Prediction of strength development in stabilized sandy clay at high water contents

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Abstract— Construction on soft ground poses many problems due to low shear strength, differential settlement, construction pore pressure development etc. It has been challenging task to improve the soft grounds. The increased land use pattern has put pressure to develop techniques for ground improvement of soft soil deposits. The ground improvement techniques are generally based on densification, inclusion of reinforcement, cementation and provision of drainage etc. Generally lime and cement are widely used to improve soft clays having high water content and compressibility. In this paper, an attempt is made to identify the critical factors governing the strength development of sandy clay soil stabilized with additives. It is found that the clay-water/additive ratio i.e., Wc/A is the prime parameter controlling the strength development when the liquidity index varies between 1 and 2. Based on this parameter and Abram's law, the strength prediction equation for various curing times and combinations of clay water content & additive content is proposed and verified. This will help to minimize the number of trials necessary to arrive at the quantity of cement to be admixed.

Keywords— Soft sandy clay, Clay-water/cement ratio, Clay-water/lime ratio, Clay-water/(lime+cement) ratio, Low-swelling clayey soil, Unconfined compression strength test.

I. INTRODUCTION

SOFT ground generally has high initial water content greater than optimum moisture content and close to its liquid limit and poses severe construction problems due to low bearing capacity, total and differential settlements and excessive seepage. The land reclamation projects in coastal areas uses dredged soft soil as reclamation material. The adverse effects of increased moisture content are a concern for the geotechnical engineers. The replacement of such problematic soil is not always feasible. Several ground improvement techniques such as densification, cementation, reinforcement and drainage are attempted to mitigate the problems of soft ground. The additive technique has gained popularity and is widely used to improve the mechanical behaviour. Additives such as cement, lime and fly ash are the most common types of stabilizers used to improve the mechanical behaviour.

Cement stabilization has gained wide acceptance for improving the mechanical behaviour of soft soils with high initial water content. Cement when added to the soft soil modifies the soil in the presence of water. In order to economize, lime and fly ash can also be used in combination with cement. Cement stabilization depends on cement content, water content, degree of compaction and initial moulding water content [2], [3], [7]-[16], [19]. References [4], [5] and many others have brought out the effect of water content and

cement content on strength development.

Many constitutive models have been developed for strength prediction based on compression and shear behaviour [7], [18]-[20]. The Abram's law [1] based on the ratio of free water content to cement content is extensively used for predicting the strength of concrete. In soils, strength is found to be independent of the absolute contents of free water and cement content in the mix. References [8], [9] and [14] have identified the clay-water/cement ratio (Wc/C) as a critical parameter influencing strength development in cement stabilized clays. It is believed that clay water content reflects the microfabric and the cement content influences the level of bonding of that fabric. Based on this parameter and Abrams' law [1], Horpibulsuk et al. [10] have revealed that for a given set of cement admixed clays, the strength development depends only on the clay-water/cement ratio (Wc/C). A generalized equation was proposed for predicting laboratory strength development in cement admixed clays at various water & cement contents and curing period.

Extending this analogy to the behaviour of soil stabilization [8], [9], [14] the clay water to cement ratio has been identified as the controlling parameter for strength gain and generalized prediction equation [10], [20] have been developed. The effect of different stabilizing agents used is different for soft soils. For the effective application of the stabilizing techniques in the field and to use proper mix proportions, it is necessary to have a basic understanding of the strength development in the form of laboratory tests on soft clays admixed with stabilizing agents. In the present work, it is intended to study the effect of cement and lime as stabilizing agents for stabilization of sandy clay at high water contents and develop methods to predict the strength. The experimental results for the strength development of cement, lime and lime+cement stabilized soft sandy clay are reported in terms of cement content, curing period and clay water to cement ratio. Based on Abraham's law, predictive equations for strength development are proposed on the lines of Horpibulsuk et. al [15].

II. EXPERIMENTAL INVESTIGATIONS

A. Materials

Sandy clay soil was collected from a local site from a depth of 2m below the ground surface from a low lying area which is generally inundated with water during rainy season. Many foundations and road bases have failed in this area. The results of index properties, gradation and standard proctor tests are

presented in Table. 1. The soil is sandy clay with the group symbol CI. It is a low swelling clayey soil with the free swell ratio less than 1.35. The consistency limits are LL = 45%, PL = 21%, Ip = 24% and its natural water content is 32%. The groundwater level in the field is at 1.0m from the surface. The dry unit weight is 18.54kN/m^3 & the in-situ void ratio is 0.85 and the soil was in state of saturated condition. The effective strength parameters in triaxial compression were c′ = 0kPa and $\phi' = 22°$.

B. Physico-Chemical Properties

The Physico-chemical properties were determined as per standard test procedures.

For determining the silica content, 10gms of oven dried soil was dissolved in concentrated HNO_3 and filtered through whatsmans filter paper. The residue was heated in muffle furnace for 24 hours and the residue left gave the silica content in the soil. The filtrate obtained during the above experiment was used to prepare stock solution of 250ml for subsequent experiments.

For 25ml of stock solution 10mg Ammonium chloride and Ammonium hydroxide were added in 1:1 proportion till excess white/reddish brown precipitate appears. The solution was then subjected to centrifuge for 10 minutes and the precipitate was separated. Sodium hydroxide was then added to the residue collected from the filter paper and filtered again. The residue was placed in silica crucible and heated in a muffle furnace till red hot. Iron content was determined by the residue left in the crucible. Ammonium hydroxide was added to the filtrate obtained in the previous step till it forms precipitate and then filtered. The residue along with the filter paper is collected and placed in silica crucible and heated in muffle furnace till red hot. The residue left in the crucible gives the percentage of Aluminum present in the soil.

For 25ml of stock solution 10mg of Ammonium chloride and Ammonium hydroxide (1:1) were added till excess white/reddish brown precipitate appears. The solution was then subjected to centrifuge for 10 minutes. Filtrate was collected and ammonium carbonate was added till white precipitate was formed and then filtered. The residue along with the filter paper is then placed in silica crucible and heated in muffle furnace till red hot. The residue left in the crucible gives the percentage of Calcium present in the soil.

Ammonia was added to the filtrate collected in previous step and filtered. The residue along with the filter paper was then placed in silica crucible and heated in muffle furnace till red hot. The residue left in the crucible gives the percentage of Magnesium present in the soil.

The pH of the soil was determined by the electrometric method as per IS: 2720 (part 26) - 1987. The cation exchange capacity of the soil was determined as per IS: 2720 (Part 24) - 1976. The specific surface area of the soil was determined as per ASTM C837, Methylene blue titration method. The chemical properties of sandy clay soil are reported in Table. 2.

