

Studying Strength and Stiffness Characteristics of Sand Stabilized with Cement and Lime Additives

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Received on: 29/9/2014 & Accepted on: 11/6/2015

Abstract

The present work investigates the strength characteristics of sand stabilized with two additives (cement and lime) each alone at different percentages ranging between 1-10%. Sand mixed with different additive contents are statically compacted in perforated tubes, 38 mm in diameter and 200mm in length, the perforated holes are 2mm in diameter along the tube. Compaction is carefully controlled by compressing the sand to the required density by two plungers at top and bottom, two ends of the samples are waxed and soaked for 7 and 28 days in water. Unconfined compression test were performed, the strength and stiffness were determined for all the samples.

Results referred to an increase in strength and stiffness of stabilized sand with increasing additives content, cement treatment improved strength significantly rather than lime and soaking time plays an important role in increasing compressive strength of sand treated with cement and lime. Also results showed that the type of failure behavior varied greatly from plastic to brittle. An empirical equation was derived for the unconfined compression strength depending on type of additive and soaking time.

Keywords: Sand stabilization, unconfined compression test, Soaking time, Strength, Stiffness.

دراسة خصائص المقاومة والصلادة للرمل المثبت بمضافات السمنت والنورة

الخلاصة

يتحرى هذا البحث عن خصائص المقاومة للرمل المثبت بمختلف النسب من المضافات مثل السمنت والنورة، يخلط الرمل بمختلف النسب المستخدمة ويرص استاتيكيًا في أنابيب صنعت لهذا الغرض بقطر 38 ملم وطول 200 ملم وذو فتحات بقطر 2 ملم على طول الأنبوب. تجرى عملية الرص بحذر شديد وبالكثافة المطلوبة بوضع الرمل بين سدادتين في الأعلى والأسفل ويشمع النموذج بالشمع ويغمر بالماء لفترة 7 و 28 يوم. اجري فحص الأنضغاط الغير المحصور لغرض قياس المقاومة والصلادة للرمل المثبت. اشارت النتائج لزيادة المقاومة و الصلادة للرمل المثبت بزيادة نسبة المادة المضافة، اظهرت النتائج ان التحسين بالمقاومة كان اكثر في السمنت مقارنة بالنورة وان زيادة وقت الغمر بالماء يلعب دور كبير في زيادة المقاومة للرمل المعالج بالسمنت والنورة. كما تم اشتقاق معادلة لحساب المقاومة اعتمادا على نوع المادة المضافة ووقت الغمر.

INTRODUCTION

Unstable soils can create significant problems for pavements and structures, therefore soil stabilization techniques are necessary to ensure the good stability of soil so that it can successfully sustain the load of the superstructure especially in case of soil which are highly active, also it saves millions of money when compared to the method of cutting out and replacing the unstable soil. Additives like lime, cement, flyash and asphalt are known as chemical admixture. These methods have been used to improve inherent properties of the soil such as increase in strength and reduction in compressibility, an improvement in swelling or squeezing characteristics and increasing the durability of soil are the main aims of the stabilization (Bergado, 1996). Lime or cement has commonly been used as chemical admixtures for soil stabilization and extensively used in both shallow and deep stabilization methods these methods have been used to improve the properties of soil since old time. The application of deep stabilization method of in situ started in the late 1970's in Japan. (Terashi et al.1979; Kawasaki et al. 1981; Suzuki 1982). Shallow stabilization of soft soil with Lime and / or cement has been extensively used for road construction purpose in order to improve mechanical properties of the bearing layers. Additional application of these additives is their use as columns to improve the stability of slopes and deep excavation; to increase the bearing capacity and reduce the total and differential settlement under lightly loaded structures. Baquir (1990) studied stabilization of soft soils from Fao city by lime and cement and conducted a series of Triaxial test, consolidation and unconfined compressive strength for sand column stabilized the soft soil with different diameters and curing for period 1, 7 and 28 days. The results showed that stabilized soil exhibited lower compressibility and higher shear strength with increase the percentages of additives and time. The sand column with the soft soil led to increase in load carrying capacity and also increase in angle of internal friction as the diameter of column increases. The drainage trough the column led to increase of load carrying capacity of composite foundation. Al-Amoudi (2002) used cement and lime each alone at five different percentages ranging from 0 to 10 percent to improve strength of silty sand soil. The results show that cement succeeded in improving the strength of the selected soil rather than lime; the range of improvement was 3.1 and 6.2 times that of untreated soil for 3% and 10% cement additions respectively. There is a linear relationship between the stabilizer content (cement or lime) and the strength, and this linear relationship depends strongly on the soil type and water content. Fonseca et al. (2009) studied the characteristics of two soils, Osorio sand and botucatu residual sand stone, which can be converted if stabilized with cement to acceptable materials for the construction of roads, railways and etc. the study of soil stabilization with cement relies on the quantification of the influence of percentage of cement and porosity adopted in the mixing process for different state and stress conditions. Single equation derived for the unconfined compression strength was used for all materials depending on amount of cement and the compaction energy.

$$q_u = A \{V_v/(V_{ce})^c\}^{-B} \quad \dots(1)$$

Where:

A, B & C = coefficients A, B and C which range according to the soil and cement type,
V_v/V_{ce} = ratio of volume of voids to volume of cement.

Sariosseiri and Balasingam (2009) conducted an experimental study on the use of Portland cement in the modification and stabilization of soils in the state of Washington. Cement was added in percentages of (2.5, 5, 7.5 and 10%) by dry weight of the soils. Laboratory tests to determine the Atterberg limits, compaction characteristics, unconfined compressive strength and consolidated-undrained triaxial behavior were performed. Results of investigation showed significant improvement in workability, unconfined compressive strength and shear strength. This improvement is dependent on type of soil. Results of undrained triaxial tests showed that while cement treatment improved shear strength significantly the type of failure behavior varied greatly. Non-treated, 5% and 10% cement treated soils displayed ductile planar and splitting type of failure, respectively. Therefore, while increased strength is achieved by cement treatment, high percentages of cement should be used with caution in field applications. Okonta and Govender (2011) studied the effect of wetting and drying cycles on the unconfined compressive strength (UCS) and California bearing Ratio (CBR) of compacted and cured sample. Mixes were prepared with (4% and 8% lime) and (0%, 6%, 12% and 18% flyash) and tested after 4, 8, 12 cycles of wetting and drying. Changes in mass of stabilized sands were measured to facilitate the interpretation changes in strength properties. The results showed a reduction in UCS and CBR with increases in the number of wetting and drying cycles that is dependent on the amount of lime and flyash and the ratio of lime to flyash. Ajorloo et al. (2012) performed experimental investigation of cement treated loose sand under triaxial tests in order to quantify the effects of cementation on the stress-strain behavior, stiffness and shear strength. Samples were cured up to 180 days. The results show that the stress-strain behavior of cemented sand is nonlinear with contractive-dilatative stages. The stress-strain response is strongly influenced by effective confining pressure and cement content. Stiffness and strength are greatly improved by an increase in binder content. An increase of the angle of shearing resistance and cohesion intercept with increasing cement content is observed consistently. Brittle behavior was observed at low confining pressure and high cement content. Even a loose specimen cemented with a small amount of cement can exhibit brittle behavior. Ajayi (2012) studied the effect of lime variation on moisture content and dry density of Lateritic soil in Ilorin, Nigeria. The lime concentrations used were 0%, 2.5%, 5% and 7.5% respectively. The results analysis showed that there is a significant variation at 5% level of significance in moisture content and dry density with lime concentration. The increase in the moisture content due to the addition of lime results lower amount of compaction or less compacting effort and this could be achieved by addition of small amounts of lime to laterite soil. Dash and Hussain (2012) have stabilized soft soil with different percentages of lime (1, 3, 5, 9 and 13%) and cured for period (3, 7, 21 and 28 day). They studied the effect of additives on liquid limit, plastic limit, swell compressive strength, mineralogy and microstructure. They found that the liquid limit of soils initially decreases with an increase in lime content while plastic limit increased because the viscosity of the pore water increased and refers to higher resistance, the swell potential of soils decreases with increased percentages of lime to a practically negligible value. Abbasi et al. (2013) investigated the improvement of silty sand desert soil from Iran using pozzolan from a cement factory in for levels (0, 5, 10 and 15 %) and lime in five levels (0, 1, 3, 5 and 7 %) for cured period including 7, 14 and 28 days. Their results show that adding lime to the soil improves the compressive strength while using both

