influence on soil properties. For

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instance, there have been notable important dissimilarities between tropical soils and the more ordinary soils of moderate climates. Rock weathering in these areas is very rigorous and can be described by the fast disintegration of feldspars as well as ferromagnesian raw materials; the displacement of bases including Na_2O , K_2O and MgO and silica and the absorption of aluminium and iron oxides (Latifi et al. 2015a; Latifi et al. 2014; Eisazadeh et al. 2011). This procedure, which includes leakage of silica and decomposition of iron and aluminium oxides, is called laterization (Gidigas 1972).

There are six areas of the globe where laterite soil is found: Africa, India, South-East Asia, Australia, Central and South America. However, it is emphasised that, due to the movement of climatic zones in the geological past, relevant regions of laterite can be located in places that are not within the tropics (Zelalem 2005). This soil category is rich in aluminium, iron and kaolinite clays (Townsend 1985). This soil group usually exists in hillsides and offers excellent extraction areas for wide adoption in many different construction operations. The optimum utilization is determined by the quantity of issues encountered in construction connected to their workability, field compaction and strength. Studies shows that laterite soil forms a large part of Malaysia's soil, and it has been used in different areas and projects as natural soil (Salih 2012; Marto et al. 2014).

Soil stabilizers are categorized as traditional and non-traditional (Latifi et al. 2015b; Turkoz et al. 2014). Traditional additives include cement, lime, fly ash and bituminous materials, while non-traditional additives consist of various combinations such as enzymes, liquid polymers, resins, acids, silicates, ions and lignin derivatives (Latifi et al. 2015c; Hafez et al. 2008). Non-calcium-based liquid soil stabilizers are actively marketed by a number of companies. In addition to being cheaper to transport than traditional bulk stabilizer materials, these products are a potentially attractive alternative for soil treatment. These are mostly sold as concentrated liquids, which are diluted with water on site. Some are directly applied to the soil before compaction while others are pressure-injected into deeper layers.

It should be noted that the results of previous studies have indicated that the non-traditional additives can help to increase soil strength with curing time (Zhu and Liu 2008; Fon 2010; Liu et al. 2011; Ahmad et al. 2013; Latifi et al. 2014; Turkoz et al. 2014). For example, previous studies indicated that bischofite is used on roads to control dust and humidity, to minimize coarse particle scattering and to prevent ice formation (Thenoux and Vera 2002; Nixon and Williams 2001; Ketcham et al. 1996; Transportation Research Board 1991). Hexahydrated magnesium chloride or bischofite is a salt. Bischofite is a hydrous magnesium chloride mineral with the formula $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$. It belongs to the halides group and is a sea salt concentrate dated from the Permian period (nearly

200 million years ago). The main bischofite compound is magnesium chloride (up to 350 g/L).

Chemical substances such as MgCl_2 solution that do not corrode vehicles, damage cement and asphalt or harm plants or living creatures have long been used in parts of the world such as North America, Scandinavia and Europe (Environmental Canada 2001). For example, magnesium chloride (MgCl_2) solution is applied to non-paved roads during the spring and summer months for dust suppression and road stabilization. Non-paved roads are a major man-made source of fugitive dust, which contributes to atmospheric particulate matter (Goodrich et al. 2009). Fine particulate matter less than $10 \mu\text{m}$ (PM-10) needs to be suppressed due to air quality standards set by the U.S. Environmental Protection Agency (EPA) (Piechota et al. 2004; Singh et al. 2003; Nixon and Williams 2001).

Unfortunately, millions of dollars are lost in some cases due to improper use of chemical stabilizers. Therefore, proper knowledge on soil additive reactions is an essential part of this technique. Traditional stabilizers such as cement, lime, fly ash and bituminous products have been intensely researched, and their fundamental stabilization mechanisms have been identified (Obuzor et al. 2012; Eisazadeh et al. 2012; Eisazadeh et al. 2013; Turkoz and Vural, 2013; Kassim and Kok 2004). Also, many studies have been done on traditionally stabilized laterite soil, which forms a large part of Malaysia's soil, and the relevant mechanisms are well understood (Eisazadeh et al. 2011). In addition, in recent years, some researches have been conducted on the effects of magnesium chloride (MgCl_2) solution on the swell potential, strength characteristics and dispersibility properties of soils (Turkoz et al. 2014; Turkoz and Tosun, 2011; 2011; Acaz 2011; Jianli et al. 2010; Goodrich et al. 2009). Nevertheless, no research on the macro- and micro-structural study of the tropical residual soil, in particular the laterite soil, mixed with magnesium chloride (MgCl_2) solution has been carried out. So, it is therefore important to fully understand the physicochemical characteristics of this soil stabilized with MgCl_2 .

In this study, the development of the micro-structure of laterite soil treated with magnesium chloride (MgCl_2) solution and its relation to the strength properties was investigated. The macro-structural tests in the present study included unconfined compression strength (UCS) and standard direct shear tests. These tests were employed to find the strength and shear properties of untreated and treated soil. In addition, various spectroscopic and microscopic techniques were used as micro-structural tests to discuss the possible mechanisms that enhance the stabilization process. The mentioned techniques consisted of X-ray diffractometry (XRD), energy-dispersive X-ray spectrometry (EDAX), field emission scanning electron microscopy (FESEM), Fourier transform infrared spectroscopy (FTIR) and Brunauer, Emmett and Teller (BET) surface area analysis.

Materials, sample preparation and testing program

Materials

This study was conducted on the residual laterite soil that is usually found in tropical areas. Residual soil was obtained from a depth of 2 to 3 m below the ground surface. The soil was air-dried under laboratory conditions, after which pebbles and plant roots were removed and sieved by a 2-mm mesh to confirm the uniformity of the soil. The colour of this clayey soil is reddish due to the high amount of iron oxides. The particle size distribution and the physicochemical properties of the natural soil are illustrated in Fig. 1 and Tables 1 and 2, respectively. In Fig. 2, the X-ray diffraction (XRD) results indicated that the main minerals present in the laterite soil were kaolinite ($2\theta=12.5^\circ, 20^\circ, 35^\circ, 38^\circ, 46^\circ, 55^\circ$), quartz ($2\theta=26^\circ, 36.5^\circ, 42.5^\circ, 50^\circ, 62^\circ$), goethite ($2\theta=21.5^\circ, 37^\circ, 41^\circ, 53^\circ$) and gibbsite ($2\theta=18^\circ, 19^\circ, 27^\circ, 39^\circ$) (JCPDS 1995; Marto et al. 2014). In addition, in Fig. 3, the energy-dispersive X-ray spectrometry (EDAX) results indicated that the dominant elements present in the laterite soil were Al, Si and Fe. The magnesium chloride (MgCl_2) solution used in this study was prepared from Merck Chemicals Company in Malaysia. Although it can be used as a solid or in solution, the solution form is more common. Table 3 shows the general chemical properties of the MgCl_2 solution used in this study.