C. Additives Used

Ordinary Portland Cement and lime were considered in the present investigation. The chemical properties of these additives are reported in Table. 3.

Table. 1 Geotechnical properties of Sandy clay soil

| Sl. No		Property	Parameter values
1		Specific Gravity	2.64
2		Bulk unit weight (kN/m^3)	18.54
3		In-situ void ratio	0.85
4		Grain Size Distribution (%)	
	a	Gravel	-
	b	Sand	64
	c	Silt	14
	d	Clay	22
5		Soil Classification	
	a	I.S Soil classification	CI
6		Atterberg's Limit (%)	
	a	Liquid Limit	45
	b	Plastic Limit	21
	c	Plasticity Index	24
7		Compaction Characteristics (Standard Proctor Test)	
	a	OMC (%)	17.28
	b	Maximum Dry Density (kN/m^3)	18.25
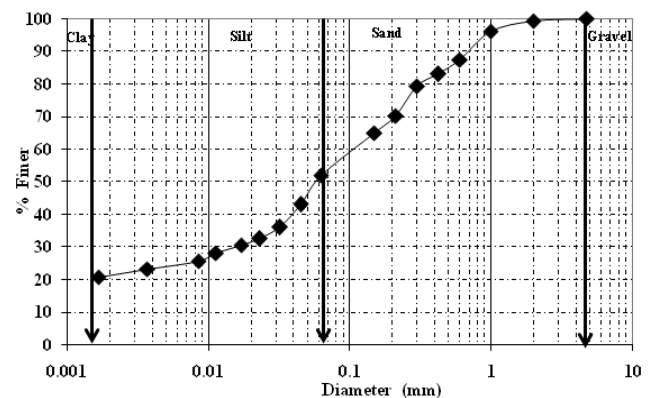
Fig. 1 Grain size distribution curve for sandy clay soil

D. Sample preparation

Unconfined compressive strength tests (UCS) were performed on natural and stabilized soil specimens to evaluate the suitability of stabilizers to achieve the target strength. Cement, lime and combination of lime & cement in 1:1 ratio were considered. The soil was sieved through a 2mm sieve to remove pieces of shell and other coarser particles.

Table. 2 Chemical properties of natural sandy clay soil

Parameter	Sandy clay soil
SiO_2	68.30%
Fe_2O_3	6.20%
Al_2O_3	13.3%
CaO	3.10%
MgO	7.5%
Others	1.6%
pH	7.53
Specific surface area	$30m^2/gm$
Cation exchange capacity	49.35milli equivalence/100gm
Organic matter	1.86%

Table. 3 Chemical properties of additives

Parameter	Ordinary Portland Cement	Lime
SiO_2	21.7%	2.50%
Fe_2O_3	4.2%	0.40%
Al_2O_3	5.0%	_
CaO	63.9%	92.40%
MgO	1.2%	1.50%
Others	4%	3.20%
pH	13.2	12.4

Cement treated specimens

Four different water/cement ratios were considered for each stabilizer combinations. The water content was adjusted to a range of liquidity indices (LI), ranging from LL to 2LL. The liquidity index has been used in this investigation as an indicator to refer to the initial water content of the clays in relation to their plasticity characteristics before the cement is admixed. Sandy clay soil was mixed with water content corresponding to the above levels of LI and the samples were thoroughly mixed with the different cement contents (in paste form) to attain the target Wc/C. The target Wc/C values were 5, 10, 15 and 20. The mixing time was arbitrarily fixed at 10 minutes as recommended by Miura et al. (2001). When cement is added to the soil, it absorbs water due to the hydration i.e., the chemical reaction between cement and water. For hydration process, the cement consumes water equal to 40% of its mass (Neville, 1996). This may mask the role of high water content used in the present study. Hence, the cement paste was prepared separately by mixing cement with de-ionized water equal to 0.4 times the mass of cement. Finally, both the soil paste and the cement paste were mixed thoroughly and this uniform paste was transferred to a cylindrical mould of 38mm diameter and 80mm height. The specimens were prepared by placing the stabilizer treated soils at high water content, in three equal layers into the split mould and gently tapping it on a rubber pad to remove the entrapped air. Since high water contents were used in the present study, high vacuum silicon grease was used to prevent any leakage of water from the split mould. The specimens along with the split mould were kept in desiccators for curing. After the specimens gained enough strength, they were taken out of the split mould and once again kept in desiccators for curing. The duration of keeping the specimens along with the split mould depends on the type of soil, initial water content, type of stabilizer and stabilizer content. All the cylindrical samples were carefully wrapped in vinyl bags and they were stored in humid conditions at constant temperature (27±2°C). Cement treated samples were compacted immediately after mixing. For cement treated samples the moulding water content are 1LL, 1.5LL and 2LL.

Lime treated specimens

To study the effect of the hydrated lime for stabilization of sandy clay, lime content was varied from 4 to 10%. The unconfined compressive strength specimens of soil lime mixtures were prepared by initially mixing the soil and water to form a soil paste. For lime treated samples the moulding water content are OMC, 0.5LL and 0.75LL. While preparing the specimens of soils treated with hydrated lime for the unconfined compressive strength tests, it was observed that when dry hydrated lime powder was added to the soil, it absorbed the water present in the soil and there was a noticeable change in the consistency of the soil lime mixture. This will interfere with the role of water content in soil stabilization. Therefore, some water was added to lime powder to prepare lime paste. By trial and error, it was found that by using water content equal to 100% weight of lime too much of change was not observed in the consistency of the specimen. Therefore, additional water content required for water lime ratio (lime water content) has been provided in the preparation of specimens. The soil-water and lime-water mixtures were stored in an airtight, waterproof bag for 1-24 hours prior to fabricating the test specimens as per ASTM D5102. Finally both soil paste and lime paste were mixed thoroughly and placed into the split mould. Samples were prepared by static compaction to achieve desired density. The specimens along with the split mould were kept in desiccators for curing. After the specimens gained enough strength, they were taken out of the split mould and once again kept in desiccators for curing. The specimens were cured in desiccators at 100% humidity ensuring the availability of water for cementitious reactions. They were taken out after curing periods of 7, 14 and 28 days and tested.

