Influence of Curing Methods on Strength of Nano-Silica Treated Soil

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Abstract. The use of nanomaterial for soil stabilization has gained immense importance in recent times. The ability of these nano additives in improving the strength and performance of soil has been ratified by the works of many researchers. However, the factors which govern these improvements have not been studied in detail. In this regard, the present work focuses on the methods of sample curing for nano-silica (SiO_2) treated soil. The soil used for the study is highly compressible clay soil (CH) collected from Ariyalur District of Tamil Nadu. It is modified using four different percentages of nano-silica (0.2%, 0.4%, 0.6% and 0.8%). The prepared soil samples were cured by moist and heat curing methods for different periods of curing namely 0 day (initial testing), 7 days, 14 days and 28 days. Unconfined Compressive Strength (UCS) test conducted on the nano-silica stabilized soil samples indicated that moist curing technique increased the UCS by 8.22 times for soil treated with 0.4% of nano-silica and an improvement of UCS by 1.28 times was observed in heat curing method with 0.4% nano-silica at 14 days of curing. Moist curing proved more effective than heat curing.

Keywords: Curing Methods, Nano-silica, Clay, UCS.

1 Introduction

The unique nature of soil is that its properties are highly heterogeneous and varies depending on various factors along the spatial regime. For the same reason, not every soil will have adequate strength to bear the structure and hence the properties of the soil need to be improved depending upon the soil type and the requirements of the structure. Soft soils and highly plastic clays are often weak in strength and are characterized by low bearing capacity. Various methods have been adopted by researchers in the past for stabilising such highly compressible clays using materials like lime, cement, flyash etc. Choice of nanomaterial for soil stabilisation has gained importance lately and many researchers proved that nano materials can improve the strength of the soil. Nano-silica is one such material which has proved to be effective in improving the strength and stiffness of the soil.

The improvement in the strength of soil by adding additives is influenced by various parameters like dosage of additive, period of curing, method of curing, and atmospheric conditions etc. Toohey et.al [1] studied the performance of lime stabilized soil at an accelerated curing temperature of 41°C. They reported that accelerated curing temperature made the sample attain a strength equivalent to that attained after 28 days at 23°C, in a period of 1.8 to 5.9 days. However, this method overestimated the 28 days strength on 7 day curing by 13- 260%. Elkady [2] studied the effect of in-laboratory, out-laboratory and normal curing conditions of expansive soil. He pointed out that controlled curing promoted cementation whereas in-laboratory and out-laboratory curing conditions caused strength gain through suction stresses. Wang et. al. [3] studied the influence of higher curing temperature ranging between 40°C and 60°C on the strength of lime/cement treated marine clays and found that higher curing temperature would increase strength and modulus at lower failure strain. However, studies on the effect of such methods of curing in nano-silica treated soil remains scarce and hence the present work focuses on the performance study of heat and moist cured nano-silica treated samples in terms of strength gain, failure strain, deformation modulus and their corresponding improvement ratio. Four different dosages of nano-silica are used namely 0.2%, 0.4%, 0.6% and 0.8% to understand the strength gain mechanism through different curing methods. Heat and moist cured samples were tested at different curing periods such as 0 day (initial testing), 7 days, 14 days and 28 days of curing and their performance was studied.

2 Materials

2.1 Soil

The soil used for the present study was taken from the fields of Ariyalur, TamilNadu, India (11°00’01.7”N, 79°03’51.8”E). The soil was black in colour and used for cultivation of cotton. Preliminary tests were conducted on the soil to determine its index properties and classify the soil. The soil is classified as clay of high plasticity (CH) as per the Indian Standard Soil Classification System and the properties of the soil are tabulated in Table 1.

Table 1. Physical Properties of the Soil and its Classification

Properties	Values
Liquid Limit (%)	50.00
Plastic Limit (%)	27.57
Shrinkage Limit (%)	5.02
Plasticity Index (%)	22.43
Soil Classification	Clay of high plasticity (CH)
Specific Gravity	2.15

2.2 Nano-Silica

The nano-silica used in this study was procured from Astrra Chemicals, Chennai, Tamil Nadu. The nano-silica had silica (SiO_2) as major constituent of its composition. The average particle size of the nano-silica used for the study was 17 nm. The detailed specifications of the nano-silica as provided by the supplier are tabulated in Table 2.