of lime and pozzolan, cause substantial increase in compressive strength up to 16 times in comparison of natural soil, and that curing time plays an important role in increasing the compressive strength of treated silty sand soil with lime and pozzolan . The optimum binder for the stabilization of this silty sand was found to be a combination of 15% natural pozzolan and 3% lime. Rajab (2013) have stabilized soft clay by implementing sand columns and sand columns stabilized with different percentages of Portland cement (1,3,5,7,9 and 11%) and cured for (7 and 28 days) to provide extra stiffness to the columns and hence provide extra improvement in terms of bearing capacity and compressibility. The investigation considered floating and end bearing types of columns. The model tests revealed optimum cement content for floating type was 9% for models cured for 7 days with bearing improvement ratio=3.19 and 7% cement content for models cured for 28 days with bearing improvement ratio=3.08; while for end bearing type was 8% cement content for models cured for 7 days with bearing improvement ratio=3.92. Al-Gharbawi (2013) investigated the behavior of sand columns and sand columns stabilized with different percentages of lime (1, 3,5,7,9 and 11%) and cured for (7 and 28 days). Three types of lime were used to stabilize stone columns (Iranian lime, Turkish lime and Turkish lime exposed to heat 512C°). The investigation considered floating and end bearing types of columns. The results showed that sand columns stabilized with 11% lime type III (floating type) provided highest degree of bearing improvement ratio of 2.91 after seven days curing and 4.1 after twenty eight-day curing, and the lowest degree of settlement reduction ratio of 0.09 after seven and twenty eight-day curing. Sand columns stabilized with 11% lime type III (end bearing type) provided a bearing improvement ratio of 3.33 and settlement reduction ratio of 0.086 after seven-day curing. Thus it is advisable to use lime type III to improve the performance of both floating and end bearing sand columns.

Experimental Work

Materials Used

Sand

The sand used in this work was obtained from Al- Ekhether city (152 km southwest Baghdad). According to the grain size distribution in Figure 1, the (sand-aggregate) sample consists of 40% gravel and 60% sand with $C_c = 1.11$ and $C_u = 7.14$. The maximum size of gravel used is 6.9mm. It is classified as a well graded sand SW. The physical and chemical properties of sand are shown in Table1.

Lime

Unhydrated lime (Turkish lime exposed to heat at 512°C) was used in this investigation. The physical and chemical properties of lime and the ASTM specifications are shown in Table2.

Cement

Sulfate resistance cement was used in this investigation which manufactured by Tasluja cement factory. Physical and chemical properties of the cement and Iraqi specification No.5 (1984) are shown in Table 3.

Equipment Used.

Plastic pipes and metal plugs:

Hollow plastic pipes with inner diameter 38mm, 200mm height and 4mm thickness were used in preparation of stabilized sand specimens. A 120mm and 40mm length metal plug, the first one is used to compact each layer of sand and additive (lime and cement) mixture and the second for close the bottom of the tube. The details of the plastic pipe and the metal plugs are shown in Figure 2.

Samples Preparation and Curing

All the experiments were carried out on 120mm long and 38mm diameter sand-additives column which was constructed in the plastic tubes. Before mix preparation, two tubes were cleaned, labeled and weighted; slight grease was applied on their inner surface. The quantity of lime and cement ranges between (1-10%) as percentages to the weight of sand (550gm) was added to the sand and properly mixed by hand while dry, the sand (lime and cement) mixture was carefully charged in the tubes in three layers each layer is (40mm) in height and received 15 blows from hammer weight (700 gm) to achieved dry density equal to 4.04 gm/cm^3 . Wax was used to close both ends of the tube, and then they are placed in water for 7 and 28 day as shown in Figure 3.

Testing

All the test specimens were subjected to unconfined compression tests in order to determine their unconfined compressive strength. Procedures of the tests were carried out in accordance to U.S. ASTM standard. According to the ASTM standard, the unconfined compressive strength (q_u) is defined as the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple unconfined compressive test. In addition, in this test method, the unconfined compressive strength is taken as the maximum load attained per unit area. Figure 4 shows sample testing.

Results of Laboratory Testing

Laboratory Test Results of Sand Columns Stabilized with Cement

In this series, sand was stabilized with (1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10%) of cement and cured for 7 and 28 day. The experimental program consists of (36) sand stabilized specimens. All samples were prepared with dia. 38mm & length 76mm for unconfined tests.

Effect of cement content on strength:

Figure 5 demonstrates the relation between the stress σ (load attained per unit area) and strain ϵ (change in length to initial length) for specimens of sand stabilized with different percentages of cement which is cured for 7 and 28 days. Figure 5 illustrates two important points; the first is the increase in compressive strength of the sand with increasing the percentage of cement as additive, this is clearly shown in the gradual change of the shapes of curves with increasing cement content for two curing periods. The second point is the increase in compressive strength of the specimens cured for 28 days as compared to the corresponding specimens cured for 7 days; this increase is due to chemical reaction process that developed during 28 days curing period. This observation is agreement with Baquir (1990), Sariosseiri and Balasingam(2009) and

Ajorloo et al. (2012). The peak stress at failure of each model after 7 and 28 days of curing are illustrated in Table 4. Figure 6 illustrates the variation in UCS versus cement content for samples of sand stabilized with cement cured for 7 and 28 days respectively. The figure define two stages, the first where the rate of increase in UCS is low up to lime content 5% followed by stage two where the rate of increase in UCS is high. This behavior was also observed by Ajorloo et al. (2012) and Abbasi et al. (2013). In general the relationship between UCS and cement content demonstrated a nonlinear increase within the range of cement content. Maximum UCS is observed at 10% cement content where strength exceeds 1292 and 4500 kN/m² for samples cured for (7&28 days) respectively. This high value encourages the use of cement as a stabilizer for sand. The test data were analyzed using **Data Fit Software** and the following equation was obtained:

$$q_u = 7822.1 C^{1.655} T^{0.99987} \dots\dots (2)$$

Where:

qu = Unconfined compression strength, C= Cement content, T= Time of curing , The R² value for equation1 is (0.9818), SEE= 207.519.

