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Alkali Activated Olivine for Sustainable Soil Stabilization

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ABSTRACT: Alkali-activated material-based binders are increasingly recognized as sustainable alternatives to conventional calcium-based binders for soil stabilization due to their superior mechanical performance and reduced carbon footprint. Magnesium-rich olivine is widely used for carbon dioxide sequestration owing to the natural weathering reaction of olivine with atmospheric carbon dioxide. Magnesium-rich olivine has a weak nesosilicate structure with high SiO_2 and MgO content, making it a potential source material for alkali activation. Additionally, stabilizing soil using magnesium-rich olivine in the presence of a strong alkali requires no energy-intensive pretreatments, unlike cement and lime treatment. On comparing with the processes involved in cement and lime manufacturing, the production of dunite rock powder rich in magnesium-rich olivine involves far less carbon dioxide emissions and energy consumption. This Study highlights the efficacy of magnesium-rich olivine as a sustainable source material for alkali activation. Experimental studies were conducted to explore the interactions between kaolinite-rich red earth and alkali-activated olivine, analysing variations in their physicochemical properties and unconfined compressive strength (UCS). A notable reduction in plasticity index, an increase in shrinkage limit, and a reduction in specific surface area values of untreated soil were noted on treatment with alkali-activated olivine. A considerable improvement in UCS value of about 14.9 times over the UCS value of untreated soil was observed when the 5% olivine-treated sample in the presence of 10 M KOH was cured for 28 days. Experimental findings suggest that introducing alkali-activated magnesium-rich olivine to soil induces olivine dissolution, cation exchange, aggregation, and hydration reactions. Microstructural investigations show the formation of Brucite, Hematite, Mullite, and Magnesium silicate hydrate gels in the treated soil, thereby enhancing soil performance.

KEYWORDS: Alkali Activation, Microstructure, Olivine, Soil Stabilization, and Unconfined Compressive Strength.

1. INTRODUCTION

Portland cement and lime have traditionally been employed for chemical stabilization of soils. Though proven effective, the production of these additives raises several environmental issues, such as high energy consumption and artificial carbon dioxide (CO_2) emissions. The widespread use of high-carbon fuels like coal and diesel in production makes the cement and lime manufacturing industry a significant contributor to CO_2 emissions. Apart from this, the calcination process of limestone itself emits significant amounts of CO_2. Additionally, a smaller indirect source of CO_2 arises from the use of electricity in manufacturing, considering the electricity is generated from fossil fuels. Collectively, these emission sources make up the total CO_2 emissions from the cement and lime industries. Literature reports CO_2 emissions associated with the manufacturing of Ordinary Portland Cement and quick lime to be around 2.16 tons/ton of Ordinary Portland Cement produced and 1.092 tons/ ton of quick lime produced, respectively (Kumar et al., 2023; Andrew, 2019; Stafford et al., 2016; Dowling et al., 2015). Thus, the continued use of cement and lime as additives for soil stabilization is not sustainable. Alternative binder materials that are sustainable with a lower carbon footprint are therefore actively sought.

A common approach in selecting new binders involves using sustainable alumino-silicate-based source materials in the presence of alkaline activators. Alkali activation, also known as geopolymerization, is a chemical process where aluminosilicate source materials react with alkaline activators such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) to form a geopolymeric gel (Rios et al., 2016; Fasihnikoutalab et al., 2017a; Fasihnikoutalab et al., 2017b). The high alkaline environment facilitates the breakdown of covalent bonds within the source material, making it highly reactive (Pourakbar et al., 2016). Against this backdrop, researchers have investigated the efficacy of various industrial wastes and by-products such as Flyash, Ground Granulated Blast-furnace Slag, Palm Oil Fuel Ash, Rice Husk Ash, Volcanic ash etc, as source materials for alkali activation (Kishor et al., 2021; Chen et al., 2020; Abdeldjouad et al., 2019; Murmu et al., 2019; Elkhebu et al., 2018; Miao et al., 2017; Pourakbar et al., 2016). These studies indicated that the resultant cementitious binding compounds, formed through the interaction of these source materials with alkaline activators, lead to more densely packed microstructures, consequently improving the engineering behaviour. Maheepala et al. (2022) conducted a detailed literature review on alkali-activated material-based binders for soil stabilization and reported that a shift from traditional stabilizers to alkali-activated material binders results in 70- 90% reductions in greenhouse gas emissions. This Study investigates the efficacy of alkali-activated magnesium-rich olivine as a binder material for soil stabilization.