Sample preparation

The results of laboratory studies on the laterite soils revealed significant changes in their properties due to oven drying (Marto et al. 2014). In order to avoid the mentioned changes, an air-drying method was used for all soil specimens. The specimens were sieved by a 2-mm mesh to confirm the uniformity of the soil. The optimum moisture content (OMC), as the required amount of water, was determined for the untreated soil and soils mixed with 1, 3, 5, 7 and 9 % of MgCl_2 by dry weight of soil. For this purpose, a series of standard Proctor

Table 1 Physical and engineering properties of natural laterite soil

Engineering and physical properties	Values
pH (L/S=2.5)	5.35
Specific gravity	2.69
External surface area ($\text{m}^2 \text{g}^{-1}$)	41.96
Liquid limit, LL (%)	75
Plastic limit, PL (%)	41
Plasticity index, PI (%)	34
BS classification	MH
Maximum dry density (mg m^{-3})	1.31
Optimum moisture content (%)	34
Unconfined compressive strength (kPa)	270

compaction tests according to the British Standard was performed. Then, the specified amount of additive was added to the water and mixed with the soils. In order to prepare a homogeneous mixture for the unconfined compressive strength (UCS) test, irregular hand-mixing with palette knives was done. Then, the target dry density and moisture content were reached by compressing the samples in a steel cylindrical mould fitted with a collar that accommodated all the mixtures. The required compaction was done by a hydraulic jack based on clause 4.1.5 of BS 1924: Part 4: 1990b. Finally, the cylindrical samples were extruded using a steel plunger, trimmed and wrapped in several layers of cling film. These samples were cured for 3, 7, 14 and 28 days in a temperature-controlled room ($27\pm 2^\circ \text{C}$) before they were used for the unconfined compressive strength test (Latifi et al. 2014). It should be stressed that to ensure the accuracy of the results, four samples for each soil mix design and the four curing periods were prepared.

A 3-day curing period was selected as a reasonable delay to allow reactions between the stabilizer and the soil before conducting the evaluation tests. Most testing on soils with added soil stabilizers is conducted after a curing period of 28 days. An additional 3 weeks can be given based on the type of stabilizer used and expected changes in soil properties.

Fig. 1 Particle size distribution of natural laterite soil

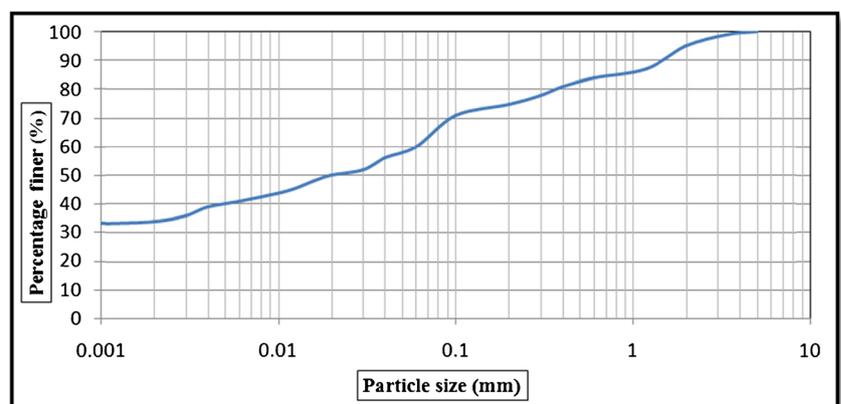


Table 2 Chemical properties of natural laterite soil

Chemical composition (oxides)	Values (%)
SiO ₂	25.46
Al ₂ O ₃	31.10
Fe ₂ O ₃	35.53
CO ₂	7.91

Nevertheless, it is widely accepted that any effective changes will be measurable after 7 days. In this study, the 28-day curing time is prescribed just to compare the difference between the short- and long-term behaviours of the stabilized soils (Chang and Cho 2012; Zhang et al. 2012; Sukmak et al. 2013; Blanck et al. 2013).

The shear strength parameters of the samples were investigated using the standard direct shear test. For this aim, a homogeneous mixture was made by irregular hand-mixing with palette knives. Then, two-layered compaction was performed on the soil specimens, which were 60 mm in diameter and 20 mm in height. The samples were then placed in a plastic bag and cured inside a humid room with a controlled temperature (27 ± 2 °C) (Latifi et al. 2015b). The untreated soil samples were sheared immediately as control specimens, but the treated samples were only sheared after being cured. The samples and nature of the work in this study were identified using designated notations shown as L for laterite soil, UNT for untreated soil, T for treated soil and D for days of curing period.