Effect of cement content on the amount of water absorbed:

The primary reaction of cement is with the water in the soil that leads to the formation of a cementation material (Das, 2007). These reactions occur almost independently of the nature of the soil and for this reason cement can be used to stabilize a wide range of soil. Figure 7 indicates the increase in the amount of water absorbed during curing period for (7 and 28 days respectively). As a matter of fact there is a consistent value of water content of average value 11% up to 8% cement content then gradual decrease was observed at 10.5% up to 5% cement content, then a gradual decrease was observed which leveled of as cement content reaches 7%. The average value at this stage is around 8%. This might be due to the change in stiffness of the stabilized soil as the brittleness of the material increases with increasing cement content.

Effect of cement content on modulus:

These strength results matches well with the modulus results demonstrated in Figure 8, the E value increases in a similar pattern of the UCS, the rate of increase is low up to 6% cement content then increases rapidly in a sharp nonlinear pattern. Maximum E values reached up to 92385.9 kN/m² at 9% cement content and 849982 kN/m² at 10% cement content during curing period for (7 and 28 days respectively). Although the strain at failure versus cement content demonstrated high scatter of results but the overall trend clarifies the change in the brittleness of the soil.

Mode of Failure:

Figure 9 and 10 shows the mode of failure for samples cured for 7 and 28 days for different percentages of cement, the mode of failure tend towards a shear pattern with increasing cement content. The mode of failure depends on the amount of cement and curing time. This observation was good agreement with Sariosseiri and Balasingam (2009).Table 4 and 5 summarizes the main results determined regarding the water content, saturated unit weight, dry unit weight, modulus of elasticity, maximum strain

stress peaks, undrained shear strength and the ratio of modulus of elasticity / undrained shear strength for all the performed samples.

Laboratory Test Results of Sand Stabilized with Lime:

In this series, sand was stabilized with (3%, 4%, 5%, 6%, 7%, 8%, 9% and 10%) of lime and cured for 7 and 28 day. The experimental program consists of (32) sand stabilized specimens.

Effect of lime content on strength:

Figure 11 illustrates the relationship between the stress σ (load attained per unit area) and strain ϵ (change in length to initial length) for samples of sand stabilized with lime cured for 7 and 28 days. From figure it can be seen that there is almost a linear increase in strength of stabilized sand and cured for 7 days with increasing lime content, at 3% lime the unconfined strength is 4.99kN/m² and increase to 41.48 kN/m² when lime content is increased to 10%. While there is a gradual nonlinear increase in strength of stabilized sand cured for 28 days as increasing lime content, at 3% lime the unconfined strength is 24.88kN/m² and increase to 93.25kN/m² when lime percent is increased to 10%. Such behavior may be explained due to the increase in strength derived from three reactions, dehydration of soil, ion exchange and pozzolanic reaction. Other mechanism such as carbonation cause minor strength increase (Bergado, 1996). The strength of cured soil increases as the lime content is increased. Figure 12 illustrates the relationship between the UCS plotted against the percentage of lime content for samples of sand columns stabilized with lime curing for (7 and 28 days) respectively. The figure define two stages, the first where the rate of increase in UCS is low up to lime content 5% followed by stage two where the rate of increase in UCS is high. This behavior was good agreement with Abbasi et al. (2013). The test data were analyzed using **Data Fit Software** and the following equation was obtained:

$$q_u = 190.049 L^{1.26501} T^{0.607554} \dots\dots (3)$$

Where:

q_u = Unconfined compression strength, L = Lime content, T = Time of curing. The R^2 value for equation 1 is (0.9667), $SEE=4.121$.

The results show that cement succeeded in improving the strength of sand rather than lime. This results was good agreement with Al-Amoudi(2002).

Effect of lime content on water absorbed during curing:

Figure 13 indicates the effect of lime variation on water content for specimens cured for 7 and 28 days, the results for 7 days defined two stages, the first where the decrease of the water content when the lime content increases up to 6% lime, then in the second stage it began to increase to its maximum value at 10 % lime this behavior clarifying the high ability of lime to absorb water. During the soaking period of 28 days there is nearly a consistent value of water content of average value 11.1. The same observation was noticed by Ajayi(2012).

Effect of lime content on modulus:

These strength results matches well with the modulus results demonstrated the modulus of the stabilized sand, expressed as the modulus of elasticity E the value increases in a similar pattern of the unconfined compressive strength, the rate of

increase is low in a sharp nonlinear pattern. Maximum E values reached up to 2100 KN/m², 7762.15 KN/m² at 10 % lime content curing for 7 and 28 days respectively as shown in Figure 14.

Mode of Failure:

Figure 15 and16 show the mode of failure for samples cured for 7 and 28 day for different percentages of lime, the mode of failure tend towards elastic to brittle pattern with increasing lime content. Table7and 8 summarizes the main results determined regarding the water content, saturated unit weight, dry unit weight, modulus of elasticity, maximum strain stress peaks, undrained shear strength and the ratio of modulus of elasticity / undrained shear strength for all the performed samples.

Conclusions:

The results of the tests for samples of sand stabilized with cement or lime additives revealed the following points within the range of the tests.

For samples stabilized with cement:

- 1- The UCS increases in a nonlinear pattern with increasing cement content. The maximum UCS was observed for samples cured for 28 days. The peak stress can be expressed as a function of cement content and time of period using an empirical equation: $qu = 7822.1 C^{1.655} T^{0.99987}$ with R² value equal to (0.9818).
- 2- The amount of water content absorbed by cement decrease by increasing cement content and period time. For 7 days curing, it decreases from 10.1% to 8.4% as cement content increase from 2% to 10% while for 28 days curing, it decreases from 12.3% to 8.8% as cement content increase from 3% to 10%.
- 3- The behavior of failure changed from shear to brittle as cement content increases.

For samples stabilized with Lime:

- 1- The UCS increases in a nonlinear pattern with increasing lime content. The maximum UCS was observed for samples cured for 28 days. The peak stress can be expressed as a function of cement content and time of period using an empirical equation: $qu = 190.049 L^{1.26501} T^{0.607554}$ with R² value equal to (0.9667). The results show that cement succeeded in improving the strength of sand rather than lime
- 2-The amount of water content absorbed was about 11% clarifying the ability of lime to absorb water.
- 3- The strain at failure changes from elastic to brittle as lime content increases.