The untreated soil samples were tested immediately after compaction, whereas the stabilized soil samples were cured in humid conditions till the desired curing periods prior to testing. After the curing period, the samples were soaked in water for one day. Porous stones were placed at the top and bottom of the treated samples which was covered by a membrane in order to prevent the entry of water from the sides. Then the samples were submerged in water bath and allowed to saturate by capillary action for 24 hours. After this,

Table. 4 Experimental program for additive stabilized sandy clay soil compacted at MDD

Sl. No.	Stabilizer type	Wc/A Ratio	% of additives added	Water content	Curing period (Days)	Test condition	Type of test
1	Cement (OPC 53 GRADE)	20	2.25	LL	7,14, 28 & 56 Days	Soaked	Unconfined Compressive Strength
		15	3.00				
		10	4.50				
		5	9.00				
		20	3.38	1.5LL	7,14, 28 & 56 Days	Soaked	Unconfined Compressive Strength
		15	4.50				
		10	6.75				
		5	13.50				
		20	4.50	2LL	7,14, 28 & 56 Days	Soaked	Unconfined Compressive Strength
		15	6.00				
		10	9.00				
		5	18.00				
2	Hydrated Lime	4.32	4	OMC	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		2.88	6				
		2.16	8				
		1.73	10				
		5.63	4	0.5LL	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		3.75	6				
		2.81	8				
		2.25	10				
		8.44	4	0.75LL	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		5.63	6				
		4.22	8				
		3.38	10				
3	Hydrated Lime + Cement (1:1)	8.64	1+1	OMC	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		4.32	2+2				
		11.25	1+1	0.5LL	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		5.63	2+2				
		16.88	1+1	0.75LL	7,14 & 28 Days	Soaked	Unconfined Compressive Strength
		8.44	2+2				

the samples were air dried for 30 minutes before UCS testing. The rate of vertical displacement in UCS tests was 1mm/min. The tests were carried out until the sample fails or 20% axial strain is achieved. Table. 4 provides the details of experimental investigation. The moulding water content varies from OMC to 2LL and the additive content varies from 2.25% to 18%.

III. RESULTS AND DISCUSSIONS

A. Effect of Cement on the Strength of Sandy Clay Soil at High Water Contents

Mixing cement with soil reduces the liquid limit, plasticity index and the potential for volume change of soils. It increases the shrinkage limit and shear strength. The strength development in cement treated soils is by primary and secondary cementitious reactions in the soil cement matrix. The primary cementation is by hydration products of Portland cement phases. A variety of different compounds and gels are formed by hydration reaction. A Portland cement particle is a heterogeneous substance, containing tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and a solid solution described as tetracalcium alumino – ferrite (C_4AF).

Table. 5 shows the results of unconfined compressive strength test on samples stabilized with 2.25 to 18% of cement keeping clay water to cement ratio as constant (20, 15, 10 & 5) and cured for 7, 14, 28 and 56 days at 1.0LL, 1.5LL and 2.0LL water content. It is observed that, the rate of strength development in cement stabilized soils vary depending on the cement contents. The results indicate that, the water content plays an important role as recognized by factor such as water to cement ratio. The strength increases by a factor of 2 to 100

Table. 5 Unconfined compressive strength of cement stabilized sandy clay soil at high water contents

Water content	W_c/C Ratio	Cement content (%)	UCC strength of untreated sandy clay soil (kPa)	Unconfined compressive strength (kPa)				Ratio of strength increase		
				7 Days	14Days	28Days	56Days	7/0	28/0	56/0
1LL	20	2.25	21.00	52.84	76.46	199.16	210.06	2.52	9.48	10.00
	15	3		76.60	145.30	210.60	270.10	3.65	10.03	12.86
	10	4.5		395.56	500.50	890.14	1074.53	18.84	42.39	51.17
	5	9		674.78	840.73	1280.03	1496.30	32.13	60.95	71.25
1.5LL	20	3.38	14.00	50.56	72.16	120.30	160.46	3.61	8.59	11.46
	15	4.5		85.12	120.10	165.90	230.45	6.08	11.85	16.46
	10	6.75		250.15	327.68	500.60	790.35	17.87	35.76	56.45
	5	13.5		425.40	610.60	1050.56	1276.44	30.39	75.04	91.17
2LL	20	4.5	10.50	48.67	73.29	103.25	145.97	4.64	9.83	13.90
	15	6		54.24	110.32	150.61	164.54	5.17	14.34	15.67
	10	9		104.60	189.75	359.38	492.89	9.96	34.23	46.94
	5	18		152.55	271.54	732.62	1076.35	14.53	69.77	102.51

Table. 6 Rate of UCS strength for different cement content and curing periods

Water content	Wc/C Ratio	Cement content (%)	Rate of strength gain (kPa per day)			
			0 to 7 days	7 to 14 days	14 to 28 days	28 to 56 days
LL	20	2.25	4.55	3.37	8.76	0.39
	15	3.00	7.94	9.81	4.66	2.13
	10	4.50	53.51	14.99	27.83	6.59
	5	9.00	93.40	23.71	31.38	7.72
1.5LL	20	3.38	5.22	3.09	3.44	1.43
	15	6.75	10.16	5.00	3.27	2.31
	10	13.50	33.74	11.08	12.35	10.35
	5	9.00	58.77	26.46	31.43	8.07
2LL	20	4.50	5.45	3.52	2.14	1.53
	15	6.00	6.25	8.01	2.88	0.50
	10	9.00	13.44	12.16	12.12	4.77
	5	18.00	20.29	17.00	32.93	12.28

compared to the unstabilized UCS depending on the curing period and cement content.

The rate of strength gain per day is maximum during the first 7 days when the water content is at LL. When water content is 1.5LL, the rate of strength gain is maximum during 7 to 14 days. At any given water content and curing period, the rate of strength gain increases with increase in Wc/C ratio.

Effect of Cement Content

Fig. 2 shows the variation of unconfined compressive strength at different water contents on sandy clay soil stabilized with 2.25 to 18% cement under soaked condition for curing period up to 56 days. The natural soil has a very low value of UCS less than 20kPa under untreated conditions. The unconfined compressive strength increases from a low value of 20kPa to as high as 1496.3kPa depending on cement content and curing period. It is observed that when the cement content is low, cement (Wc/C = 20 and 15) stabilized sandy clay soil shows very low strength at high water content for 7 days curing period. During this phase the primary reaction components (hydration products) are not formed fully as the cement content is low when compared to samples prepared at Wc/C ratios of 10 and 5. When the sample contains substantial cement content (Wc/C ratios of 10 and 5) the calcium silicates and calcium aluminates (hydration compounds) are formed and the cement particles bind the adjacent cement grains together during hardening and form a hardened skeleton matrix, which encloses unaltered soil particles. The silicate

and aluminate phases are internally mixed, so it is most likely that none is completely crystalline. When the cement content is sufficiently high, the hydration products induce cementation between the soil particles and the treated sample shows higher strength. In these cases, as the curing period increases alkaline conditions prevail in the pore fluid zone due to dissolution of hydrated lime. The silica and alumina from both clay minerals and amorphous materials on the surface of clay particles get dissolved and which in turn react with the calcium ions from the hydrolysis of cement to form insoluble compounds which hardens when cured to stabilize the soil. When the initial water content is 1LL, a minimum of 5% cement is necessary for a reasonable strength gain of 400kPa. When the initial water contents are more than 1LL (1.5LL and 2LL), very high cement content i.e., more than 10% is required for a minimum strength of 100kPa. The pattern of strength gain is similar in both cases i.e., at 1.5LL and 2LL. When the water content is in excess of LL, the stabilized strength at 7 and 14 days is relatively low even at high cement content mainly because of the increased capillary pore size and lower level of crystalline structure. In these cases, longer curing periods and lower water content to cement ratio are beneficial to attain desired strength to be able to sustain the infrastructure on soft grounds at high water contents corresponding to liquid limit and in excess of liquid limit water contents.