Table 2. Properties of Nano-Silica

Properties	Values
SiO_2 (%)	99.88
Carbon (%)	0.06
Chlorides (%)	0.009
Al_2O_3 (%)	0.005
TiO_2(%)	0.004

3 Methods

3.1 Soil preparation

The soil collected from the field was pulverized and sun dried for one day to remove the moisture in it. Materials like twigs, pebbles were removed from the soil sample and the soil was rammed and sieved for various particle sizes as per the test requirements. Nano-silica of dosages 0.2%, 0.4%, 0.6% and 0.8% were added by the dry weight of the soil and was thoroughly hand-mixed until homogeneous mixture is obtained. Then, water was sprinkled on the sample equivalent to its corresponding optimum moisture content. Further mixing was done, until the water spreaded uniformly in the sample. Soil samples for the UCS test were moulded at their respective maximum dry unit weight.

3.2 Unconfined compression strength (UCS) test

In order to study the variation of strength at different curing periods and curing methods, unconfined compression test was conducted on the soil as per the guidelines outlined in IS: 2720 (Part 10) [4]. Soil passing through IS 425-micron sieve was mixed with corresponding dosage of nano silica as mentioned earlier. Water content equivalent to OMC of the corresponding dosage was added, mixed to obtain a homogeneous mixture and cylindrical specimens were prepared with density equivalent to MDD. Cylindrical samples with diameter 38 mm and height 76 mm were moulded. The compression test was conducted at a strain rate of 1.25 mm/min. For each curing period, a set of three samples were tested for each dosage to obtain consistent values and the methodology for UCS test indicating the same is shown in Table 3.

Table 3. Test plan for the Study

Dosage	Method of curing							
	Heat Curing				Moist Curing			
	0 day	7 days	14 days	28 days	0 day	7 days	14 days	28 days
S	3	-	-	-	3	-	-	-
S+0.2	3	3	3	3	3	3	3	3
S+0.4	3	3	3	3	3	3	3	3
S+0.6	3	3	3	3	3	3	3	3
S+0.8	3	3	3	3	3	3	3	3

S-Untreated soil; S+0.2 – Soil + 0.2% Nano-silica; S+0.4 – Soil + 0.4% Nano-silica; S+0.6 – Soil + 0.6% Nano-silica; S+0.8 – Soil + 0.8% Nano-silica

Procedure for heat curing

Cylindrical samples were prepared at OMC and were transferred to hot air oven for a period of 4 hours at 60ºC [3]. The curing period was restricted to four hours, because prolonged curing at such higher temperatures lead to cracking and crumbling of samples. The samples for initial testing (0-day testing) were tested immediately after removing from oven. After four hours of curing, the samples were allowed to cool to room temperature and were then packed in airtight zip-lock cover for the rest of the curing period.

Procedure for moist curing

Moist curing was tried using four different methods. Initially the soil specimen was submerged in a water bath [5-6], however the sample got dissolved in water and this method was eliminated. In the second method, the soil sample was prepared at OMC, wrapped in moist cloth for a period of 24 hours and then transferred to a zip-lock cover for further curing. However, this method made the sample softer, making the soil extremely difficult to handle while testing. In the next method, the soil samples prepared were wrapped in moist cloth for a period of 24 hours and then air dried for the remaining curing period, but doing so made the sample dry and behave like heat cured sample, hence this method was also not adopted.

Finally, the prepared soil sample was covered with a moist cloth for the entire curing period, by dampening the cloth periodically [6-7]. Care was taken that the moist cloth was well squeezed before covering such that the moisture of the cloth didn't soak the sample. So, the moist cloth just acted as a method to promote wet curing of the sample. This method worked out successfully and was followed for the entire study. The samples intended for initial testing (0-day testing) were tested after 24 hours of curing. The rest of the samples for other curing periods (7, 14 and 28 days of curing) were wrapped until the test period.