Table (1) Properties of Sand Used.

Index Property	Index Value
Max. Dry Unit Weight (kN/m ³)	20.5
Min. Dry Unit Weight (kN/m ³)	16.5
D ₁₀ (mm)	0.28
D ₃₀ (mm)	0.79
D ₆₀ (mm)	2
Coeff. of Uniformity(Cu)	7.14
Coeff. of Curvature(Cc)	1.11
Gravel (%), G	40

Sand (%),S	59
Fines (%)	1
Classification	SW
Specific Gravity (Gs)	2.65
Organic Material (%), (O.M)	0.09
Total Dissolved Salts (%) (TDS)	0.3
SO ₃ Content (%)	0.15

Table (2) Properties of Lime Used

Index Property	Index Value	ASTM specifications
Retained on Sieve#30(% by weight)	0	3% (max.)
Retained on Sieve#200(% by weight)	10	25% (max.)
CaO Content (%)	93.34	90% (min.)
Free Water Content (%)	0.08	2% (max.)
IR (%)	2	
SO ₃ Content (%)	0.07	
L.O.I (%)	25.24	

Table (3) Properties of Cement Used

Index Property	Index Value	Iraqi specifications No. 5/1984
Compressive strength after 3 days (MPa)	17	15 (min.)
Compressive strength after 7 days (MPa)	26	23 (min.)
Time of initial setting (minute)	93	45(min.)
Time of final setting (hour)	4.28	10(max.)
SiO ₂ %	19.79	-----
CaO%	63.8	-----
MgO%	3.19	5 (max.)
SO ₃ %	2.15	2.5(max.)
C ₃ A%	3.27	≤ 3.5
LOI %	0.89	4.0(max.)

Table (4) Results for Cement Curing for 7 Days

% cement	% Wc	γ wet (kN/m ³)	γ dry (kN/m ³)	E (kN/m ²)	ϵ (σ max) ($\Delta L/L$)	Peak stress (kN/m ²)	Cu (kN/m ²)	E/Cu
1% -1	10.16 %	19	16.51	4008.9	0.01665	30.5	25.63	156.4
1%-2	10.07 %	19.08	16.58	4008.9	0.01665	32.6	25.63	156.4
2%-1	10.99 %	19.92	17.23	4990.3	0.01875	43.15	28.5	175.1
2%-2	11.15 %	20.00	17.52	4990.2	0.01875	43.15	28.5	175.1
3%-1	10.55 %	20.84	18.51	5010.76	0.01974	59.13	29.56	169.5
3% -2	10.99 %	20.76	18.55	5010.76	0.01974	59.13	29.56	169.5
4%-1	10.09 %	21.76	19.96	10597.51	0.01987	223.96	111.98	94.64
4%-2	10.45 %	21.45	19.23	11408.73	0.01645	148.30	74.16	153.84
5% -1	10.53 %	21.76	19.52	37326.39	0.03618	339.12	169.56	220.1
5% -2	9.60 %	21.29	19.24	44494.05	0.01645	444.94	222.47	200.0
6% -1	9.83 %	21.88	19.67	13169.64	0.02961	526.79	263.39	50.0
6% -2	9.35 %	21.51	19.52	13169.64	0.02961	526.79	263.39	50.0
7% -1	8.79 %	23.01	20.47	35909.60	0.02303	574.55	287.28	125
7% -2	8.43 %	22.34	19.89	35909.60	0.02303	574.55	287.28	125
8% -1	8.30 %	22.12	19.97	62710.44	0.01974	689.81	344.91	181.8
8% -2	8.18 %	21.45	19.39	47536.38	0.02961	560.93	280.46	169.5
9% -1	8.35 %	22.31	20.29	68223.44	0.01645	886.90	443.45	153.85
9% -2	8.37 %	21.60	19.68	92385.91	0.01974	1108.63	554.32	166.7
10%-1	7.98 %	22.99	21.09	58753.46	0.02961	1292.58	646.29	90.9
10%-2	8.78 %	22.51	20.74	58753.46	0.02961	1292.58	646.29	90.9

Table (5) Results for Cement Curing for 28 Days

% cement	% Wc	γ wet (kN/m ³)	γ dry (kN/m ³)	E (kN/m ²)	ϵ (σ max) ($\Delta L/L$)	Peak stress (kN/m ²)	Cu (kN/m ²)	E/Cu
1% -1	13.75	21.18	19.23	6138.39	0.02303	98.21	49.11	125.00
1%-2	13.62	21.00	19.08	5767.75	0.01645	69.21	34.61	166.67
2%-1	12.98	21.59	19.45	4465.45	0.02961	126.82	63.41	70.42
2%-2	12.83	21.45	19.30	10906.08	0.04276	327.18	163.59	66.67
3%-1	12.62 %	21.51	19.45	11685.09	0.04276	327.18	163.59	71.43
3% -2	11.96 %	21.46	19.34	87924.38	0.00987	527.55	263.77	333.33
4%-1	10.52 %	21.79	19.80	205670.3	0.00806	1645.36	822.68	250.00
4%-2	11.54 %	22.62	20.48	11673.09	0.04276	320.18	160.09	71.43
5% -1	11.52 %	21.78	19.70	24470.9	0.02632	562.83	281.42	86.96
5% -2	10.65 %	21.65	19.75	134535.1	0.02418	1883.49	941.75	142.86
6% -1	11.24 %	22.42	20.41	66954.92	0.02533	2008.65	1004.32	66.67
6% -2	10.20 %	22.34	20.43	77255.67	0.02533	2008.65	1004.32	76.92
7% -1	10.41 %	23.18	21.31	429813.7	0.01266	2406.96	1203.48	357.14
7%-2	11.33 %	23.24	21.43	259860.7	0.00806	3066.36	1533.18	169.49
8%-1	10.74 %	22.70	20.96	252807.5	0.01382	3033.69	1516.85	166.67
8%-2	10.61 %	22.75	21.03	246080.2	0.01382	3445.12	1722.56	142.86
9%-1	9.92 %	22.52	20.78	218940.1	0.01842	3503.04	1751.52	125.00
9%-2	9.74 %	22.47	20.73	406285.3	0.01151	3900.34	1950.17	208.33
10% -1	8.98 %	22.26	20.61	1155676	0.00576	3698.16	1849.08	625.00
10% -2	8.53 %	22.30	20.50	849982.9	0.01151	4759.90	2379.95	357.14