Olivine $[(Mg^{2+}, Fe^{2+})_2 SiO_4]$ is a nesosilicate mineral, constituting a mixed crystal of Mg_2SiO_4 (forsterite) and Fe_2SiO_4 (fayalite), with the magnesium component typically dominant. Olivine is a prominent mineral within the Earth's mantle. As a result of plate tectonic activities, extensive areas of rocks rich in olivine have been raised from the Earth's mantle to its surface, allowing for their extraction through open-pit mining (Schuiling, 2013). Owing to the natural weathering reaction of olivine with atmospheric CO_2, it is widely used for CO_2 sequestration (Schuiling, 2013). Magnesium-rich olivine is a significant component in Ultramafic rocks such as dunite rocks (Klein and Dutrow, 2007; Winter, 2014). Production of Dunite in India is mainly from mines located in the Salem district of Tamil Nadu. Dunite rocks mined from open pit mines are crushed and powdered into fine particle sizes. The final product is then transported to the desired location. On comparing with the processes involved in cement and lime manufacturing, production of dunite rock powder rich in magnesium rich olivine involves far less carbon dioxide emissions and energy consumption.

Olivine has a weak nesosilicate structure with high silicon dioxide (SiO_2) and magnesium oxide (MgO) content, making it a potential

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source material for alkali activation. A potent alkali like KOH or NaOH can easily break the MgO-SiO_2 bond, resulting in chemical alterations (Fasihnikoutalab et al., 2017a; Fasihnikoutalab et al., 2017b). The MgO present in olivine has the potential to react with soluble silica and/or alumina in the soil, resulting in the formation of Magnesium Silicate Hydrate (M-S-H) and/or Magnesium Aluminate Hydrate (M-A-H) (Emmanuel et al., 2019; Fasihnikoutalab et al., 2017a; Fasihnikoutalab et al., 2017b). Literature reports that KOH exhibits greater efficacy than NaOH as an alkaline activator for soil stabilization (Fasihnikoutalab et al., 2017a; Fasihnikoutalab et al., 2017b; Pourakbar et al., 2016). This superiority is attributed to the larger size of potassium ions compared to sodium ions, enabling denser and more intense polycondensation reactions (Fasihnikoutalab et al., 2017b). Thus, potassium hydroxide (KOH) was chosen as the alkaline activator for this research.

Although magnesium-rich olivine appears to be a promising material for alkali activation, very few works, such as Tahir and Sert (2023), Fasihnikoutalab et al. (2017a), and Fasihnikoutalab et al. (2017b) have been reported in this area. The chemical composition, ease of availability, low cost and environmental advantage of magnesium rich olivine makes it worth to investigate the use of alkali activated olivine as a binder material for soil stabilization. This paper studies the interactions between kaolinite-rich red Earth and alkali-activated olivine, examining changes in their physico-chemical properties and strength characteristics. Additionally, microstructural investigations are conducted to understand the underlying mechanisms influencing the behavior of the treated soil.

2. MATERIALS AND METHODS

2.1 Materials used

Figure 1 illustrates the materials used in this Study. The red Earth used in the current Study is from Bangalore, Karnataka, India. Bulk samples collected from pits 3 m deep, were air-dried and pulverized to achieve uniformity in the samples used for various laboratory tests. Table 1 shows the properties of soil and olivine samples used in this Study. It can be seen that the red Earth is an inorganic clay with intermediate compressibility (CI) (IS (Indian Standards) 1498: 1970 (Reaffirmed in December 2021)). According to the Unified Soil Classification System, red Earth used in the Study can be classified as inorganic clay of low to medium plasticity (CL) (ASTM D2487-$17^{\varepsilon 1}$(2017)). The chemical Analysis of the red Earth indicates that silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) is the major oxides present in the soil.

(a) Red Earth (b) Magnesium-rich Olivine

(c) KOH Pellets

Figure 1 Materials used for Study

The magnesium-rich olivine employed in this research as source material was sourced from raw dunite rocks powdered and supplied by M/S Navbhan Exporters, located in Bangalore, India. As seen from Table 1, the olivine sample used in this Study is non-plastic and predominantly consists of silt-sized particles. Chemical analysis revealed that the major oxides in olivine are MgO and SiO_2. The high MgO concentration (42%) in pure olivine affirms the magnesium-rich nature of olivine, indicating its potential to facilitate hydration reactions.

The alkaline activator used in this Study, potassium hydroxide (KOH), was supplied in pellet form by Karnataka Fine Chemicals, Bangalore, Karnataka, India.