4 Results and Discussions

4.1 Stress-strain behavior

The stress-strain responses for soil treated with different dosages of nano-silica at various curing periods are shown in Fig. 1 and Fig. 2 for both heat and moist curing methods respectively. Separate set of tests were conducted on untreated samples subject to heat and moist curing such that, each curing method results can be compared to corresponding untreated sample. Fig. 1 shows that the untreated soil in heat curing experienced failure with distinct failure peak. The loss of moisture would have imparted a brittle nature to the soil leading to such failure. Similar results are reported by Wang et. al., in lime/cement stabilized soil[3].

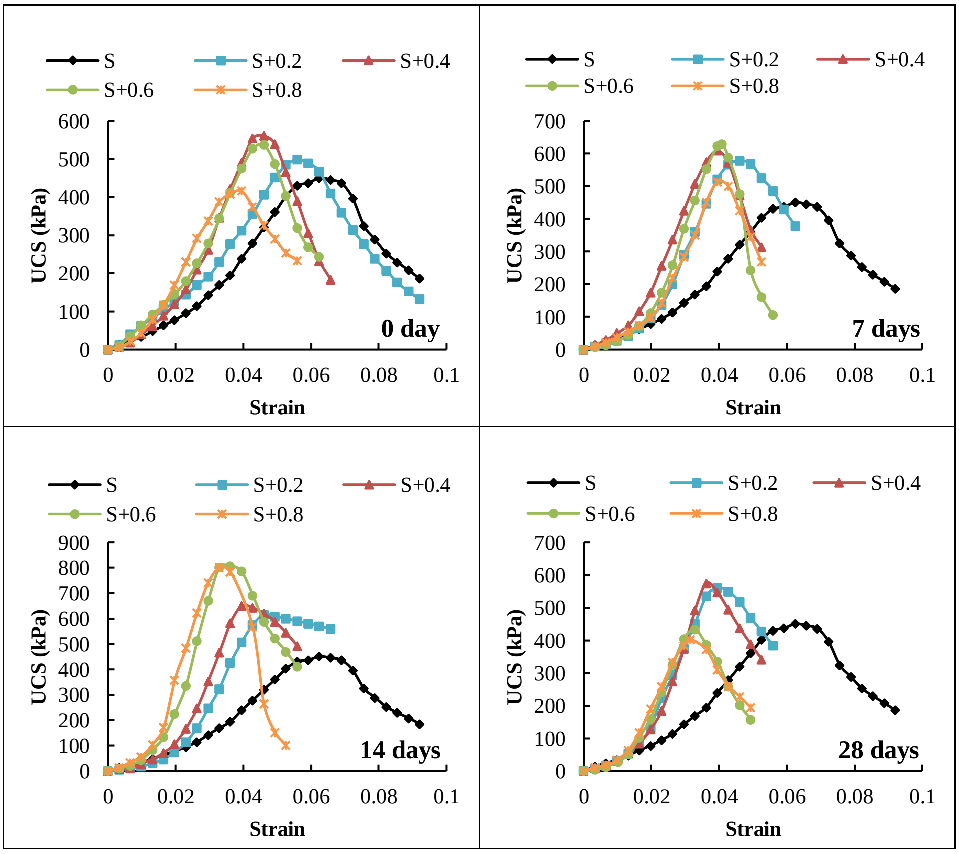

Fig. 1. Stress-strain response of untreated and treated soil after heat curing

Upon increase in dosage of nano silica, the soil sample failed at a comparatively lesser strain and higher stress indicating the increase in stiffness of nano-silica treated sample. The post-peak behaviour of treated soil shows drastic reduction in strength and failure by complete crushing. A more distinct peak stress and rapid reduction in strength post-peak is witnessed with the increase in the curing period indicating that stabilized soil samples tend to become more brittle with increase in curing period [3].