Testing program

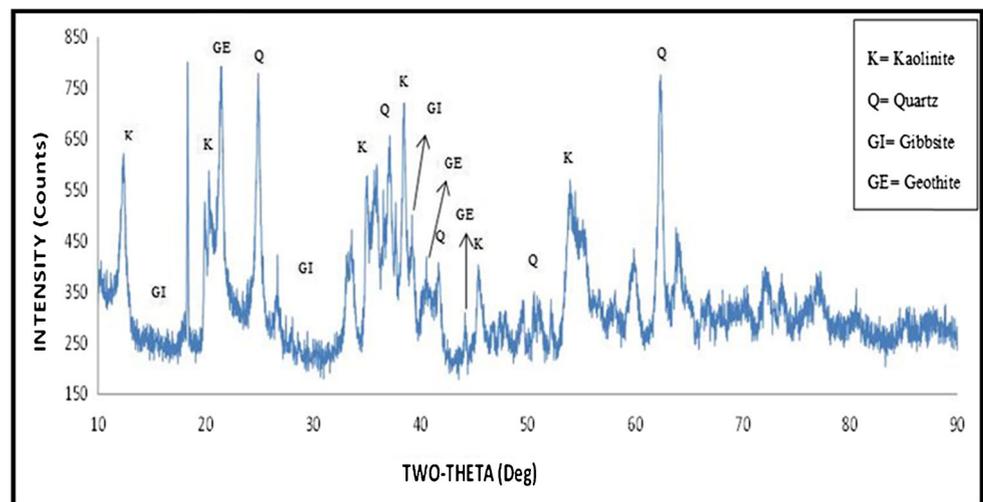
The soil improvement index was determined by conducting a series of UCS tests (BS 1924: Part 2: 1990a) on the specimens at different time intervals. A rate of axial strength equal to 1 % per minute was applied to the samples. The acquisition data

unit (ADU) was used to record the applied load and axial deformation automatically. The failure of each specimen was defined by its peak axial stress. The failed specimens were dried and weighed at the end of each test to calculate their moisture content.

The shear strength tests were carried out by applying a constant strain rate of 0.6 mm/min on the soil samples placed inside standard shear boxes until the soil had failed or reached a maximum horizontal displacement of 10 mm. This displacement was chosen based on the capability of the machine used. The standard procedures used were BS 1377: Part 7: 1990c and ASTM 3080 (as mentioned in Head (1990b)). In addition, the three different normal stresses exerted on the samples were 28, 56 and 112 kPa. It should be noted that the shear strength tests were carried out by applying a constant strain rate of 0.6 mm/min on the soil samples placed inside standard shear boxes (Ahmad et al. 2010). Finally, based on the several tests on the natural soil and treated samples with the application of different normal stresses, the cohesion (c) and internal friction angle (ϕ) of the unstabilized and stabilized samples, at different curing times, were obtained.

In the present study, the X-ray diffraction (XRD) technique was used to achieve two goals: firstly, to measure mineralogical changes of the selected soil structure due to the presence of the additive, and secondly, to find newly formed crystalline cementitious compounds. A Bruker D8 advanced diffractometer was employed for the analysis of the cured samples. Cu-K α radiation ($k=1.54$ Å) at an angle scan (2θ) of 6° to 90°, step size of 0.02°, and 1s lodging at each step was used for scanning. Finally, a comparison was made between the resultant patterns and the standard dataset of the Joint Committee for Powder Diffraction Standards (JCPDS 1995).

Field emission scanning electron microscopy (FESEM) is a common technique used to determine the micro-structural properties of soil fabric, providing information on the size, shape and the state of orientation and aggregation of soil

Fig. 2 Diffractogram of natural laterite soil

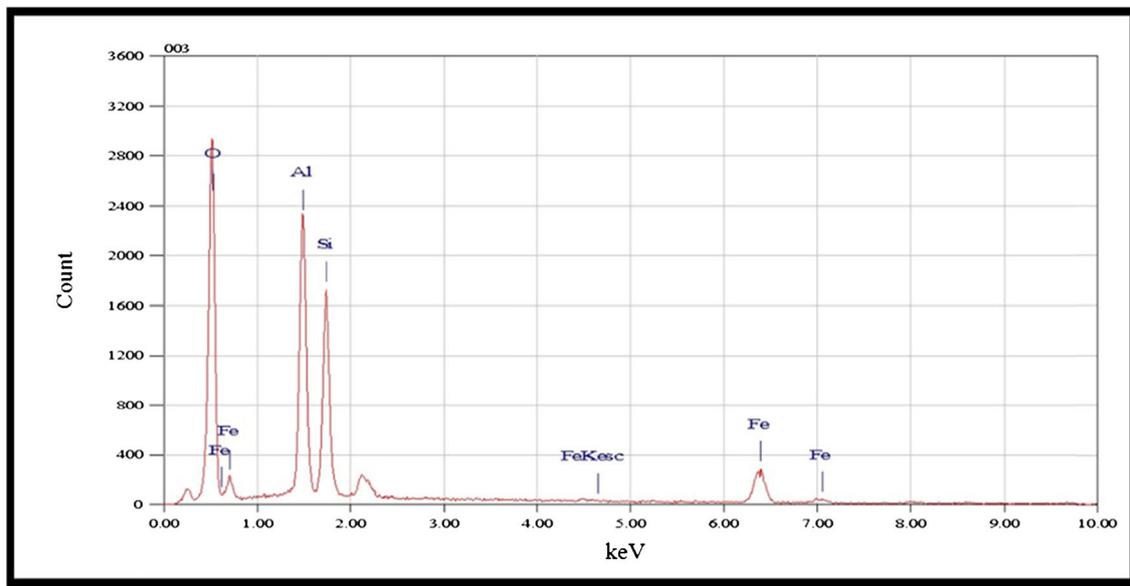


Fig. 3 EDAX spectrum of natural laterite soil

particles. This method can be implemented in soil stabilization studies, in order to visualize the topographical features and moreover to observe the formation of new cementitious materials. In this technique, each sample was sputtered with platinum for 120 s at 30 mA under high vacuum until they were completely covered and ready to be used for the microscopic analysis. Moreover, the energy-dispersive X-ray spectrometry (EDAX) method was used to find the major elemental composition on the surface of the treated particles.

FTIR analysis was applied on the untreated and treated samples to determine their molecular structural changes. In order to measure the absorption bands of the prepared KBr disc, a 2-mg sample of ground dried soil was mixed with 200 mg KBr. The sample was scanned by a Perkin Elmer Spectrum 2000 gadget in the 400 to 4000 cm^{-1} infrared spectrum range.

The particle surface area is an essential feature to understand both the physical and chemical properties of the treated soil. This is because many chemical reactions in soils occur at the surface (Mitchell and Soga 2005). In this study, the nitrogen-based Brunauer–Emmett–Teller (N_2 -BET) surface

area method has been used to determine the changes that occurred on the surface area and micropores of the treated samples with the selected additive. In this method, the surface area was derived through physical adsorption of nitrogen gas by means of a Micromeritics surface area analyzer. It is also microprocessor-controlled and interacts with an XP-based PC which allows for physisorption investigation. In this method, a small amount of the cured sample was placed in the sample container. Nitrogen gas was pumped in after degassing for 1 h at 130 $^\circ\text{C}$, and the outer area value was estimated by adopting the single point BET technique (Quantachrome 2007).