2.2 Sample preparation

Pulverized soil samples finer than 425-µm were oven-dried and later mixed with various olivine dosages (0%,5%,10%, etc) by dry weight of the mixture. From the trial tests conducted on olivine-treated red earth samples, a 10 molar (10M) solution of KOH was identified as the optimum KOH dosage in order to enhance the strength characteristics of red Earth. This finding is in agreement with the existing literature (Pourakbar et al., 2016; Fasihnikoutalab et al., 2017a; Fasihnikoutalab et al., 2017b). This paper presents the variations in the physicochemical properties and strength characteristics of olivine-treated red earth samples activated using a 10M KOH solution. KOH pellets were dissolved in distilled water to obtain a 10M concentration (Fasihnikoutalab et al., 2017b; Pourakbar et al., 2016). Due to the highly exothermic nature of the KOH-water reaction, the resulting solution was allowed to cool for 24 hours before use. The prepared and cooled 10M KOH solution was then added to the soil-olivine mixtures according to Optimum Moisture Content (OMC) values obtained for each mix from the standard proctor compaction tests carried out on each sample (IS (Indian Standards) 2720 (Part-7): 1980 (Reaffirmed in December 2021)). The test samples for various laboratory tests were prepared as per the mix compositions given in Table 2. Samples labelled "$S_RO_YK_{10M}$" denote 10M alkali-treated samples with varying olivine dosages. "S_R" denotes red Earth, and "O_Y" represents olivine dosages, where Y = 0%, 5%, 10%, and so on. The untreated red Earth is referred to as "S_R" in subsequent sections of this paper.

Table 1 Properties of materials used for Study

Property	Red Earth	Olivine
Liquid Limit (%)	40	31
Plastic Limit (%)	21	Non-Plastic
Plasticity Index (%)	19	-
Shrinkage Limit (%)	14	20
Soil Classification as per the Indian Standard Soil Classification System	CI (Inorganic clay with Intermediate Compressibility)	-
Soil Classification as per Unified Soil Classification System	CL (Inorganic clay of low to medium plasticity)	-
Grain size Distribution		
Fine Sand Size (%)	11.2	1.0
Silt Size (%)	60.8	95.9
Clay Size (%)	28.0	3.1
Specific Gravity	2.65	2.75
pH	7.40	8.62
Electrical Conductivity (mS/m)	19.19	17.09
Standard Proctor Compaction Characteristics		
Optimum Moisture Content (OMC) (%)	18.53	15.75
Maximum Dry Density (MDD) (g/cm^3)	1.71	1.70
Major oxides (wt %)	SiO_2 – 57.8 Al_2O_3– 19.13 Fe_2O_3 – 14.66 CaO – 1.63 MgO – 0.94 Na_2O – 0.59 TiO_2 – 0.35	MgO– 41.81 SiO_2–37.38 Fe_2O_3– 8.87 CaO – 1.55 Al_2O_3 – 0.4 TiO_2 < 0.10

Table 2 Mix compositions prepared for this Study

Sample Designation	Olivine Dosage (%)	OMC (%)	MDD (g/cc)	KOH/Olivine Weight Ratio
$S_RO_0K_{10M}$	0	15.56	1.76	-
$S_RO_5K_{10M}$	5	14.40	1.81	1.62
$S_RO_{10}K_{10M}$	10	16.76	1.77	0.94

2.3 Laboratory tests

2.3.1 pH and Electrical conductivity test

The untreated soil and alkali-activated olivine-treated samples shown in Table 2 were subjected to pH and electrical conductivity tests in accordance with the Indian Standard Code ((IS (Indian Standards) 2720 (Part 26): 1987 (Reaffirmed in December 2021); IS (Indian Standards) 14767: 2000, (Reaffirmed in March 2021)).

2.3.2 Atterberg limit tests

Atterberg limit tests were also conducted on these samples following the Indian Standard code (IS (Indian Standards) 2720 (Part 5):1985 (Reaffirmed in May 2020); IS (Indian Standards) 2720 (Part-6): 1972 (Reaffirmed in December 2021)). The cone penetration method was used for the Liquid Limit tests.