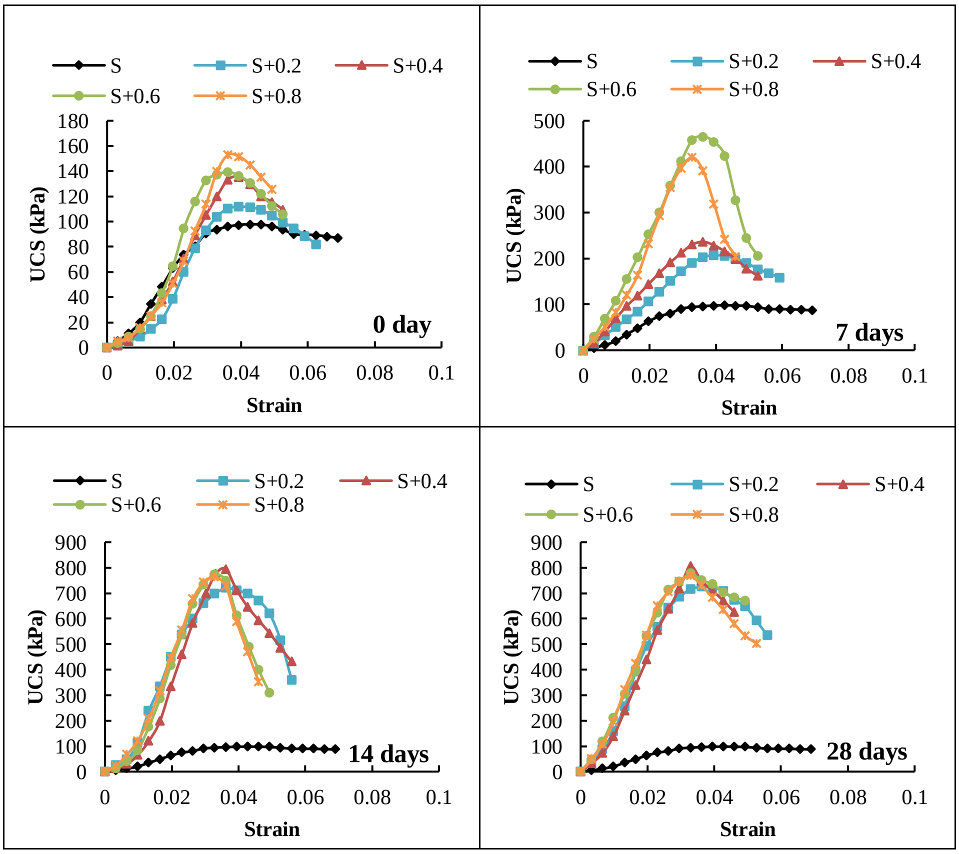

Fig. 2. Stress-strain response of untreated and treated soil after moist curing

The stress-strain response of untreated soil by moist curing shows that there is no distinct peak at the failure as compared to the heat cured sample. Unlike heat cured untreated soil, the change in stress is very gradual indicating an almost plastic failure. This could be due to the presence of moisture in the soil. With increase in dosage of nano-silica in wet cured sample, the stress-strain curves show distinct failure peaks at comparatively lesser strain confirming the performance improvement by nano-silica. With increase in curing period, the stress strain response of the nano silica treated moist cured sample showed a similar pattern with steeper post failure curve as that of heat cured sample.

4.2 Failure strain

The strain experienced at failure by a sample is studied in terms of failure strain ratio which is defined as the ratio of failure strain for a particular dosage of nano silica treated soil at a specific curing period to that of the untreated soil. The failure strain ratio of various samples under heat and moist curing methods are shown in Fig. 3. Fig. 3 indicates that the ratio remains less than one throughout the plot implying that the nano silica treated soil experienced comparatively lesser deformation at failure than the untreated soil [8]. The untreated soil sample upon heating and subsequent heat curing experienced a strain of 0.0625 and a greater reduction in strain was experienced at a dosage of 0.8% nano-silica on heat curing at all the curing periods. The failure strain ratio corresponding to 28 days of curing for 0.2%, 0.4%, 0.6% and 0.8% of nano-silica dosage are of 0.63,0.58, 0.53and 0.51 respectively. Also, a failure strain ratio of 0.63, 0.63, 0.53 and 0.51 was experienced at the dosage of 0.8% for 0, 7, 14 and 28 days of curing respectively. This also indicates that failure strain continues to decrease with the increase in nano-silica. It is also observed that the strength of the sample was the highest after 14 days of curing. Hence, upon heat curing maximum strain reduction was experienced with almost 53% of the strain of the untreated sample.