This has clearly brought out the importance of clay water/cement ratio on the strength of cement treated soft soils. The effect of micro fabric [4], [9], [14] also plays a significant role in the development of strength particularly at high water contents due to capillary pore. This depends on both effective stress and liquid limit water content. The pore diameter varies from 200Å up to 10000Å units as the water content increase to liquid limit [14]. This suggests that the micro fabric of sandy clay at high water content depends on the water content. Even at constant cement content of say 4.5%, the strength decreases significantly from 1074kPa to 145kPa as the water content increases from LL to 2LL. This is attributed to increased capillary pore size with increase in water content.
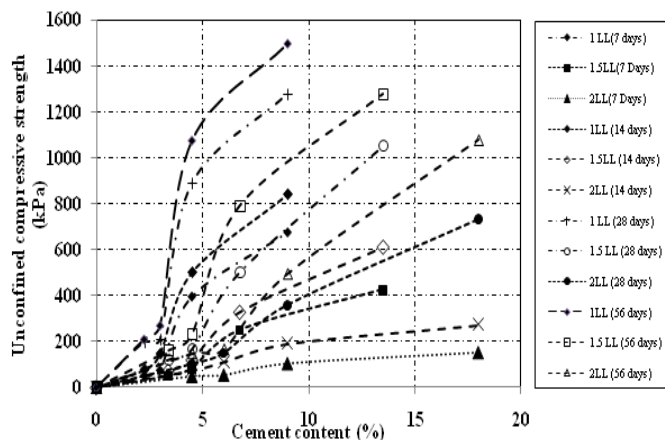

Fig. 2 Variation of unconfined compressive strength of sandy clay soil with cement content for various initial water contents cured for 7, 14, 28, 56 days

Effect of Curing Period

Fig. 3 shows the variation of unconfined compressive strength with curing period at water contents of 1.0LL, 1.5LL and 2.0LL under soaked condition treated with different cement contents. At lower cement contents (<4.5%) and water contents in excess of liquid limit (i.e., 1.5LL & 2LL), the strength gain is insignificant irrespective of curing period. At high water contents, cement content in excess of 7% and curing periods greater than 7 days yields reasonable strength in excess of 400kPa.

At liquid limit water contents a minimum cement content of 3% and higher curing period of 56 days is necessary to attain a reasonable strength of 270kPa. Cement content in excess of 3% is beneficial and strength gain is significant with increase in curing period.

The UCS variation shows three distinct trends with increase in curing period. The UCS is low at 2.25% and it will attain a strength of 270kPa at 3% cement content cured for 56 days. Similar UCS values can be obtained at higher cement contents with increase in water content. With the addition of 3% cement the unconfined compressive strength increases from 77kPa to 270kPa, with the addition of 4.5% cement the unconfined compressive strength increases from 396kPa to 1075kPa, with the addition of 9% cement the unconfined compressive strength increases from 675kPa to 1496kPa with a curing period of 7 to 56 days.
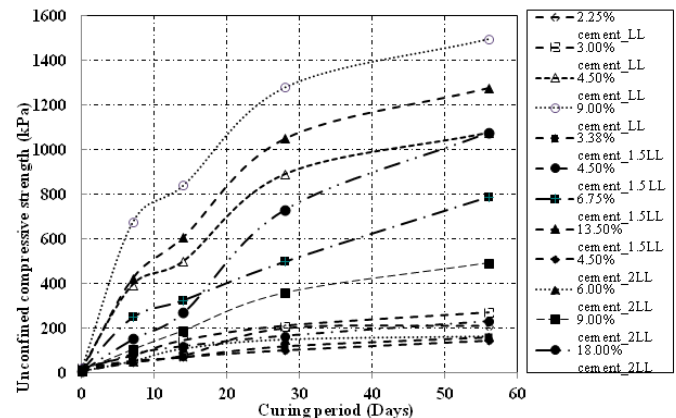

Fig. 3 Variation of unconfined compressive strength of sandy clay with curing period for various initial water contents and cement contents

B. Effect of Lime on Unconfined Compressive Strength

Soil stabilization occurs when lime is added to a reactive soil to generate long term strength gain through pozzolanic reactions. These reactions produce stable calcium silicate hydrates and calcium aluminate hydrates as the calcium from the lime reacts with the aluminates and silicates solubilized from the clay. The pozzolanic reaction will continue for a very long period of time, even for decades as long as enough lime is present and the pH remain high (above 10). As a result, lime treatment can produce high and long lasting strength gains. The key to pozzolanic reactivity and stabilization is a reactive soil, a good mix design protocol and reliable construction practices.

A basic understanding of clay mineralogy and proper lime-soil mix that satisfy all cation replacement and exchange reactions and provide enough residual lime for the pozzolanic reactions will ensure development of adequate strength of lime stabilized soils.

In stabilization of soil using lime, quantity of lime plays a major role. The strength of sandy clay soil increases with increase in lime content up to certain limit, then the rate of increase in strength is negligible or even decreases. This lime content is called the optimum lime content for soil. The selection of optimum amount of lime is very important factor both for economical and technical reasons. When excess lime is added, it acts as a filler material resulting in lowering strength. The optimum lime content depends on the clay content of the soil and the reactive silica. The soluble silica increases as the fineness of clay increases and the lime required to completely react with this silica increases. Water content is essential for pozzolanic reaction to produce gelatinous compounds. Effective formation of pozzolanic compounds does not take place when sufficient quantity of water is not available for soil lime reaction. On the other hand, when water is more than required, the soil particle distance increases which lead to lowering of strength because of ineffective binding by pozzolanic reaction compounds. Hence, type of clay and water content present in the system influence the optimum lime content. Thus at optimum moisture content, optimum lime content required for effective stabilization of soil is found to be 3 to 6%. Cylindrical samples were prepared at the respective optimum moisture content and water contents of 0.5LL & 0.75LL for the determination of unconfined compressive strength.