2.3.3 Methylene blue spot test

Methylene blue spot tests were carried out following the procedure as reported in the literature (Yukselen & Kaya, 2006) to determine the Specific Surface Area (SSA) of untreated soil and alkali-activated olivine-treated samples shown in Table 2. The fundamental principle underlying this test relies on the rapid adsorption of molecules by Methylene blue [$C_{16}H_{18}N_3SCl$ ($3H_2O$)] through ion exchange upon contact with a soil solution (Sivapullaiah et al., 2008). The amount of Methylene blue solution adsorbed relies on the SSA of the soil (Turkoz & Tosun, 2011). Thus, SSA can be determined based on the quantity of Methylene blue required to achieve the endpoint, as shown in Eq. (1) (Yukselen & Kaya, 2006):

$$SSA = \frac{1}{319.87} \times \frac{1}{200} \times (V_{CC}) \times A_V \times A_{MB} \times \frac{1}{10} \quad (1)$$

where,
SSA = Specific Surface Area (m^2/g)
V_{CC} = Total Volume of Methylene Blue solution added to achieve the endpoint (ml)
A_V = Avogadro's number (6.02×10^{23}/mol)
A_{MB} = Area covered by one Methylene Blue molecule (130$Å^2$)

2.3.4 Unconfined Compressive Strength (UCS) test

Unconfined compressive strength (UCS) tests were conducted on specimens prepared at their respective OMC and MDD values following the guidelines outlined in the Indian Standard Code (IS (Indian Standards) 2720 (Part 10): 1991 (Reaffirmed in May 2020)). Three identical specimens were subjected to UCS tests. The unconfined compressive strength presented in this paper is the average of the values obtained from these tests. To investigate the effect of curing on the UCS of treated soils, UCS tests were conducted on the specimens prepared at their respective OMC and MDD after these samples were cured in a desiccator for 7, 14 and 28 days.

2.3.5 Microstructural analysis

The mineralogical compositions of the untreated soil (S_R) and $S_RO_5K_{10M}$ sample cured for 28 days were determined by X-ray diffraction (XRD) Analysis. The Analysis was conducted at a generated current of 25 mA and voltage of 40 kV. The wavelength of the X-rays generated using the Cu-tube was 1.5418 Å. Samples were scanned for one hour. The scan was conducted at 2Θ values between 10^0 and 80^0 with a step size of 0.020. Different clay and non-clay minerals in the samples were identified based on Bragg's Law and standard references. The samples were also examined using a TESCAN – VEGA 3 SEM equipment. Oven-dried specimens were carefully cut, mounted on aluminium sample holders using adhesive carbon tape, vacuum coated with gold using a sputter coater and imaged using a scanning electron microscope.

3. RESULTS AND DISCUSSION

3.1 Effect of alkali-activated olivine inclusion on pH and Electrical Conductivity

Figure 2 shows the pH values of alkali-activated olivine treated samples for various curing durations. The pH value of untreated soil is 7.40. On adding KOH solution, the pH value of red Earth increased to 10.93 and the addition of various olivine dosages further increased the pH value significantly. It was noted that the pH value of alkali-activated olivine-treated samples are greater than 12. The addition of the KOH solution to the soil promotes the breakdown of the silicon-oxygen and aluminium-oxygen bonds in the soil, liberating silicon (Si) and aluminium (Al) ions and forming soluble silicates and aluminates in the process. Literature reports that the solubility of SiO_2 and Al_2O_3 within the soil improves considerably at pH values ≥ 12 (Sargent, 2015). Thus, the potential solubility of silicates and aluminates within the soil and the chances of undergoing hydration reactions with olivine are high in alkali-activated olivine-treated samples.

Figure 3 illustrates the Electrical Conductivity values of alkali activated olivine treated samples for various curing durations. The Electrical Conductivity of the untreated red Earth is 19.19 mS/m. An increase of around 3 times in electrical conductivity values was noted for the $S_RO_{10}K_{10M}$ sample. When the alkaline activator is added to the soil-olivine mixture, olivine undergoes dissolution, leading to the release of magnesium ions, silicate ions, and hydroxide ions into the pore fluid. This initiates cation exchange reactions where the divalent magnesium ions replace the monovalent sodium ions present in the soil, increasing the ion concentration of the pore water. This is, in turn, reflected in the electrical conductivity values of alkali-activated olivine-treated samples.