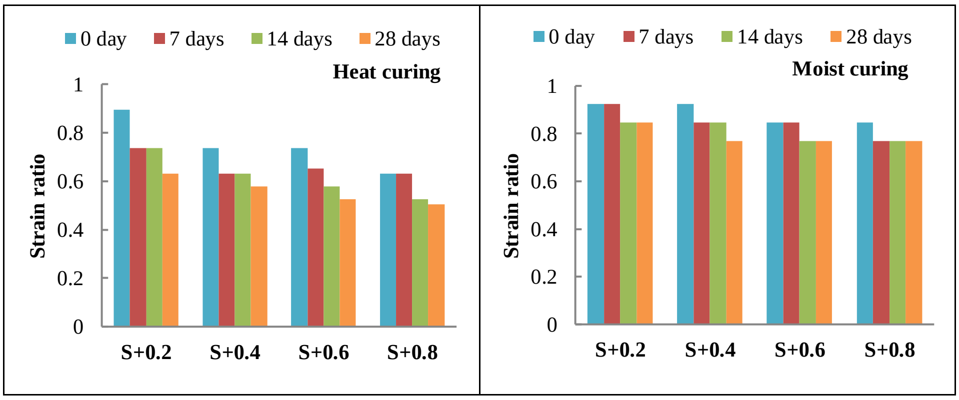

Fig. 3. Failure strain ratio for specimens under heat and moist curing

The strain experienced by untreated soil at moist curing is 0.0428. This indicates that the soil failed at a comparatively lesser displacement than the heat cured sample. This could due to the fact that heat cured sample has more resistance to deformation hence yielded higher strength. However, moist cured samples were softer initially and subjecting them to loads lead to failure at comparatively lesser load at a lower strain. Similar to heat curing, inclusion of nano-silica reduces the failure strain of moist cured samples also. Under moist curing, except in the case of dosage of 0.4% of nano-silica, all other dosages experienced maximum reduction in 14 days itself and almost similar strain values were observed after 28 days of curing. The reduction in failure strain can be due to the gel action [8] of nano-silica with the soil and this would have promoted the hydration reactions under moist conditions. The maximum failure strain ratio in moist curing was experienced at a dosage of 0.8% of nano silica with values 0.85, 0.77, 0.77 and 0.77 at 0, 7, 14 and 28 days of curing respectively. Comparing the trend as presented in Fig. 3, the strain experienced at 14 days of curing could serve as an indicative to the maximum strain that the treated soil could experience upon moist curing with nano-silica treatment.

4.3 Deformation modulus

The stiffness offered by the sample is measured in terms deformation modulus at failure which is defined as the ratio of failure stress to failure strain. The deformation modulus at failure for an untreated soil sample under heat and moist curing conditions are 7208.26 kPa and 2289.553 kPa respectively. For better understanding and comparison, a ratio called deformation modulus ratio is introduced. It is defined as the ratio of deformation modulus for a nano-silica treated soil at a specific curing period to that of an untreated soil sample. The deformation modulus ratio corresponding to heat and moist curing methods are shown in Fig. 4. Under heat curing method, all the soil samples treated with nano-silica showed an increased deformation modulus ratio indicating that the presence of nano-silica promoted stiffness. However, it can be understood that beyond optimum dosage there was a reduction in strength of the sample, which lead to reduction in deformation modulus ratio even though soil failed at comparatively lesser strain. Except soil treated with 0.2% of nano-silica with deformation modulus ratio of 1.97 at 28 days of heat curing, all other dosages offered more stiffness at 14 days of curing with ratios of 2.28, 3.09 and 3.38 for 0.4%, 0.6% and 0.8% of nano-silica. The reason for reduction in deformation modulus ratio at 28 days of heat curing though with lesser strain is because of the fact that heat cured samples experienced differential cracks which worsened after 28 days leading to reduced strength thereby reducing the deformation modulus.