Table. 7 shows the results of unconfined compressive strength test on samples stabilized with 4, 6, 8 & 10% of lime and cured for 7, 14 & 28 days at OMC, 0.5LL & 0.75LL water contents. It is observed that, the rate of strength development in lime stabilized soils vary depending on the range of lime contents. However, the water content also plays an important role as recognized by factor such as water to lime ratio. The data in Table. 8 suggests that the strength gain per day is highest till 7 days and significant till 14 days, however the rate of increase is low between 14 to 28 days.

Fig. 4 shows the variation of unconfined compressive strength with lime content at different initial water contents on samples cured for 7 to 28 days on sandy clay soil specimens stabilized with 4, 6, 8 and 10% lime under soaked condition. UCS values show a general trend of decrease with increase in water content and increase with increase in curing period. The results show a similar trend and the treated assemblies at OMC show higher strength development. There is a linear increase in strength till 4% lime content for 14 & 28 day cured samples and beyond 4% the increase in UCS is marginal. However, for 7 day cured specimens 6% is optimum.

Fig. 5 shows the variation of unconfined compressive strength of lime stabilized sandy clay soil at different water contents obtained from unconfined compressive strength tests on 7, 14 and 28 days cured sandy clay soil stabilized with 4 to 10% lime under soaked condition. The trend of strength increase is similar in all cases. The variation in UCS values is

similar in all cases, the strength increase is significant up to 14 days and beyond 14 days there is decrease in the rate of strength development. The maximum UCS value is 300kPa for 28 day cured sample with initial water content corresponding to OMC.
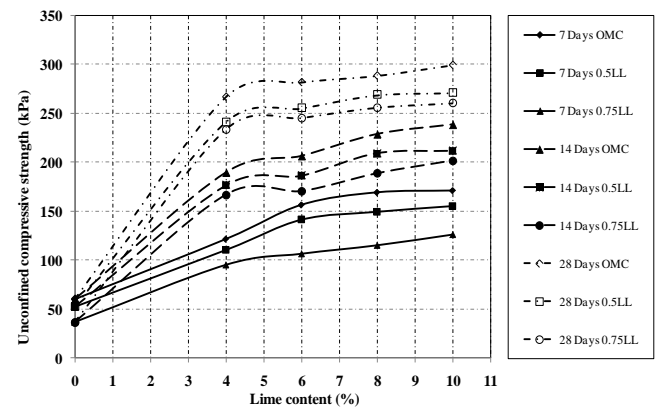

Fig. 4 Variation of unconfined compressive strength of sandy clay with lime content cured for 7, 14, and 28 days at different moulding water contents
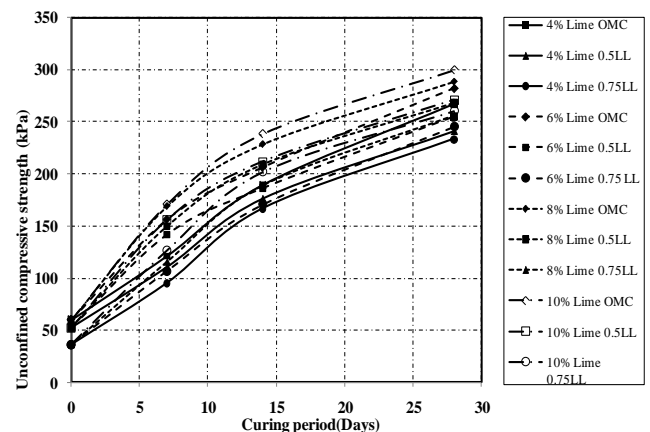

Fig. 5 Variation of unconfined compressive strength of sandy clay with curing period for different lime contents and different water contents

C. Effect of Cement and Lime on the Strength of Sandy Clay Soil at High Water Contents

Cement performs the role of a binder material that binds the constituents in soil stabilization. In fine-grained soils a pozzolanic reaction occurs between the calcium hydroxide released from cement during hydration. The soil alumina and silica are the important aspects of soil stabilization process. Cement and lime may be used successfully in stabilizing granular and fine-grained soil as well as aggregate materials due to the presence of calcium hydroxide (lime). Cement and lime have been found to be effective in stabilizing a wide variety of soils including granular materials, silts and clays.

Since lime does not contribute to desired strength, combination of cement and lime are used in 1:1 proportion for additive percentage of 1% and 2% (lime + cement) for water contents varying from OMC, 0.5LL & 0.75LL for curing periods of 7, 14 & 28 days. The cured samples were soaked as

explained earlier and UCS tests were carried out. Table. 9 shows the results of unconfined compressive strength test. It is observed that, the rate of strength development in lime and cement stabilized soils vary depending on the range of lime and cement contents. The results indicate that the water content plays an important role as recognized by factor such as water to lime and cement ratio.

Fig. 6 shows the variation of unconfined compressive strength of soil stabilized with lime and cement content at different water contents on 7, 14 and 28 days cured soil stabilized with 1 and 2% lime and cement in 1:1 proportions

under soaked condition. The 7 days strength is linear for both combinations. The 14 and 28 days results show distinct trend. Samples cured for 28 days show good strength. The optimum additive content is 1% for all the water contents giving a UCS value 400kPa.

The rate of strength gain is very effective till 28 days and is nearly uniform in all the three curing periods. The rate of strength gain is significant over various curing periods. Addition of 1% cement has produced enough bonding and has clearly negated the influence of initial water content.

Table. 7 Unconfined compressive strength of lime stabilized sandy clay at different initial water contents and curing periods

Water content	Wc/L Ratio	Lime (%)	UCS strength of untreated Sandy clay soil (kPa)	7 Days	14 Days	28Days
OMC	4.32	4	60	121.28	189.25	266.85
	2.88	6		156.14	206.185	281.85
	2.16	8		168.87	228.5	288.6
	1.73	10		170.72	238.3	299.5
0.5 LL	5.63	4	52	110.36	176.1	241.05
	3.75	6		141.491	186.1	255.05
	2.81	8		149.61	209.16	268.5
	2.25	10		155.52	211.61	270.853
0.75 LL	8.44	4	36	95.1	166.54	233.411
	5.63	6		106.56	170.273	245.18
	4.22	8		115.29	188.5	255.729
	3.38	10		126.36	201.6	260.28

Table. 8 Rate of UCS strength for different lime contents and curing periods

Water content	Lime content (%)	Rate of strength (kPa per day)		
		0 to 7 days	7 to 14 days	14 to 28 days
OMC	4	10.03	9.71	5.54
	6	15.01	7.15	5.40
	8	16.83	8.52	4.29
	10	17.09	9.65	4.37
0.5LL	4	10.05	9.39	4.64
	6	14.50	6.37	4.93
	8	15.66	8.51	4.24
	10	16.51	8.01	4.23
0.75LL	4	9.14	10.21	4.78
	6	10.78	9.10	5.35
	8	12.03	10.46	4.80
	10	13.61	10.75	4.19

stabilized with 1% and 2% are being taken from Fig. 4 and are compared with 1:1 & 2:2 lime+cement combination. With this comparison, the strength development with 1% and 2% cement can be determined. It can be concluded that the strength development is more due to cement rather than lime.