A decrease in pH and electrical conductivity values was observed when these samples were cured, as seen in Figure 2 and Figure 3. However, it was observed that the pH values of all the alkali activated olivine treated samples remain > 10.5 even after curing for 28 days. On curing, treated samples undergo hydration reactions forming M-S-H and/or M-A-H gels. This causes a reduction in the concentration of dissolved ions in the pore fluid and, hence, a reduction in pH and electrical conductivity values. A notable reduction in electrical conductivity value was observed when curing the $S_RO_5K_{10M}$ sample for 28 days, whereas the $S_RO_{10}K_{10M}$ sample showed a comparatively lower reduction in electrical conductivity value during curing. It may be due to the insufficient availability of soluble silica and/or alumina in the $S_RO_{10}K_{10M}$ sample to react completely with olivine thereby the excess olivine added remained unconsumed.

3.2 Effect of alkali-activated olivine inclusion on Atterberg Limits

Figure 4 presents the plasticity index values of treated samples for various curing durations. A general reduction in plasticity index was observed with the addition of various alkali-activated olivine dosages, with the lowest value of plasticity index obtained corresponding to 5% olivine dosage, indicating that 5% may be the optimum olivine dosage for stabilizing the red Earth in the presence of 10M KOH. This is in agreement with the variations in the pH and electrical conductivity values shown in the previous section. A reduction of about 53% in plasticity index was observed for the $S_RO_5K_{10M}$ sample tested immediately without curing. Figure 5 presents the shrinkage limit values of alkali-activated olivine-treated samples for various curing durations. A 43% increase in the shrinkage limit value of the $S_RO_5K_{10M}$ sample was observed over the untreated red Earth. The olivine interactions with soil in the presence of KOH, including dissolution and cation exchange reactions, result in aggregation of mineral particles (Mitchell and Soga, 2005). This, in turn, resulted in a reduction in the plasticity Index and an increase in the shrinkage limit.

The alkali-activated olivine-treated samples tested after curing were observed to be non-plastic (NP). The shrinkage limit values of these samples showed an initial increase in curing, as observed in Figure 5; however, these values showed no changes beyond 7 days of curing. The reduction in plasticity characteristics and improvement in shrinkage limit on curing is attributed to the deposition of hydration products.