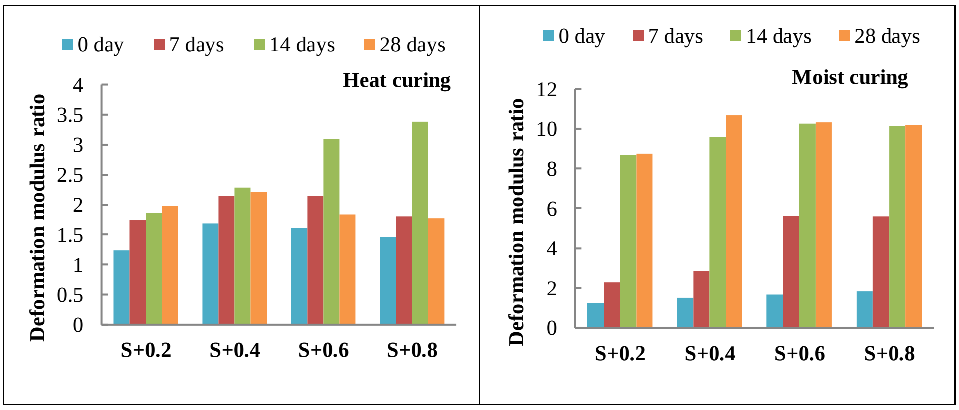

Fig. 4. Deformation modulus ratio for specimens under heat and moist curing

Unlike heat cured samples, wet cured sample showed a constant trend in deformation modulus ratio as shown in Fig. 5. Samples after 28 days moist curing showed more stiffness, with deformation modulus ratio of 8.74, 10.69, 10.31 and 10.19 at dosages of

0.2%, 0.4%, 0.6% and 0.8% respectively. The deformation modulus of moist cured samples is higher than the untreated soil inspite of failure at lower strain due to its capacity to resist much higher stresses and this can be attributed to the formation of hydration compounds during moist curing [8]. Due to their ability to gain more strength at less deformation, compared to that of the modulus value of untreated sample, these moist cured nano-silica samples show deformation modulus ratio increased to greater folds.

4.4 Strength

Strength of the sample is measured in terms of its UCS value. The UCS of untreated heat cured and moist cured samples are 450.52 kPa and 97.91 kPa respectively. The strength achieved by nano-silica treated samples are measured in terms of UCS ratio which is defined as the ratio of strength of nano-silica treated soil at a particular dosage and curing period to that of the untreated soil. The UCS ratio for both heat cured and moist cured samples are portrayed in Fig. 5. In general, both curing methods showed greater strength gain and thereby higher UCS ratio up to the optimum dosage but beyond the optimum dosage, there was a reduction in the UCS [8-9]. Initially at 0-day testing after heat curing, the optimum dosage was 0.4% of nano-silica, however in later days of curing the optimum dosage increased and the dosage of 0.6% showed even better performance.