Results and discussion

Compaction, UCS and direct shear tests

The addition of a single anion or cation introduced by the stabilizers has a significant impact on the compacted soil. The chemical reactions are affected by the initial compactive effort, since this has a direct influence on the particle spacing and the subsequent crystallization process (Latifi et al. 2013).

Compaction tests were performed on the unstabilized and stabilized soil with 1, 3, 5, 7 and 9 % MgCl_2 solution. The relationships between the maximum dry density, ρ_{dmax} and optimum water content, w_{opt} versus additive content are presented in Fig. 4. The addition of MgCl_2 solution to the laterite soil increased the dry density and reduced the optimum moisture content for the same compactive effort. This increase in ρ_{dmax} associated with the decrease in w_{opt} is typical for compacted cohesive soils (Horpibulsuk et al. 2008; Horpibulsuk et al. 2009). The increase in the dry density could

Table 3 Properties of the MgCl_2 solution

Property	Quantity
Colour/appearance	Amber/transparent
Baume degree	35.50 (min)
Density (g/cm^3)	1.320 (min)
H_2O (%)	57.00 (min)
Solid material (%)	43.00 (max)
MgCl_2 in solid material (%)	94.00 (min)
pH (in 1 % solution)	10.0

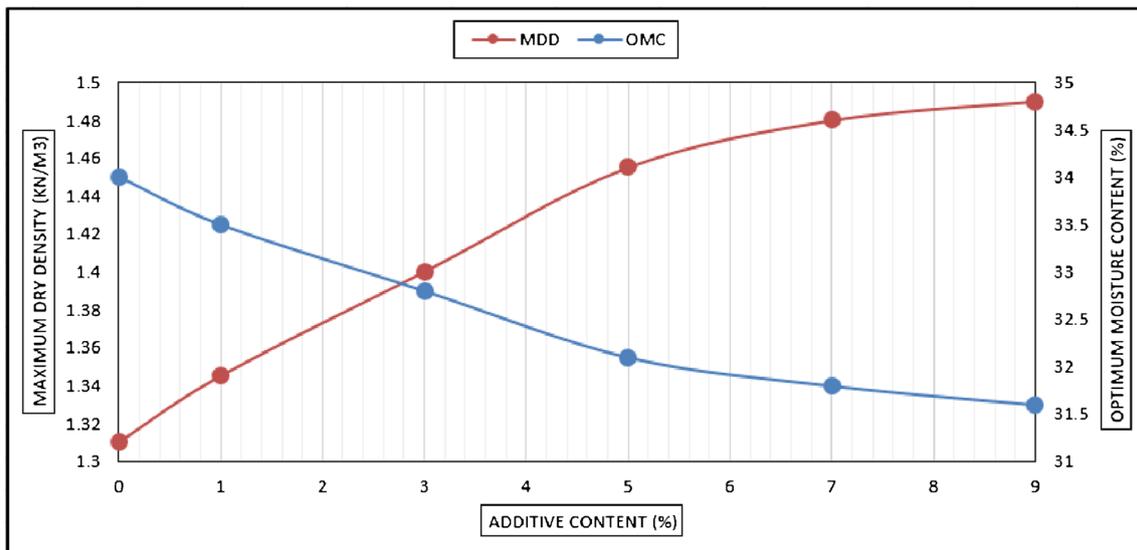


Fig. 4 The result of the compaction test on stabilized laterite soil at different MgCl₂ contents

be due to the flocculation and agglomeration effect caused by the rapid cation exchange in the soil–MgCl₂ solution mixture (Marto et al. 2014; Turkoz et al. 2014). The changes in ρ_{dmax} and w_{opt} at higher additive contents were smaller, which is attributed to a balance between the magnesium ions in the solution and the negative ions at the clay surfaces at high additive concentrations (Randolph 1997; Turkoz et al. 2014). This flocculated structure caused the reduction in the specific surface of the stabilized soils and hence the reduction in the water absorption capability and the increase in dry density.

The unconfined compressive strength (UCS) test was used as an index test to investigate the effectiveness of the selected additive on the compressive strength of laterite soil. Figure 5

shows the results of UCS tests on stabilized mixtures for different time intervals. The enhancement in the compressive strength of 5 % MgCl₂-treated samples was 598 kPa after 7 days of curing. This was approximately two times greater than the untreated soil strength, and the increase in strength is much faster in comparison to the traditional type of stabilizers, such as lime, which required an 8-month curing period to achieve a 633-kPa compressive strength (as reported by Eisazadeh et al. 2011). It can be noted that the rate of strength increment was rather limited after the 7-day curing period, reaching a value of 645 kPa for the 28-day cured samples. This indicated that most of the soil–stabilizer reactions happened within the first 7 days. On the other hand, it was clear that for the samples treated with higher MgCl₂ content (more