IV. UNCONFINED COMPRESSIVE STRENGTH PREDICTION

The UCS results have indicated the dependence of strength of soft sandy clay on Wc/C ratio and curing period. The results have also confirmed the fact that strength increases when Wc/C ratio is low and vice versa [20]. In this background, the strength development can be analysed using the concept of Abram's law for additive treated soils. This concept has been successfully adopted [9], [10], [15], [20] to predict strength development for cement stabilized soils. The Power function of the following form is widely used to predict the strength development of cement stabilized coarse [15] and fine grained soils [20].

$$q_u = \frac{A}{(w_c / C)^B} \qquad (1)$$

Where, q_u = Unconfined compressive strength, A and B are empirical constants

The parameter 'A' accounts for soil type & curing time and 'B' is generally taken as a constant though it varies over a narrow band for a particular soil.

Table. 11 Unconfined compressive strength of sandy clay soil stabilized with lime, cement and lime+cement at different water contents

Curing Period (Days)	Additive Content	Unconfined Compressive Strength (kPa)					
		Lime		Cement		Lime + Cement	
		1%	2%	1%	2%	1%	2%
7	OMC	76	80	50	120	126	200
14		93	129	146	161	239	290
28		115	170	291	312	406	482
7	0.5 LL	68	76	53	112	121	188
14		84	119	159	183	243	302
28		103	150	316	337	419	487
7	0.75 LL	50	68	70	88	120	156
14		70	105	143	152	213	257
28		89	140	300	327	389	467

Fig. 8 shows the present experimental values of unconfined compressive strength with clay water/cement ratio for curing periods of 7 to 56 days. The results indicate that the UCS of the soil for low Wc/C ratio is higher and vice versa. The strength can be expressed in the form of a power function (1).

The empirical constant A varies from values of 11131 to 20114 and 'B' over a narrow band from 1.75 to 1.54 as the curing period varies from 7 to 56 days.

Table. 12 Percentage of unconfined compressive strength of sandy clay soil stabilized with lime and cement at different water contents

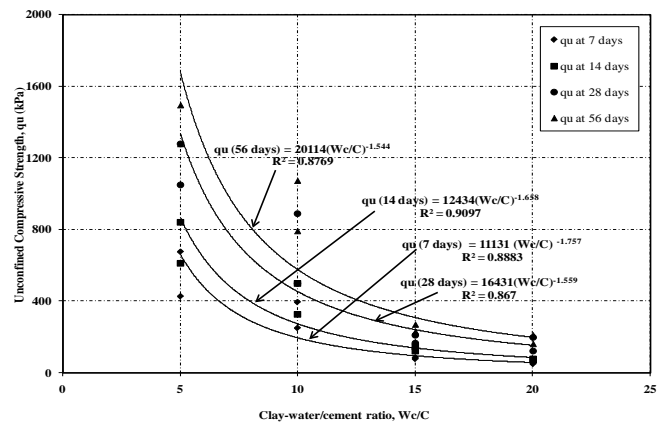| Curing Period (Days)	Additive Content	Unconfined Compressive Strength (%)			
		Lime		Cement	
		1%	2%	1%	2%
7	OMC	60.32	40.00	39.68	60.00
14		38.91	44.48	61.09	55.52
28		28.33	35.27	71.67	64.73
7	0.5 LL	56.20	40.43	43.80	59.57
14		34.57	39.40	65.43	60.60
28		24.58	30.80	75.42	69.20
7	0.75 LL	41.67	43.59	58.33	56.41
14		32.86	40.86	67.14	59.14
28		22.88	29.98	77.12	70.02

Fig. 8 Unconfined Compressive Strength (UCS) vs. Clay-water/Cement ratio (Wc/C)

Using the (1), the stabilized strength at any curing time 'D' and for a given Wc/C ratio can be expressed in terms of 28 day strength as shown below.

$$\left\{ \frac{q_{(Wc/C)_D}}{q_{(Wc/C)_{28}}} \right\} = \left[\frac{(Wc/C)_{28}}{(Wc/C)_D} \right]^D \qquad (2)$$

Where, D is the curing time (days) and q_D is strength at D days of curing

At a particular Wc/C ratio, the strength development depends on curing time. A linear regression of the test data yields the following relation (3) and is applicaple for high Wc/C ratio of 20 and 15 but liquidity index between 1 and 2.

$$\frac{q_D}{q_{28}} = 0.2475nD - 0.2253 \qquad (3)$$

Where, D is the curing time (days) and q_D is strength at D days of curing

The generalized interrelationship for strength prediction based on Wc/C and curing period can be expressed as (4) below for cement stabilized sandy clay.

$$\left\{ \frac{q_{(Wc/C)_D}}{q_{(Wc/C)_{28}}} \right\} = \left[\frac{(Wc/C)_{28}}{(Wc/C)_D} \right]^{1.54} (0.2475 \ln D - 0.2253) \qquad (4)$$

Where, $q(W_c/C)_D$ - strength of cement admixed sandy clay to be estimated at sandy clay-water/cement ratio (W_c/C) after D days of curing

$q(W_c/C)_{28}$ – strength of cement admixed sandy clay at clay-water/cement ratio (W_c/C) after 28 days of curing

The value of B in (4) is determined on trial basis for minimum error in the predicted strength.