Table (6) Results of Lime Curing for 7 Days

% cement	% Wc	γ wet (kN/m ³)	γ dry (kN/m ³)	E (kN/m ²)	ϵ (σ max) ($\Delta L/L$)	Stress peaks (kN/m ²)	Cu (kN/m ²)	E/Cu
3%-1	10.54 %	21.78	19.70	744.05	0.01316	5.95	2.98	250.00
3% -2	11.53 %	21.67	19.43	780.22	0.00658	4.99	2.50	312.50
4%-1	10.19 %	21.92	19.90	985.45	0.01974	14.78	7.39	133.33
4%-2	10.48 %	22.42	20.30	1529.43	0.02632	14.68	7.34	208.33
5% -1	10.30 %	21.88	19.84	760.51	0.02303	17.19	8.59	88.50
5% -2	11.82 %	21.54	19.27	760.51	0.02303	17.19	8.59	88.50
6% -1	9.99 %	22.18	20.17	1631.39	0.02632	19.58	9.79	166.67
6% -2	10.22 %	21.20	19.23	755.49	0.02303	19.64	9.82	76.92
7% -1	10.75 %	21.95	19.82	1584.78	0.02632	33.28	16.64	95.24
7%-2	10.72 %	22.51	20.33	766.49	0.02961	10.73	5.37	142.86
8%-1	10.61 %	22.51	20.35	3871.41	0.01974	54.20	27.10	142.86
8%-2	11.00 %	21.90	19.73	609.71	0.02961	17.07	8.54	71.43
9%-1	11.04 %	22.20	20.00	1929.21	0.02303	27.01	13.50	142.86
9%-2	11.14 %	22.09	19.88	1569.11	0.03947	31.38	15.69	100.00
10% -1	12.17 %	22.01	19.62	3031.31	0.01316	27.28	13.64	222.22
10% -2	12.04 %	21.87	19.52	1594.61	0.02961	41.46	20.73	76.92

Table (7) Results of Lime Curing for 28 Days

% cement	% Wc	γ wet (kN/m ³)	γ dry (kN/m ³)	E(kN/m ²)	ϵ (σ max) ($\Delta L/L$)	Peak stress (kN/m ²)	Cu (kN/m ²)	E/Cu
3%-1	10.81 %	21.25	19.18	2539.21	0.00987	24.88	12.44	204.12
3% -2	11.57 %	21.78	19.52	859.38	0.02303	17.19	8.60	99.99
4%-1	10.02 %	21.75	19.77	3769.63	0.01645	30.16	15.08	249.98
4%-2	10.53 %	21.17	19.15	3188.78	0.01316	22.32	11.16	285.73
5% -1	11.06 %	21.91	19.73	3908.26	0.01645	57.84	28.92	135.14
5% -2	10.68 %	22.20	20.05	1898.06	0.01645	21.26	10.63	178.56
6% -1	11.60 %	21.70	19.44	4851.44	0.01974	63.07	31.54	153.84
6% -2	12.35 %	21.55	19.18	3089.86	0.01316	24.72	12.36	249.99
7% -1	10.35 %	22.34	20.25	4494.35	0.01645	49.44	24.72	181.81
7%-2	11.55 %	22.17	19.88	4197.55	0.01645	44.49	22.25	188.70
8%-1	11.17 %	22.24	20.01	7130.46	0.01645	74.16	37.08	192.30
8%-2	11.83 %	21.70	19.41	3468.62	0.01645	43.01	21.51	161.29
9%-1	10.98 %	22.32	20.11	9689.92	0.01316	83.33	41.67	232.57
9%-2	10.74 %	21.96	19.83	5520.56	0.01645	66.25	33.13	166.66
10% -1	11.19 %	22.63	20.35	10597.04	0.01316	93.25	46.63	227.28
10% -2	11.24 %	22.68	20.39	4927.25	0.01974	73.91	36.96	133.33

Where:

γ wet.= wet unit weight, γ dry=dry unit weight, E= modulus of elasticity,

ϵ = strain, σ = peak stress, C_u = undrained shear strength, E/C_u = ratio of modulus of elasticity to undrained shear strength.