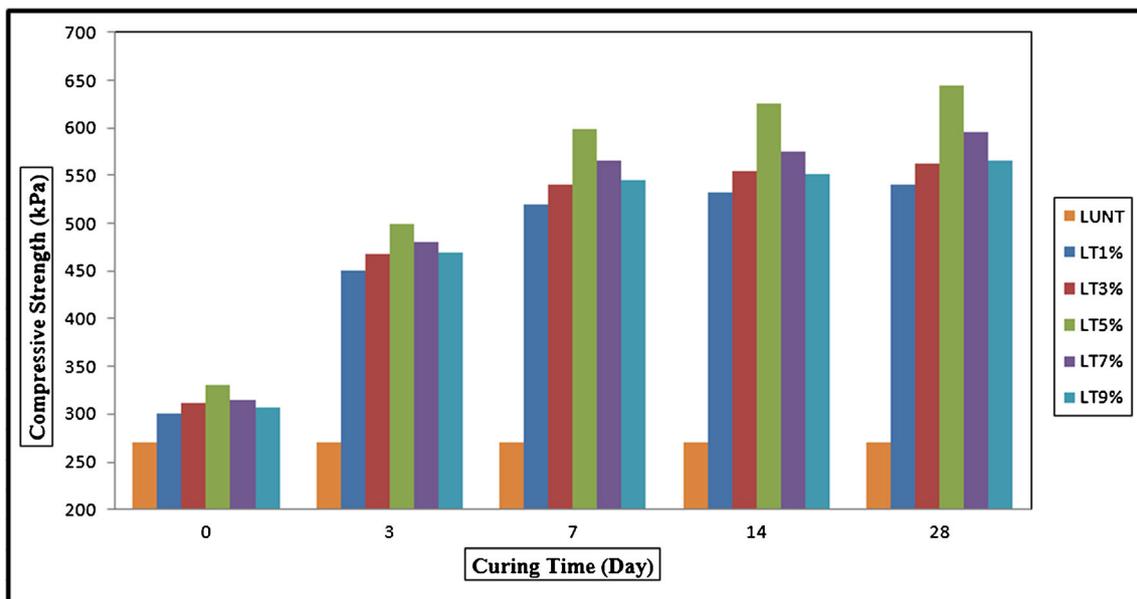


Fig. 5 Strength gained for MgCl₂-treated laterite soil with different additive contents and curing time

than 5 %), a lower compressive strength was achieved. This was probably due to the increase in the positive surcharge and the subsequent repulsion of soil particles inside the mixture (Latifi et al. 2014; Tingle and Santoni 2003; Katz et al. 2001; Rauch et al. 2002; Tingle et al. 1989). The degradation of strength could also have been due to the amount of alkaline stabilizer (pH value=10), which exceeded the requirement for chemical reaction in the samples (Marto et al. 2014; Sukmak et al. 2013). Hence, based on the obtained results, 5 % of magnesium chloride solution was chosen as the optimum value to add to the laterite soil for direct shear and micro-structural studies.

Shear strength is another important feature in geotechnical engineering or, more specifically, the stability of slopes, shallow foundations, cuts, fills, dams, pavements design and the stresses on retaining walls. Generally speaking, it governs the stability and robustness of a particular structure under expected maximum loading. The achieved parameters of shear strength (cohesion (c) and internal friction angle (ϕ)) of the untreated and treated laterite soil with 5 % of $MgCl_2$ at different curing times are presented in Figs. 6 and 7. The untreated sample's cohesion and internal friction angle were 38.6 kPa and 22.3° , respectively. It is observed that the cohesion of specimens increased significantly with the curing time, but the internal friction angle changes were negligible. The cohesion of the treated sample obtained after 7 days of curing was 78 kPa, which is about two times more than the untreated specimen. The maximum of cohesion is observed at 28-day curing time as 90 kPa. However, it is clear from the results that most of the increment in both of the shear parameters occurred

in the first 7 days, which indicated the rapid reaction between laterite soil and $MgCl_2$.

Generally, the strength increase during curing can be explained through the cementing gel material (hydrates), formed through pozzolanic reactions. Tingle et al. (1989). Latifi et al. (2015a). Turkoz et al. (2014) and Ahmad et al. (2013) reported that the activities of cationic exchange as well as the presence of a cementitious component can decrease soil porosity while increasing its strength properties. Their studies reported interesting results on different types of soil that had been mixed with additives; it seems that clayey minerals are more susceptible to stabilizer effects. This is logical because with the right amount of additive that can work as a cementing bond, soil voids can be filled up. In other words, the chemical stabilizers acted as cementitious products that filled the soil voids and thus increased the soil's shear resistance. In order to confirm these findings, the micro-structural characterization was carried out using X-ray diffraction (cementitious crystals detection), field emission scanning electron microscopy (morphology of cementitious materials) and Fourier transform infrared spectroscopy (cementitious materials bonding).

XRD

As a popular fundamental investigation technique, X-ray diffraction (XRD) is easy to use and can give a wide range of instantly interpretable data on soil minerals. In this study, it was employed to analyse mineralogical changes to the laterite soil structure caused by the magnesium chloride solution and to identify any new crystalline compound formed during the