Table. 13 shows the experimental results and predicted strength values. The predicted strength values compares well

Table. 13 U.C.S Strength Prediction for Cement treated Sandy clay soil

Water Content	Curing time	Cement content	Clay water content	Clay water/ cement, Wc/C ratio	Laboratory strength	Predicted strength	Percent error qup-qul/qulx100
	days	C (%)	wc(%)	wc/C	qul(Kpa)	qup(Kpa)	(%)
LL	7	2.25	45.00	20.00	52.84	51.05	3.393
	14	2.25	45.00	20.00	76.46	85.21	11.449
	28	2.25	45.00	20.00	199.16	119.38	40.058
	56	2.25	45.00	20.00	210.06	153.55	26.903
1.5LL	7	3.375	67.50	20.00	50.56	51.05	0.964
	14	3.375	67.50	20.00	72.16	85.21	18.090
	28	3.375	67.50	20.00	120.3	119.38	0.764
	56	3.375	67.50	20.00	160.46	153.55	4.308
LL	7	3.00	45.00	15.00	76.6	79.50	3.788
	14	3.00	45.00	15.00	145.3	132.71	8.662
	28	3.00	45.00	15.00	210.6	185.93	11.716
	56	3.00	45.00	15.00	270.1	239.14	11.463
1.5LL	7	4.50	67.50	15.00	85.12	79.50	6.600
	14	4.50	67.50	15.00	120.1	132.71	10.503
	28	4.50	67.50	15.00	165.9	185.93	12.071
	56	4.50	67.50	15.00	230.45	239.14	3.770
Mean Absolute Percent Error, MAPE							10.906

Table. 14 Empirical Constants of Sandy clay Soil stabilized with different additives

Additives	Empirical constants	Curing Period (days)				Average Values of A & B	Optimum value of B for minimum percentage error
		7days	14days	28days	56days		
Cement	A	5391.9	5945.5	8009.5	8507.3	6963.5	
	B	1.55	1.31	1.26	1.18	1.32	1.54
Lime	A	222.5	268.7	317.9	-	269.7	
	B	0.41	0.24	0.10	-	0.25	0.39
Lime + Cement	A	352.2	443.5	634.4	-	476.7	
	B	0.41	0.24	0.17	-	0.27	0.19

with the experimental values and the mean absolute percent error (MAPE) is around 10%. The (4) can be used for strength prediction of cement treated soft sandy clay soil.

Similarly, the strength prediction equations for the sandy clay soil treated with Lime, Lime+Cement have been developed as mentioned in (5) and (6) respectively. The

optimum value of A and B for different additives are reported in Table. 14.

U.C.S Strength Prediction equation for Lime

$$\left\{ \frac{q_{(Wc/L)_D}}{q_{(Wc/L)_{28}}} \right\} = \left[\frac{(Wc/L)_{28}}{(Wc/L)_D} \right]^{0.39} (0.3\ln D - 0.2) \qquad (5)$$

Where, W_c/L = Clay water – Lime ratio

$q_{(Wc/L)_D}$ = Strength estimated at a clay- water/lime ratio of $(W_c/L)_D$

$q_{(Wc/L)_{28}}$ = Strength estimated at a clay- water/ lime ratio of $(W_C/L)_{28}$

D = Curing time(days)

q_D =strength at D days of curing

U.C.C. Strength Prediction equation for Lime+ Cement

$$\left\{ \frac{q_{(Wc/(L+C))_D}}{q_{(Wc/(L+C))_{28}}} \right\} = \left[\frac{(Wc/(L+C))_{28}}{Wc/(L+C))_D} \right]^{0.19} (0.51\ln D - 0.65) \qquad (6)$$

Where, $Wc/(L+C)$ = Clay water/ (Lime+Cement) ratio

$q_{(Wc/(L+C))_D}$ = Strength estimated at a clay water/(Lime + Cement) of $(W_c/(L+C))_D$

$q_{(Wc/(L+C))_{28}}$ = Strength estimated at a clay water/ (Lime +cement) of $(W_C/(L+C))_{28}$

D = Curing period in days

q_D = Strength at D days of curing

Tables. 15 and 16 show the experimental results and predicted strengths for both lime and lime+cement treated sandy clay soils. The predicted strength values compares well with experimental values and the mean absolute percent error (MAPE) is around 12% and 10% respectively.

Effect of Atterberg Limits on the strength prediction constantants S and B

The parameters S, B and a are listed in Table. 17.

$$\left\{ \frac{S_D}{S_{28}} \right\} = a + S \ln(D)$$

$$q_u = \frac{A}{(w_c/C)^B}$$

Where, S_D is the UCS at curing period D days

S_{28} is the UCS at curing period 28 days

A, B, are constants

S and B are strength prediction parameters

From the Fig. 9, it is found that the value of parameter 'S' varies between 0.2 and 0.3 for clayey soils irrespective of plasticity index (Ip) of soils.

Similarly from Fig. 10, it is found that the value of parameter 'a' varies between 0 and 0.1 for CH soils and -0.05 to -0.30 for CM/CI soils irrespective of plasticity index (Ip) of soils.
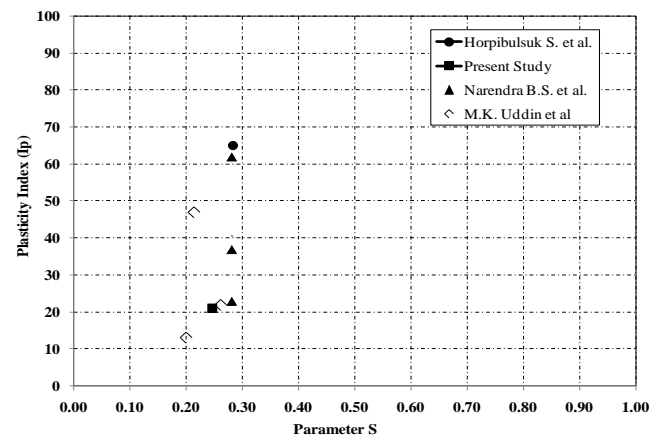

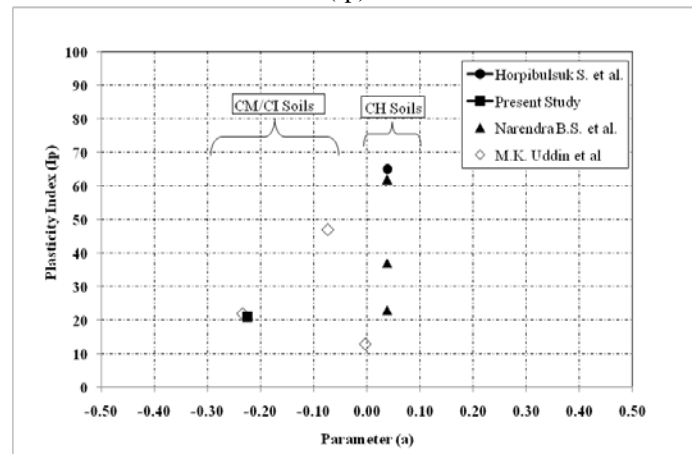Fig. 9 Strength prediction parameter (S) vs. Plasiticity Index (Ip)

Fig. 10 Strength prediction parameter (B) vs. Plasiticity Index (Ip)

V. CONCLUSIONS

The conclusions drawn from this study are summarized below.