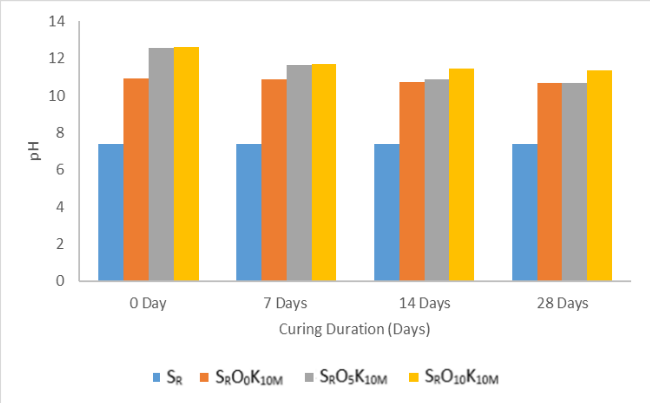

Figure 2 pH of treated soil samples

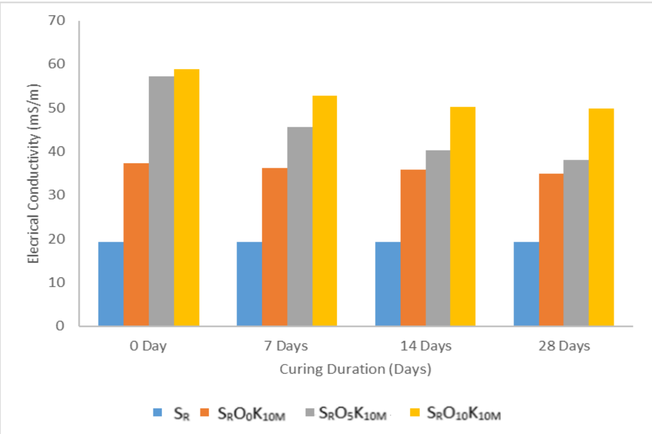

Figure 3 Electrical Conductivity of treated soil samples

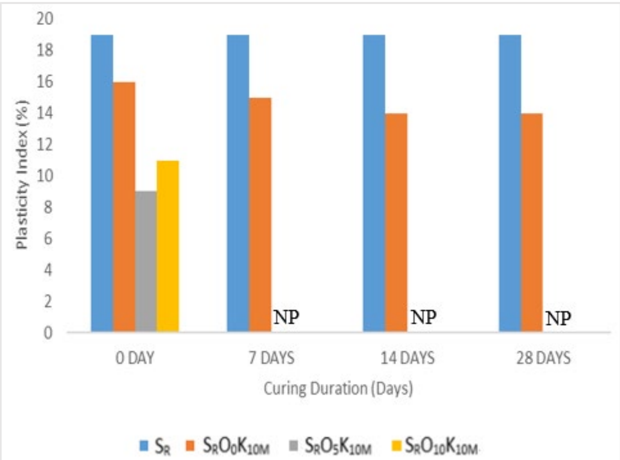

Figure 4 Plasticity Index of treated soil samples

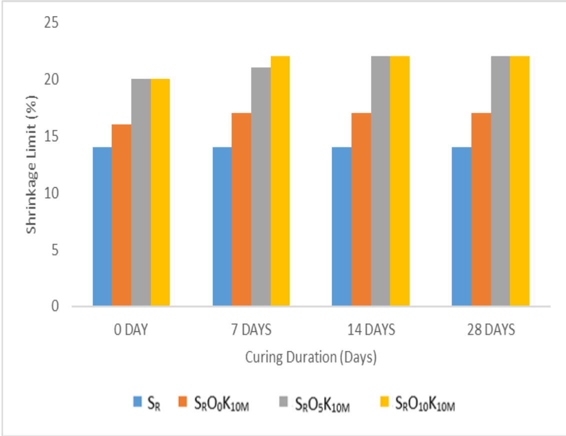

Figure 5 Shrinkage limit of treated soil samples

3.3 Effect of alkali-activated olivine inclusion on Specific Surface Area (SSA)

The SSA of fine-grained soils is expected to be strongly influenced by the particle size (Sivapullaiah et al., 2008). Thus, variations in SSA values can be used to explain the effect of binders on the particle size of soil. Figure 6 illustrates the variations in SSA values of alkali-activated olivine-treated samples with curing duration. In addition to various alkali-activated olivine dosages, a general reduction in SSA values was observed. The reduction in SSA suggests an increase in particle size of the red Earth on addition of various alkali-activated olivine dosages. A considerable reduction of 34% in SSA value over the untreated soil was observed for the $S_RO_5K_{10M}$ sample tested immediately without curing. Olivine dissolution and subsequent cation exchange reactions result in the aggregation of mineral particles. Thus, the increase in particle size of untreated soil reflected by the decrease in SSA values confirms the olivine-soil interactions in the presence of KOH, resulting in aggregation.

On curing, the SSA values of these alkali-activated olivine-treated samples were observed to reduce further. The lowest value of SSA was observed, corresponding to 5% olivine dosage. The $S_RO_5K_{10M}$ sample cured for 28 days showed a significant reduction of 59% in SSA value over the untreated soil. Olivine undergoes hydration reactions in the presence of KOH, resulting in the development of M-S-H and/or M-A-H gels that bind soil particles. Thus, the increase in particle size indicated by a reduction in SSA values on curing treated samples indicates a dense and compact microstructure as a result of the cementation of soil particles.

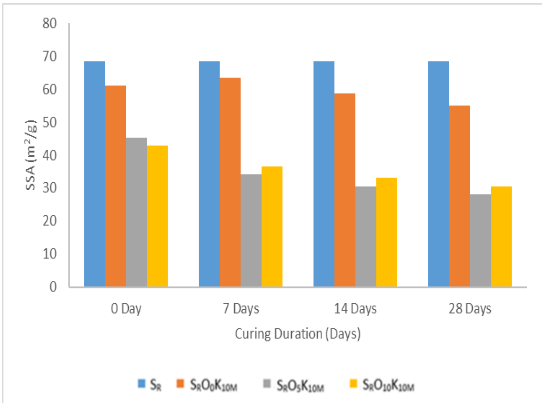

Figure 6 Specific Surface Area values of treated soil samples

3.4 Effect of alkali-activated olivine inclusion on Unconfined Compressive Strength (UCS)

Figure 7 illustrates the UCS values of untreated and alkali-activated olivine-treated red earth samples for various curing durations. The "S_R" sample showed a UCS value of 280.77 kPa, whereas the "$S_RO_0K_{10M}$" sample showed a UCS value of 390.06 kPa. The introduction of KOH solution to red Earth was noted to cause a marginal improvement in the compressive strength of the untreated soil. This phenomenon is due to the presence of KOH, which facilitates the dissolution of silicon and aluminium within the soil, giving rise to the formation of alkali silicates and aluminates, acting as cementing agents that bind the soil particles together (Fasihnikoutalab et al., 2017b).