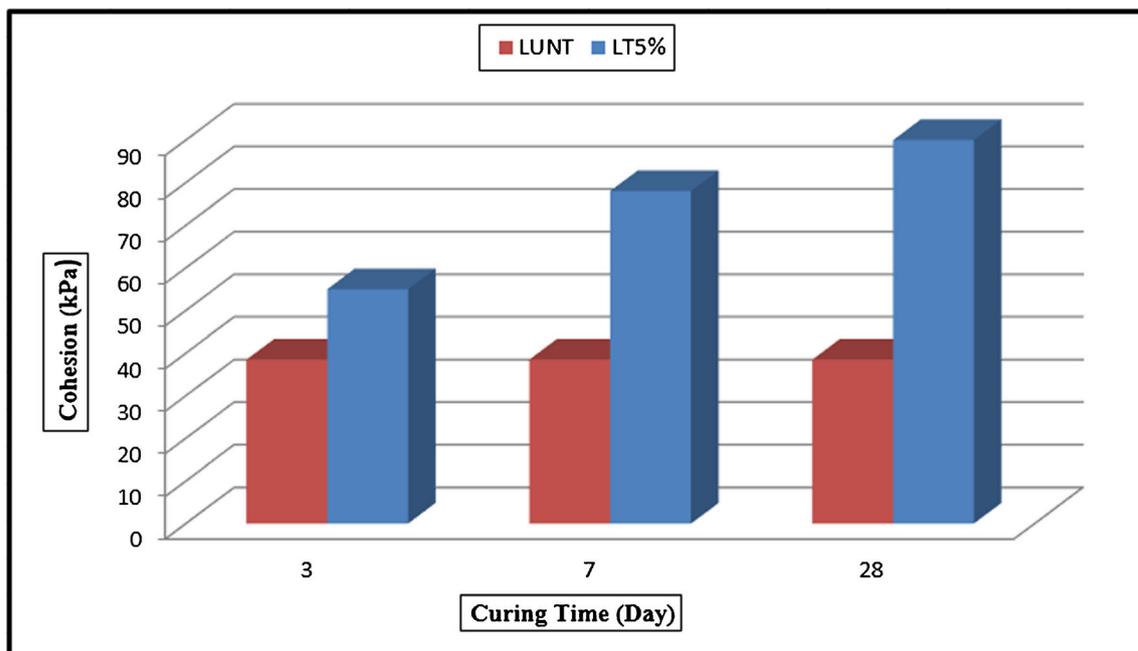
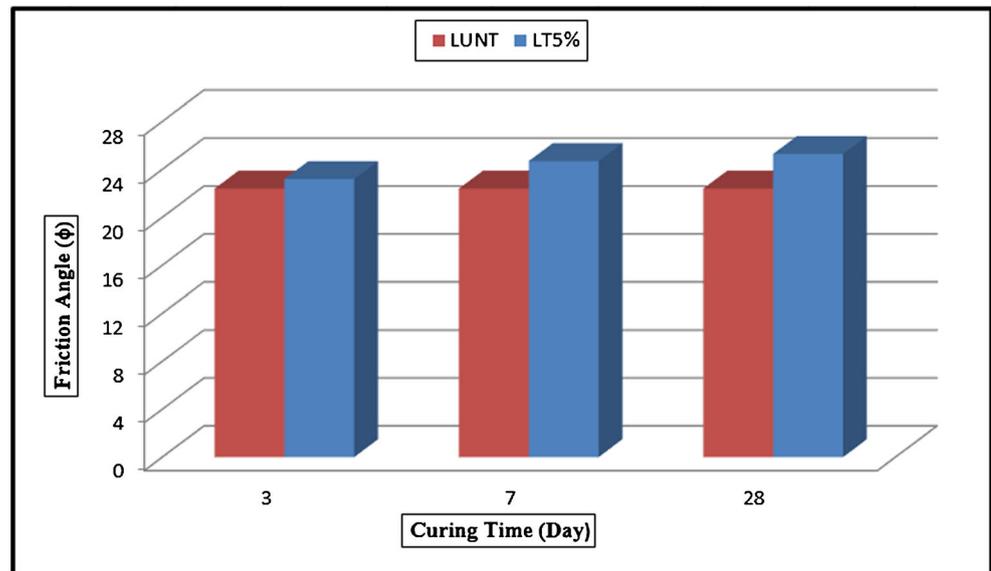


Fig. 6 Variation of cohesion of laterite soil treated samples at different time intervals

Fig. 7 Variation of friction angle of laterite soil treated samples at different time intervals



process. The XRD patterns for untreated and $MgCl_2$ -treated laterite soil are illustrated in Fig. 8. As can be seen, no fundamental changes took place in the XRD patterns of the treated samples in comparison to the natural laterite soil, while the intensity of the peaks for kaolinite mineral decreased slightly. The reason for this reduction was the effect of the stabilizer on the soil matrix and the weathering of kaolinite mineral (Latifi et al. 2014; Eisazadeh et al. 2011). The intensity of the peaks for quartz mineral was intact. The apparent occurrences of several new reflections were also detected due to the formation of new products at various 2θ angles, including 28° , 31°

and 43° for $MgCl_2$ -treated samples. These peaks were assigned to the crystalline cementing compounds of magnesium aluminate hydrate (M-A-H) (Jayaseelan et al. 2007; Ganesh et al. 2001; JCPDS 1995).

FESEM and EDAX

In order to evaluate the morphological changes of the stabilized soil, FESEM was used in the present study. Figure 9a–d shows the results of FESEM for the untreated laterite soil and treated samples after 3-, 7- and 28-day curing periods,

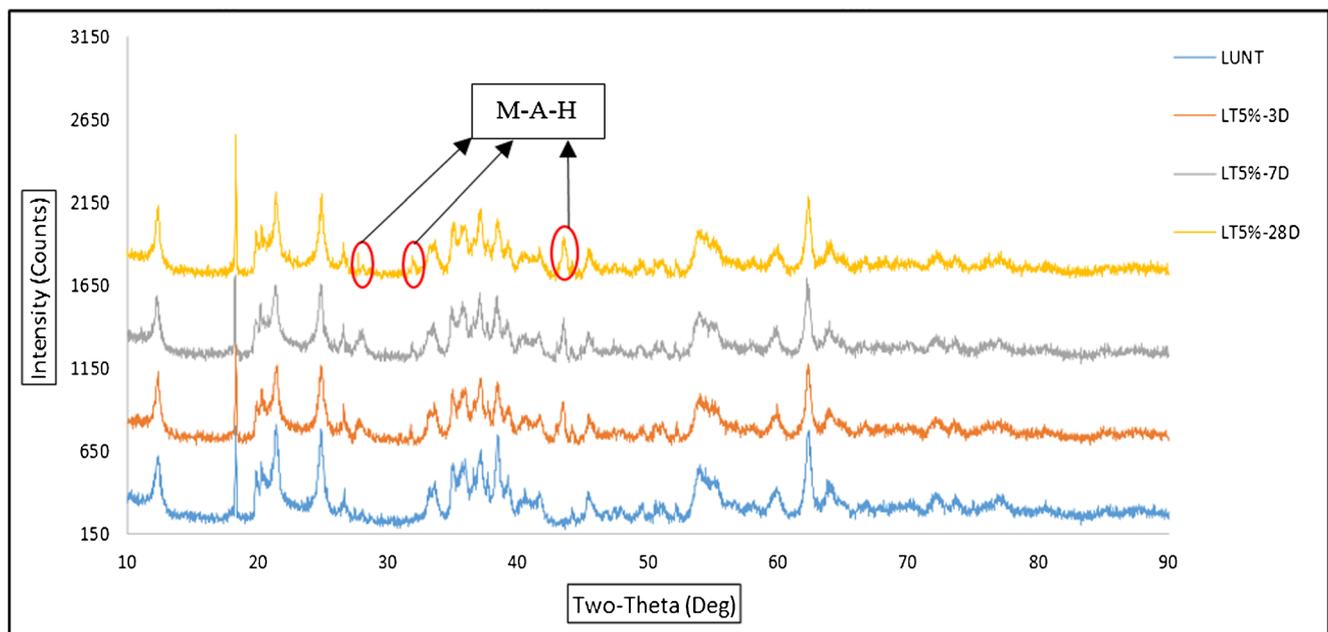


Fig. 8 XRD patterns for the natural and $MgCl_2$ -treated laterite samples at different curing times