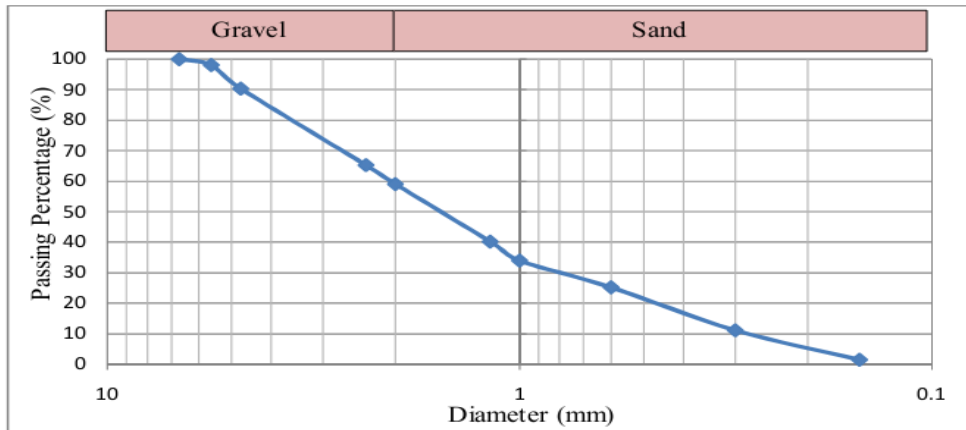


Figure (1) Particle size distribution of sand



Control of Density with two way plugs

Hole dia. 2 mm @ 20 mm c /c

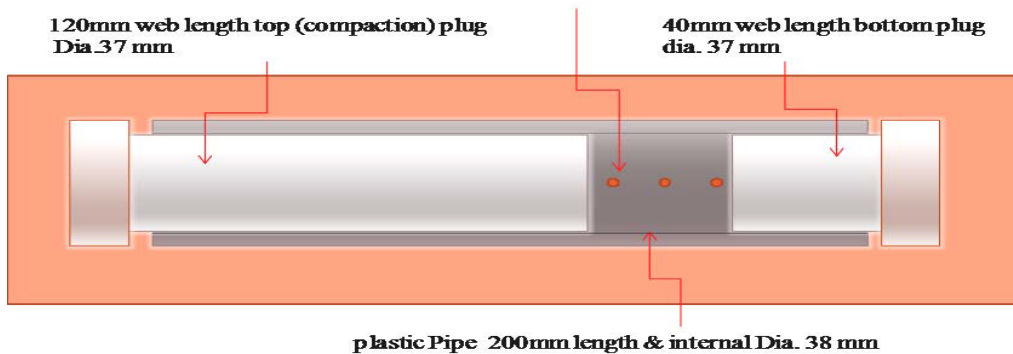


Figure (2) Details of plastic pipe & metal plugs Used



Figure (3) Preparation of Samples

Figure (4) Sample Testing

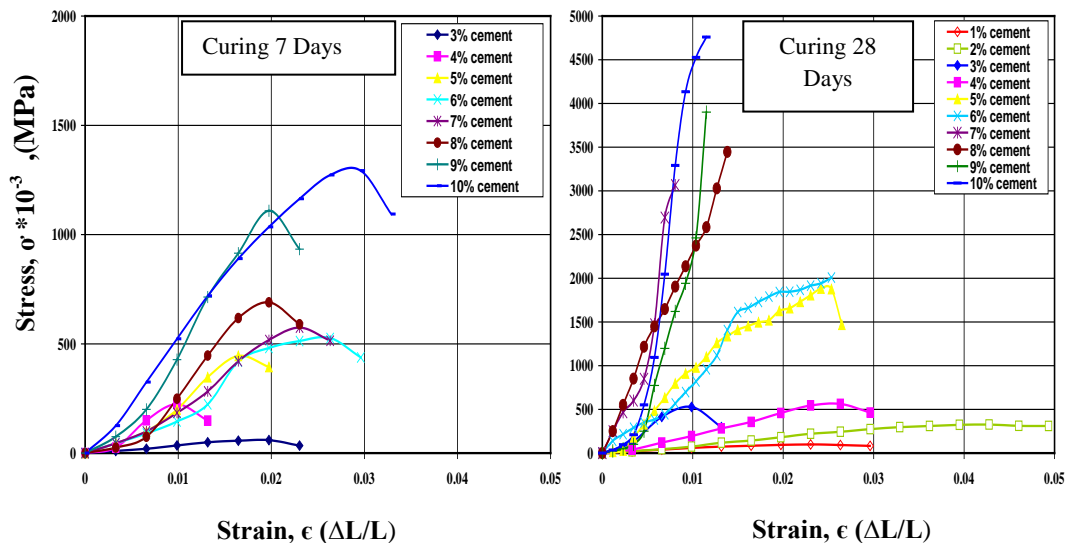


Figure (5) Stress versus strain for samples of sand stabilized with different percentages of cement curing for 7 & 28 days

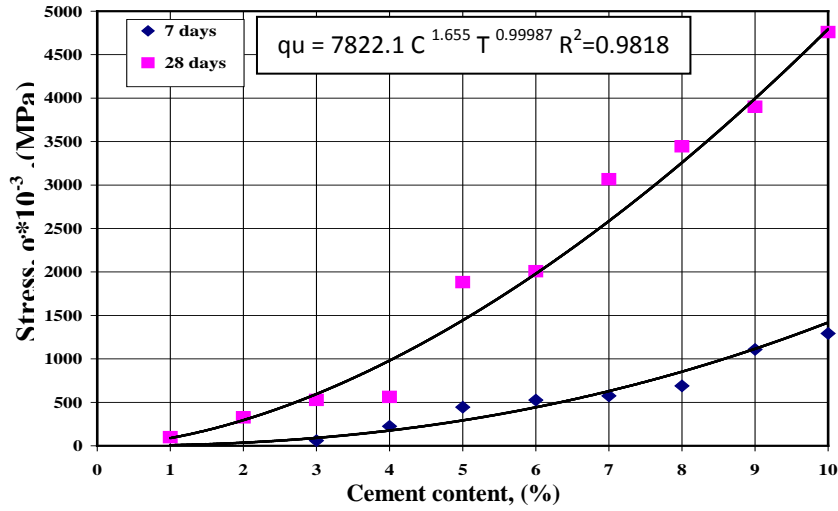


Figure (6) Peak stress versus cement content at different curing period

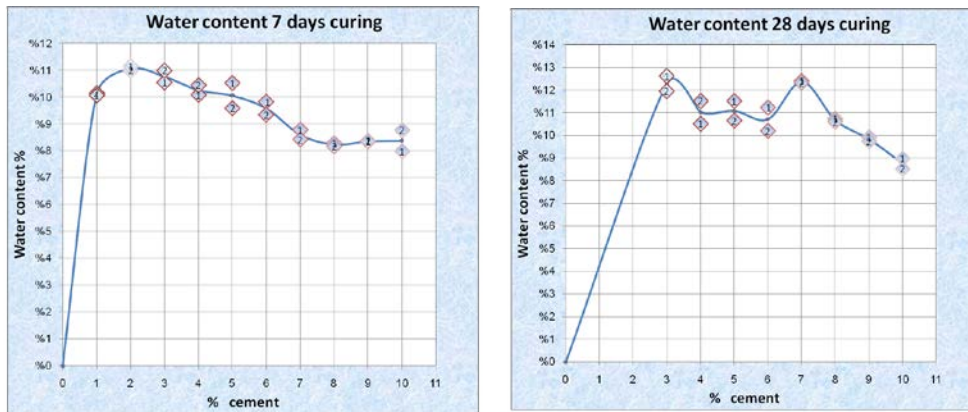


Figure (7) Water content versus cement content at different curing period

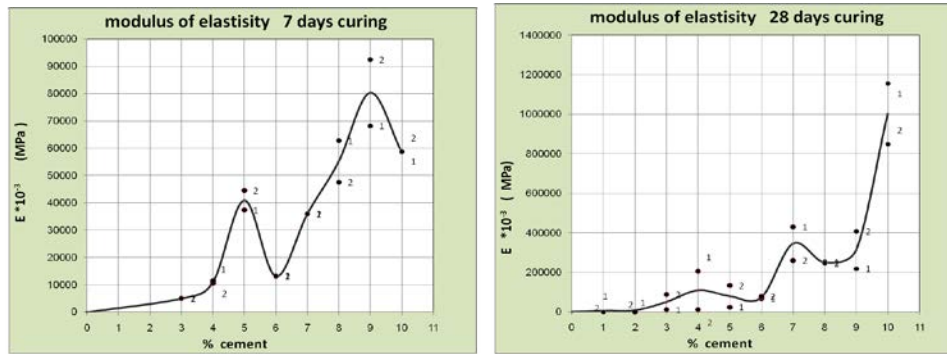


Figure (8) Modulus of elasticity versus cement content at different curing period

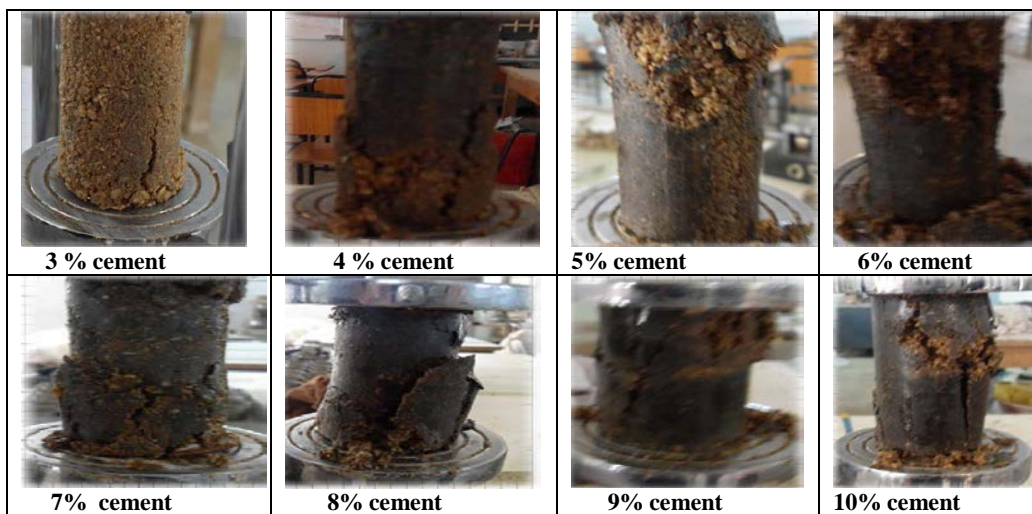


Figure (9) Mode of failure for samples curing for 7 day.