The addition of various alkali-activated olivine dosages improved the UCS values up to 3 times the UCS of untreated soil. Addition of KOH breaks the MgO – SiO_2 bond in magnesium-rich olivine leading to the production of brucite (Mg $(OH)_2$) and potassium silicate (K_2SiO_3) as shown in Eq. (2) (Fasihnikoutalab et al., 2017b).

$$\mathrm{Mg_2SiO_4 + 2KOH + H_2O \rightarrow 2Mg(OH)_2 + K_2SiO_3} \quad (2)$$

Thus, in addition to the aggregation effect, the excess brucite precipitating on the clay surface contributes to initial strength enhancements by filling the pores spaces, thereby improving the density and strength of treated samples.

On curing, these samples showed significant improvements in UCS values. The strength characteristics of untreated red Earth (S_R) remained unaltered on curing. Meanwhile for alkali-activated olivine-treated samples, an improvement in UCS values was observed with an increase in binder dosage up to 5% olivine dosage. However, a further increase in olivine dosage resulted in a reduction in UCS value. A similar trend was observed for all curing durations. Thus, the optimum olivine dosage to stabilize the red Earth in the presence of 10M KOH is confirmed as 5%, which corresponds to a KOH/olivine weight ratio of 1.62. A considerable improvement in UCS value of about 14.9 times over the UCS value of untreated soil was observed when the $S_RO_5K_{10M}$ sample was cured for 28 days.

The olivine dissolution and the improved solubility of silicates in soil in the presence of KOH facilitates hydration reactions when the treated samples are allowed to cure resulting in development of M-S-H gels as shown in Eq. (3) (Fasihnikoutalab et al., 2017b).

$$Mg^{2+} + OH^- + SiO_2 \rightarrow M - S - H \quad (3)$$

These cementing phases fill the pore spaces between soil particles, improving the stiffness and bonding and hence the soil strength. It may be noted that olivine was effectively utilized for hydration reactions up to 5% dosage and the additional olivine added beyond this dosage acted as unbonded particles responsible for a reduction in UCS value.

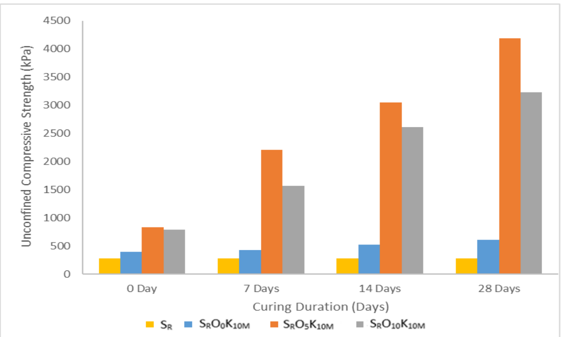

Figure 7 UCS of treated soil samples for various curing durations

3.5 Microstructural analysis

Figure 8 shows the X-ray diffraction pattern of S_R and $S_RO_5K_{10M}$ samples after curing for 28 days. Peaks corresponding to quartz were observed throughout the pattern (2ϴ values of around 21, 26, 36, 39, 50 and 60^0) for S_R sample (Mitchell & Soga, 2005). It can be seen that the major minerals found in the S_R sample are quartz and kaolinite; whereas, illite and feldspar were observed as minor minerals. Several new peaks were observed at various 2ϴ values on alkali-activated olivine treatment. The pattern of the $S_RO_5K_{10M}$ sample after curing for 28 days showed brucite (2ϴ values of $22\text{-}24^0$), serpentine (2ϴ value of $12\text{-}13^0$) and potassium silicate (2ϴ values of $27\text{-}29^0$ and $30\text{-}32^0$) peaks (Fasihnikoutalab et al., 2017b; Yi et al., 2013). Apart from this, strong peaks of mullite ($25\text{-}27^0$, $42\text{-}43^0$ and $60\text{-}62^0$), M-S-H ($25\text{-}27^0$ and $28\text{-}30^0$) and hematite ($55\text{-}56^0$) were also observed in the treated sample (Fasihnikoutalab et al., 2017b). Literature reports that during the geopolymerization process, depending on the chemical composition of the soil, if sufficient silica and alumina are present in the sample, Mullite and/or Hematite can form (Fasihnikoutalab et al., 2017b). A mild peak corresponding to magnesium carbonate was observed at 2ϴ values of 32^0 as a result of olivine interactions with atmospheric carbon dioxide (Fasihnikoutalab et al., 2017b). Thus, the XRD patterns confirm the formation of brucite, hematite, mullite, and M-S-H gels in the structure of the treated soils, resulting in strength development in alkali-activated olivine-treated soils.