respectively. As can be seen, the untreated samples showed a dispersed and discontinuous structure, where the voids and porosity are more visible because of the absence of hydration products. From the 3-day curing time image of the treated mix designs with the MgCl_2 additive, it can be seen that there was new formation of cementing products in the form of crystals. These new products filled the pores in the soil structure. For the 7-day curing time, the image showed clearly that the newly formed products already filled most of the voids. For that reason, there was a significant change in the surface of the soil particles. At 28 days of curing, the image indicated that the soil particles were joined strongly together by the new cementation products. It should be noted that the formation of the new cementitious materials which were created from the early stage of the curing period indicated the fast reaction between the laterite soil and magnesium chloride solution. It should be stressed that, in line with the XRD test results, by means of the energy-dispersive X-ray spectrometer (EDAX) technique, these new compounds were identified as magnesium aluminate hydrate (M-A-H) (Pal et al. 2010a; Pal et al. 2010b; Harrison 2008; Jayaseelan et al. 2007; Harrison 2008; Ganesh et al. 2001).

In general, from the images of the MgCl_2 -treated samples, it can be concluded that the new cementitious products filling the pores in the soil structure in the form of white lumps were found to occur with curing time. The latter is the main reason for soil particles interlocking and results in the denser fabric that helps to increase the strength properties of the soils.

FTIR

In order to determine the functional groups of soil minerals, analysis of the molecular characteristics from the Fourier transform infrared spectroscopy (FTIR) test was employed in this study. The absorption bands at characteristic wavelengths of bonds that vibrate independently of one another were measured in the FTIR process. Figure 10 illustrates the common features of the FTIR spectra for the natural and stabilized laterite soil with MgCl_2 solution. These spectra included bands at 1111 and 1032 cm^{-1} , respectively, for the perpendicular and in-plane Si–O stretching. According to Madejova and Komadel (2001) and Latifi et al. (2014), the peaks at 3615 and 3692 cm^{-1} were recognized, respectively, as the O–H stretching vibrations of the inner and inner-surface hydroxyl groups. Although the latter band was specific to a kaolinite mineral, the former was a common band of phyllosilicate minerals. Gadsen (1975), Latifi et al. (2014) and Eisazadeh et al. (2011) revealed the existence of haematite and quartz for the bands at 913 and 792 cm^{-1} , respectively. The remaining bands were allocated to water vibrations. A stretching vibration was indicated by the band at 3446 cm^{-1} , while an H–O–H bending band of water was detected by the band at 1635 cm^{-1} with an overtone occurring at 3378 cm^{-1} . The results of the

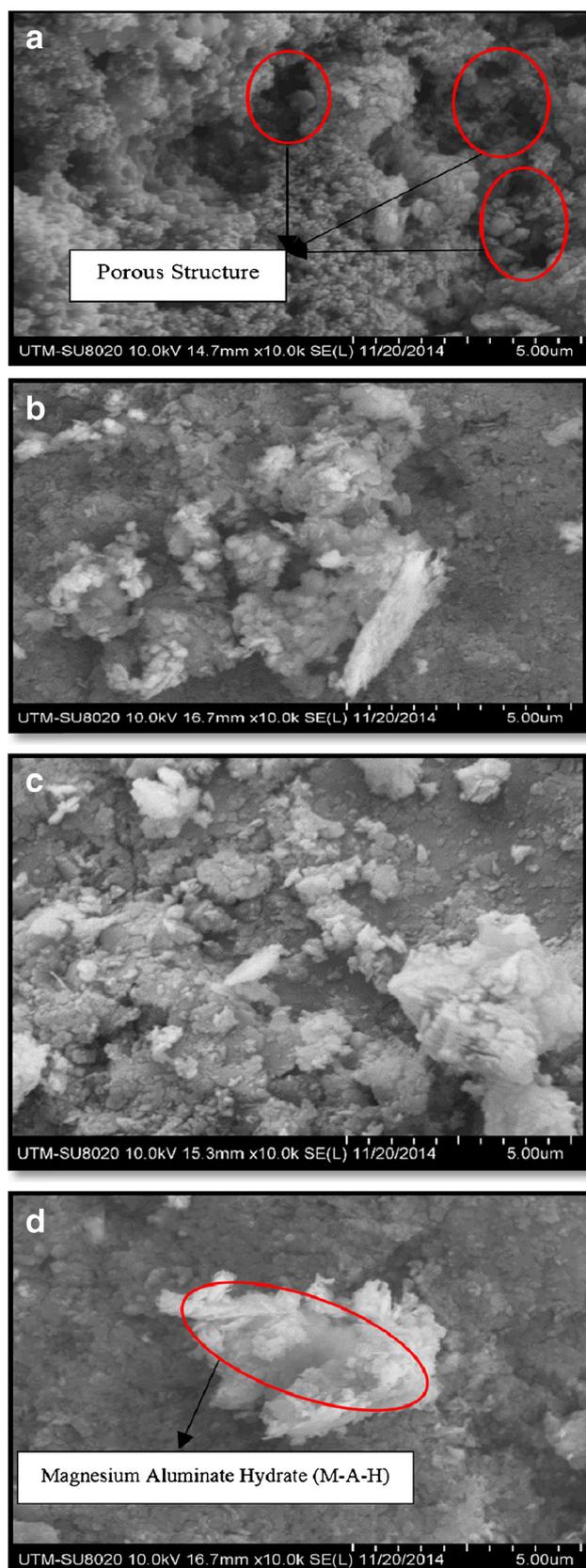


Fig. 9 FESEM results of **a**: natural laterite soil, **b**: 5 % MgCl_2 -treated laterite soil after 3-day, **c**: after 7-day and **d**: after 28-day curing time