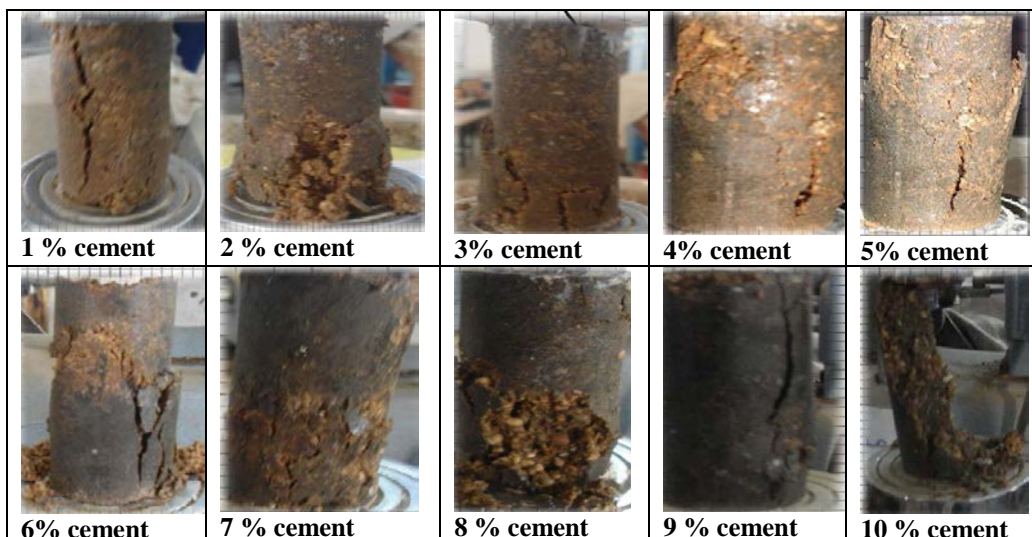


Figure (10) Mode of failure for samples curing for 28 days.

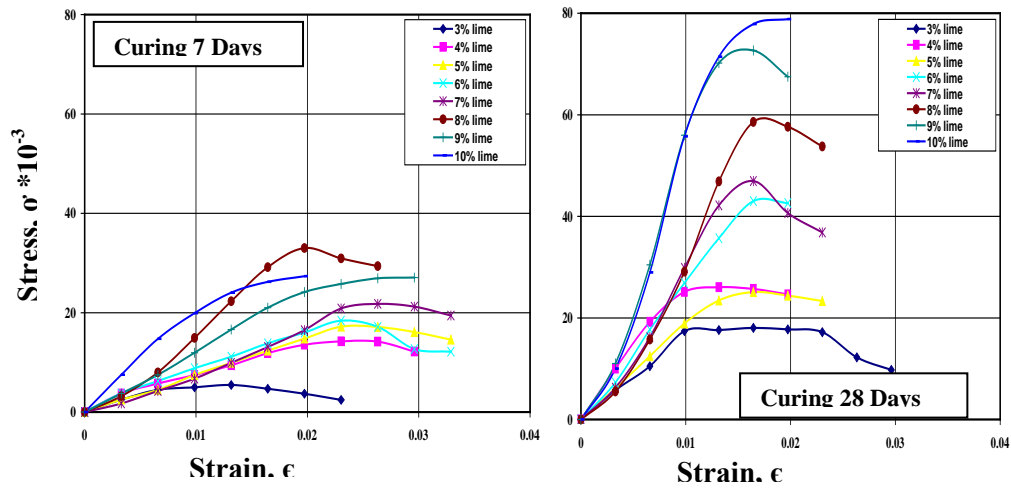


Figure (11) Stress versus strain for samples of sand stabilized with different percentages of lime curing for 7 & 28 days