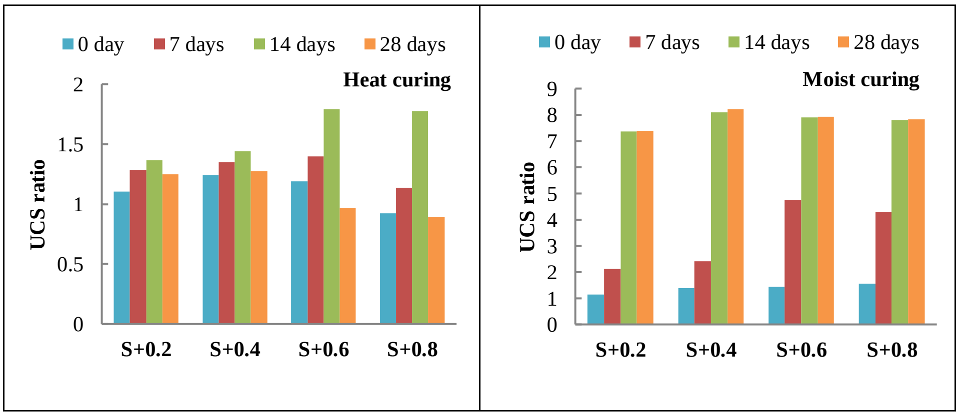

Fig. 5. UCS ratio for specimens under heat and moist curing

The increased UCS after heat curing can be reasoned in two ways, (i) the presence of nano-silica should have resulted in gelling action [8] with the soil upto the optimum dosage and (ii) dehydration through heating could have resulted in stiffening of hydration products resulting in higher strength [3]. The decrease in strength at dosage beyond optimum value could have been due to aggregation of particles, and subsequent increase in the voids within the treated soil matrix [8] would have caused a reduction in the strength. The samples showed maximum UCS ratios at 14 days of curing with values 1.37, 1.44, 1.79 and 1.78 respectively after heat curing. Samples after 28 days of curing experienced lesser UCS ratio than that of 14 days cured samples because, in general all heat cured samples showed differential cracks after oven drying which worsened during these 28 days curing period. UCS test on samples heat cured for 28 days showed that the soil should have failed in a predefined failure pattern following the surface cracks formed during curing and thereby would have attained lesser strength. Hence it is inferred that prolonged drying of nano-silica treated sample would cause them lose their strength due to the formation of cracks. Also, the UCS ratio got reduced to 0.96 and 0.89 at 0.6% and 0.8% after 28 days of heat curing indicating that dosage beyond 0.4% with prolonged heat curing would reduce the strength lesser than that of untreated soil.

Wet curing showed a constant increase in UCS ratio with increase in curing period as well as with increase in dosage up to an optimum value. The improvement in the UCS ratio after initial 0-day testing and 7 days testing was comparatively less, however sample showed tremendous increase in strength after 14 days and 28 days of curing and the strength of 14-days and 28-days curing periods were very close to each other. These inferences indicate that moist environment could have promoted gel formation [8] in between the pores of soil through water-nanosilica reaction and based on the UCS ratio trend of moist curing from Fig. 5, a period of minimum 14 days is required to gain the strength from the gel formation. Soil treated with 0.6% of nano silica showed more strength initially with UCS ratio values 1.42 and 4.76 at 0 day and 7 days of moist curing respectively. However, further curing should have promoted aggregation of particle with dosage of 0.6% leading to the formation of voids between particle groups; hence more strength was obtained with dosage of 0.4% nano-silica with UCS ratio values 8.11 and 8.22 at 14 days and 28 days of moist curing respectively.

4.5 Failure pattern

a) b)

Fig. 6. Failure pattern observed in a) Heat curing b) Moist curing

The failure pattern observed in nano-silica treated soil after 14 days of heat and moist curing are shown in Fig. 6(a) and Fig. 6(b) respectively. Fig. 6(a) indicates that upon heat curing sample experienced complete brittle failure and the sample almost split into two parts along the path of the crack. However, in moist curing, the sample experienced vertical cracks, and further loading made the sample crush along with the remaining mass and this may be due to the presence of hydrated gel which might have hold the sample from falling apart.

5 Conclusions

The influence of heat and moist curing methods on the strength of nano-silica treated clay was analyzed for different curing periods. Untreated clay cured by moist curing method showed lesser strength when compared to that of untreated clay cured by heat curing. Both heat and moist curing methods were effective in decreasing the failure strain. The deformation modulus increased by 10.69 times by moist curing after 28 days of curing. The UCS ratio by heat curing method increased upto 14 days of curing and the UCS ratio showed a decrease due to failure of sample at the predefined path formed due to crack of drying. Hence, it is inferred that although drying improved the strength of the sample, prolonged drying reduced the strength to value lesser than that of untreated sample. On the other hand, although untreated moist cured sample showed lesser strength initially, with increase in period of curing to 14 days and beyond showed an increase in strength of 8.22 times the untreated sample at 0.4% of nano-silica dosage. And the strength obtained at 28 days are very closer to the strength of 14 days cured moist sample, hence 14 days strength could serve as an indicative range for the maximum strength that such soils could attain upon moist curing. Therefore, the optimum dosage of nano-silica for moist curing is 0.4%.

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