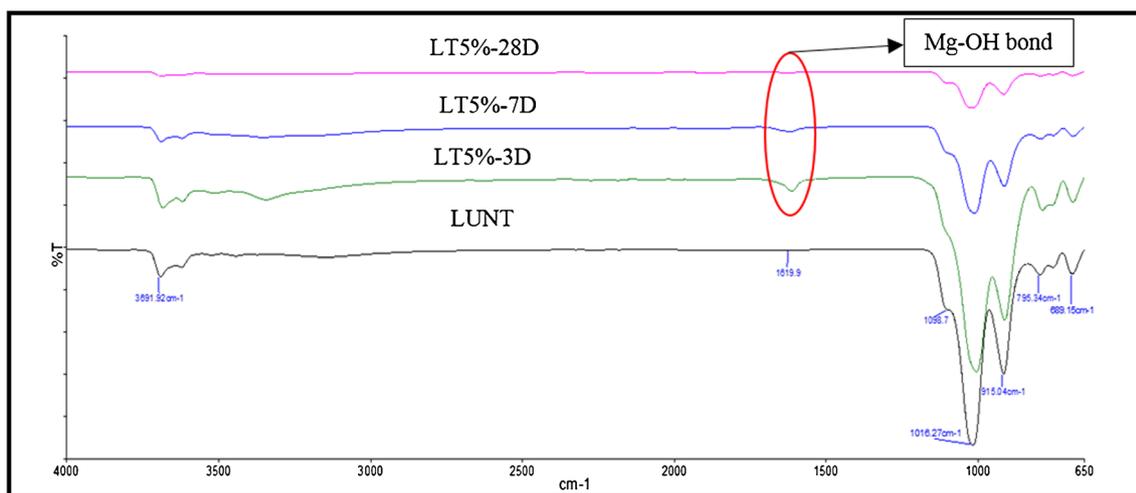


Fig. 10 FTIR spectrums for untreated and MgCl_2 -treated laterite soil at different curing times

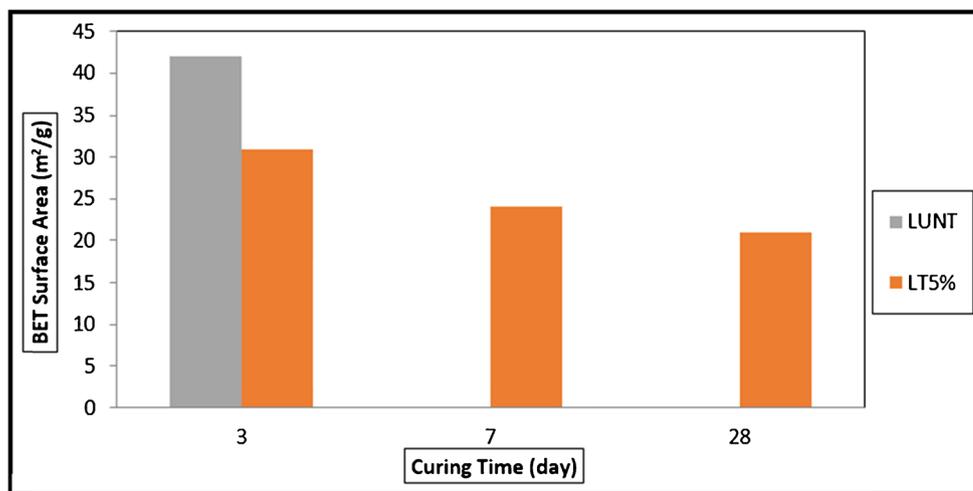
FTIR spectra for 3-, 7- and 28-day cured samples confirmed that the chemical treatment made a noticeable difference in the Si–O functional groups of soil particles. However, a new absorption band at 1619 cm^{-1} with a weak intensity attributed to the Mg–OH bond of magnesium chloride solution was evident. Also, in general, the peaks' intensities reduced with curing time. This was because of the weathering action of the stabilizer on the clay minerals, as also found by García Lodeiro et al. (2009); Bobet et al. (2011) and Eisazadeh et al. (2012).

N_2 -BET

In this study, the nitrogen-based Brunauer–Emmett–Teller (N_2 -BET) surface area method has been used to determine the changes that occurred on the surface area and micropores of the treated samples with the selected additive. The results for the untreated laterite soil showed

that the external surface area of the natural soil was $41.96\text{ m}^2/\text{g}$. The N_2 -BET results of 5 % MgCl_2 -treated laterite soil at 3, 7 and 28 days of curing together with the results for the untreated soil are presented in Fig. 11. As shown, a significant reduction in the surface area of the treated samples was evident at the early stage (3 days) of curing. In addition, with further curing (7 days), a considerable reduction in the BET surface area of the treated samples was evident. This was due to the continuous chemical reaction between the stabilizer and the soils, causing the reduced number of accessible pores among the clay particles. However, for the 28-day cured samples, the time-dependent alteration in the surface area was less significant and comparatively stable. Analysis of the surface area from BET tests confirmed that the new cementitious products filled the porous structure and micropores of the laterite soil. This indicated the transformation of the untreated soil's

Fig. 11 N_2 -BET results for untreated and MgCl_2 -treated samples



structure to a completely flocculated new material. Hence, it can be deduced that the new materials formed were the main reason for soil strength changes and improvement (Latifi et al. 2015b).

Conclusion

In this study, different analytical techniques related to the strength behaviour and micro-structural characteristics of laterite soil stabilized with magnesium chloride solution were studied. The UCS data for various mix designs indicated a significant and rapid strength improvement for the selected non-traditional additive. Also, it was found that for the samples treated with higher additive content (more than 5 % MgCl_2), a lower compressive strength was achieved. Hence, 5 % of MgCl_2 was chosen as the optimum value to add to the laterite soil. Also, it is observed from the direct shear test that the cohesion also increases with the increase of curing time, but the variation of friction angles is low. The XRD results showed that the intensity of the peaks for kaolinite mineral decreased slightly with curing time. This was due to the weathering action of the additive on the clay mineral structure. In addition, some new peaks were observed inside the treated samples. These peaks were assigned to the cementing compounds of magnesium aluminate hydrate (M-A-H). Based on the FESEM and EDAX results, the newly formed crystalline cementitious compounds of magnesium aluminate hydrate were believed to be the main cause of strength development by coating the soil particles. Furthermore, the result of BET analysis indicated that the stabilization process reduces the external surface area by filling the soil pores. The FTIR results indicated the presence of a new absorption band at 1619 cm^{-1} with a weak intensity attributed to the Mg–OH bond in the treated soil matrix.

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