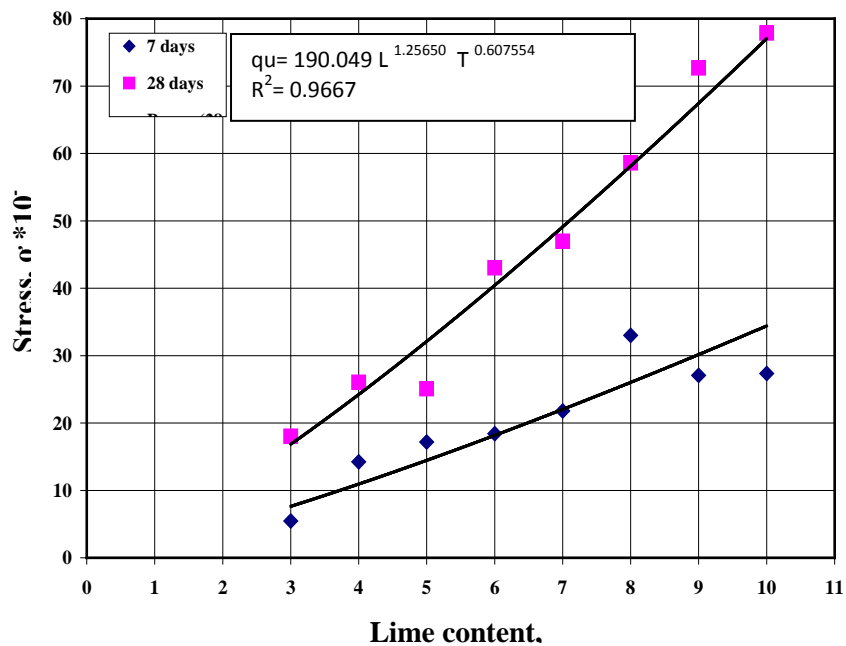


Figure (12) Peak stress versus lime content at different curing period

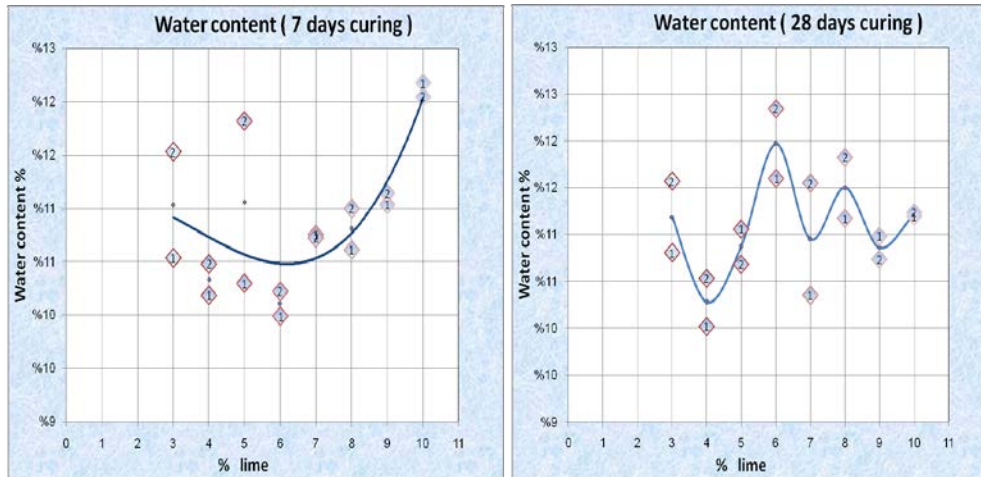


Figure (13) Water content versus lime content at different curing period

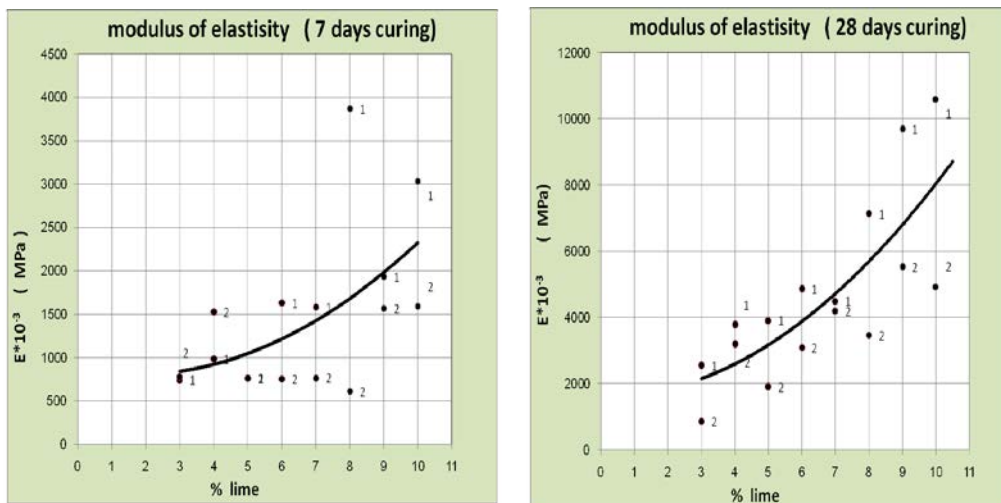


Figure (14) Modulus of elasticity versus lime content at different curing period

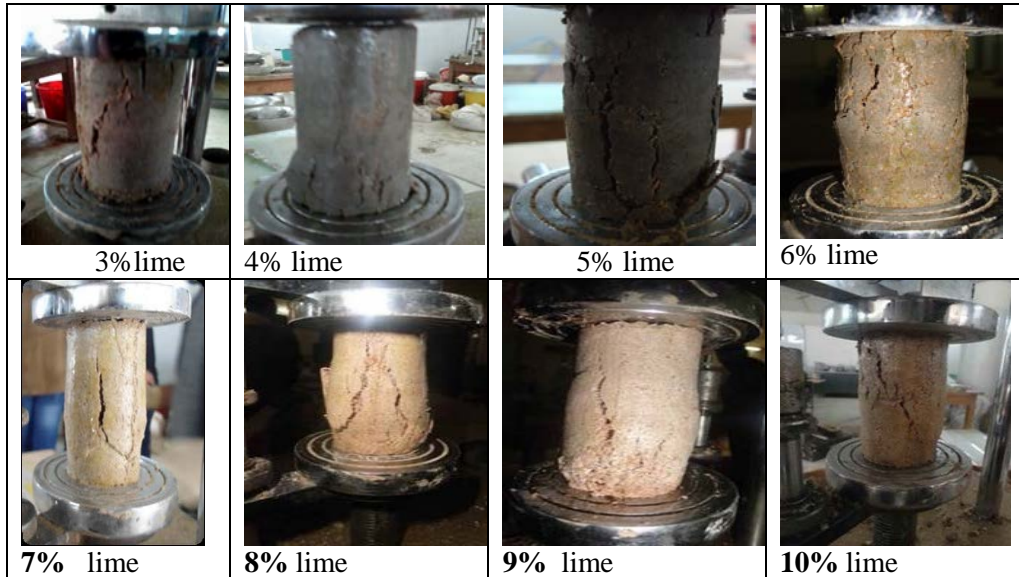


Figure (15) Mode of failure for samples curing for 7 day.

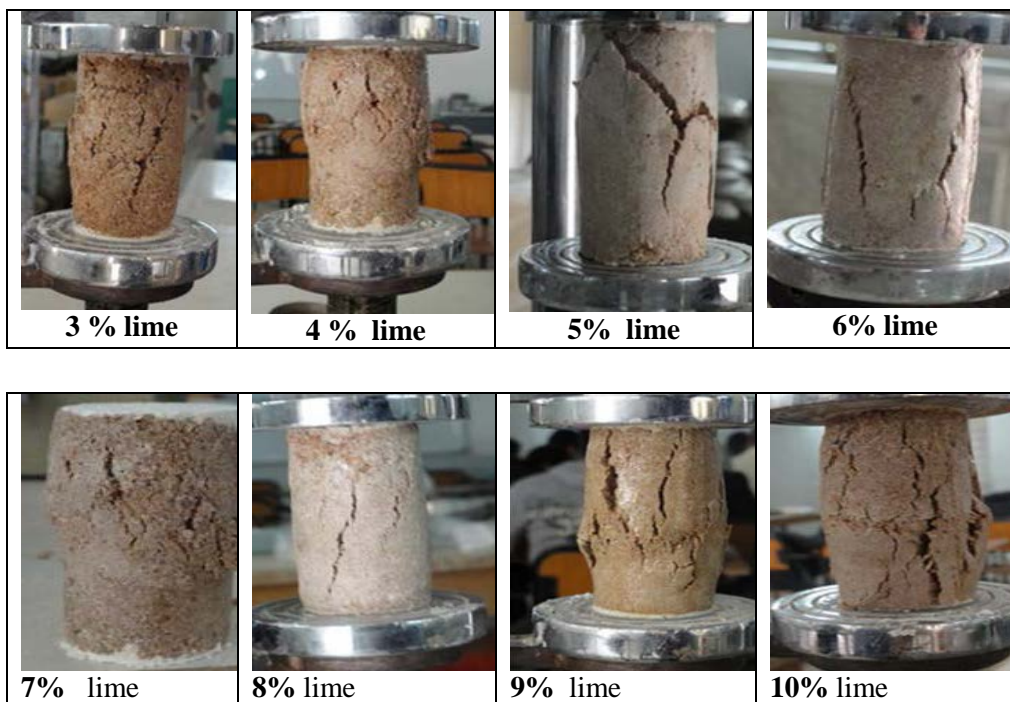


Figure (16) Mode of failure for samples curing for 28 days.

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