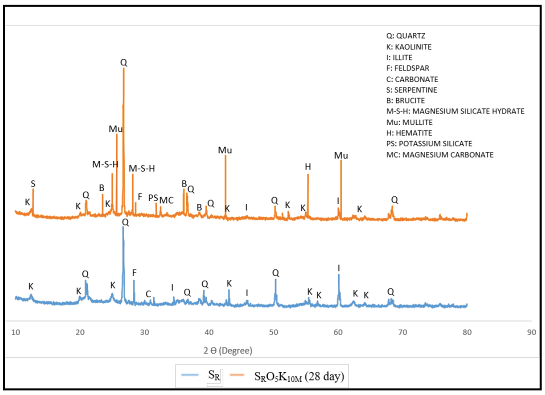

Figure 8 X-ray diffraction pattern of S_R and $S_RO_5K_{10M}$ sample (28 days)

The SEM images of the S_R and $S_RO_5K_{10M}$ samples after curing for 28 days, were enlarged to similar exposure levels, as shown in Figure 9. Figure 9 (a) represents the micrograph of untreated red Earth (S_R). The characteristic plate-like shape, visible as individual flakes that appear to be flat and thin, is associated with kaolinite-rich soils. The structure appears to be dispersed. Figure 9 (b) represents the $S_RO_5K_{10M}$ sample after curing for 28 days. The SEM images of the treated samples demonstrate a densely packed and compact structure without any major discontinuities. The change in the soil structure may be attributed to the coating and binding of clay particles due to the formation of Brucite, M-S-H, Mullite, and Hematite, hence achieving higher strengths.

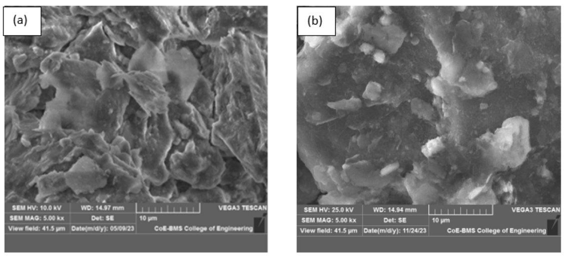

Figure 9 SEM Micrographs of (a) S_R and (b) $S_RO_5K_{10M}$ sample (28 days)

4. CONCLUSIONS

This Study investigated the effectiveness of alkali-activated magnesium-rich olivine for stabilizing a red earth. The effect of the alkali-activated binder on physicochemical properties and the unconfined compressive strength of kaolinite-rich red earth was studied. It was observed that the addition of various alkali-activated olivine dosages increased the pH and electrical conductivity values of red Earth significantly. Also, a reduction in plasticity index, an increase in shrinkage limit and a reduction in specific surface area values of untreated soil were noted during treatment with alkali-activated olivine. The addition of various alkali-activated olivine dosages improved UCS values up to 3 times the UCS of untreated soil. The immediate effect of various alkali-activated olivine dosages on the properties of red Earth is attributed to olivine dissolution and cation exchange reactions resulting in aggregation of mineral particles. In addition, the precipitation of excess brucite on the soil surface as a result of olivine alterations in the presence of KOH contributed to the immediate enhancements in soil strength. A decrease in pH and electrical conductivity values was observed when these samples were cured. The alkali-activated olivine-treated samples, after curing, were observed to be non-plastic. Shrinkage limit values of these samples showed an initial increase in curing; however, these values showed no changes beyond 7 days of curing. Also, on curing, the Specific surface area values of these alkali-activated olivine-treated samples were observed to reduce further. A considerable improvement in UCS value of about 14.9 times over the UCS value of untreated soil was observed when the 5% olivine-treated sample in the presence of 10M KOH was cured for 28 days. Analysing the behaviour of soil on treatment with various alkali-activated olivine dosages, 5% was observed as the optimum olivine dosage for stabilizing the red earth in the presence of 10M KOH. The behaviour of alkali-activated olivine-treated samples on curing is mainly due to the formation of hydration products (M-S-H), Mullite and Hematite in the structure of treated soil as confirmed from XRD and SEM analysis. Experimental findings suggest that introducing alkali-activated magnesium-rich olivine to soil induces olivine dissolution, cation exchange, aggregation, and hydration reactions, thereby enhancing soil performance. Magnesium-rich olivine, with its environmental benefits, has a huge potential for its use as a natural source material for developing alkali-activated mixtures for soil stabilization.

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