➤ With cement stabilization, the unconfined compressive strength increases by a factor of 2 to 100 depending on the water content, cement content and curing period.

➤ At a particular additive content, the unconfined compressive strength decreases significantly with the increase in water content and this is due to increased capillary pore size with increase in water content.

➤ For water contents ranging from OMC to LL, addition of lime increases the unconfined compressive strength as a function of curing period and lime content. The optimum lime content is 4% for a curing period of 28 days.

➤ Combination of lime and cement in equal proportion of 1:1 gives better strength with the curing period when compared with lime alone.

➤ For sandy clay treated with lime + cement, the strength development is mainly attributed of cement.

➤ Longer curing periods and lower clay water/additive ratio is very effective for attaining desired strength.

➤ The proposed relationships for strength prediction based on clay water/additive ratio and curing period are very useful

to estimate the laboratory strength of sandy clay stabilized with corresponding additives.

➤ For clayey soils, parameter 'S' varies from 0.2 and 0.3 irrespective of plasticity index (Ip) of soils.

➤ Parameter 'a' varies from 0 to 0.1 for CH soils and -0.05 to -0.30 for CM/CI soils irrespective of plasticity index (Ip) of soils.

Table. 15 U.C.S Strength Prediction for Lime treated sandy clay soil

Water content	Curing time (Days)	Lime content, L (%)	Clay water content, Wc(%)	Clay water/ Lime ratio Wc/L	Laboratory strength qu-l (kPa)	Predicted strength qu-p (kPa)	% Error $\dfrac{q_{u-p} - q_{u-l}}{q_{u-l}} X100$
Lime (4%)							
OMC	7	4	17.29	4.32	121.2789	139.17	14.752
	14	4	17.29	4.32	189.25	205.89	8.790
	28	4	17.29	4.32	266.85	272.60	2.155
0.5LL	7	4	22.50	5.63	110.36	125.58	13.794
	14	4	22.50	5.63	176.1	185.79	5.500
	28	4	22.50	5.63	241.05	245.99	2.049
0.75LL	7	4	45.00	11.25	95.1	95.84	0.774
	14	4	45.00	11.25	166.54	141.78	14.868
	28	4	45.00	11.25	233.411	187.72	19.575
Lime (6%)							
OMC	7	6	17.29	2.88	156.14	163.01	4.401
	14	6	17.29	2.88	206.185	241.16	16.962
	28	6	17.29	2.88	281.85	319.30	13.288
0.5LL	7	6	22.50	3.75	141.491	147.10	3.963
	14	6	22.50	3.75	186.1	217.62	16.935
	28	6	22.50	3.75	255.05	288.13	12.971
0.75LL	7	6	45.00	7.50	106.56	112.26	5.345
	14	6	45.00	7.50	170.273	166.07	2.469
	28	6	45.00	7.50	255.18	219.88	13.833
Lime (8%)							
OMC	7	8	17.29	2.16	168.87	182.37	7.992
	14	8	17.29	2.16	228.5	269.79	18.070
	28	8	17.29	2.16	288.6	357.21	23.775
0.5LL	7	8	22.50	2.81	149.61	164.56	9.995
	14	8	22.50	2.81	209.16	243.45	16.396
	28	8	22.50	2.81	268.5	322.34	20.053
0.75LL	7	8	45.00	5.63	115.29	125.58	8.928
	14	8	45.00	5.63	188.5	185.79	1.440
	28	8	45.00	5.63	255.729	245.99	3.809
Lime (10%)							
OMC	7	10	17.29	1.73	170.72	198.95	16.535
	14	10	17.29	1.73	238.3	294.32	23.509
	28	10	17.29	1.73	299.5	389.69	30.115
0.5LL	7	10	22.50	2.25	155.52	179.53	15.436
	14	10	22.50	2.25	211.61	265.59	25.509
	28	10	22.50	2.25	270.853	351.65	29.831
0.75LL	7	10	45.00	4.50	126.36	137.00	8.422
	14	10	45.00	4.50	222.29	202.68	8.822
	28	10	45.00	4.50	266.28	268.36	0.780
Mean Absolute Percent Error, MAPE							12.27

Table. 16 U.C.S Strength Prediction for Lime+Cement treated sandy clay soil

Water content	Curing time (Days)	Lime+Cement content (%)	Clay water content, Wc (%)	Clay water/ Lime+Cement ratio (Wc/(L+C))	Laboratory strength qu-l(kPa)	Predicted strength qu-p(kPa)	% Error $\dfrac{q_{u-p} - q_{u-l}}{q_{u-l}} X100$
Lime+Cement (1%+1%)							
OMC	7	2	17.29	8.65	119.84	140.43	17.178
	14	2	17.29	8.65	239.266	285.25	19.220
	28	2	17.29	8.65	406.34	430.08	5.842
0.5LL	7	2	22.50	11.25	126.28	133.57	5.774
	14	2	22.50	11.25	243.07	271.33	11.626
	28	2	22.50	11.25	418.57	409.09	2.266
0.75LL	7	2	33.75	16.88	156.04	123.67	20.746
	14	2	33.75	16.88	213.221	251.21	17.817
	28	2	33.75	16.88	389.43	378.75	2.742
Lime+Cement (2%+2%)							
OMC	7	4	17.29	4.32	188.912	160.19	15.202
	14	4	17.29	4.32	290.182	325.41	12.138
	28	4	17.29	4.32	481.995	490.62	1.789
0.5LL	7	4	22.50	5.63	200.211	152.37	23.894
	14	4	22.50	5.63	301.78	309.52	2.565
	28	4	22.50	5.63	486.648	466.67	4.105
0.75LL	7	4	33.75	8.44	120.644	141.08	16.935
	14	4	33.75	8.44	285.56	286.57	0.354
	28	4	33.75	8.44	466.969	432.07	7.474
Mean Absolute Percent Error, MAPE							10.426

Table. 17 Stabilization of different soils with cement with liquidity index (LI) <2.50

Soil No.	Soil Name	Atterberg Limits			IS Classification	Dry density γ_{dmax} (gm/cc)	OMC (%)	S	a
		LL (%)	PL (%)	PI (%)					
1	Bankok Clay (Sukraphiban district)	90	25	65	CH	γb = 14 - 16	wn = 89%	0.283	0.039
2	Indian Sandy Clay	45	21	24	SC	18.15	17.29	0.247	-0.225
4	Indian Black Cotton Soil	97	35	62	CH	11.48	36.50	0.281	0.038
5	Indian Brown Earth Soil	60	23	37	CH	14.32	28.3	0.281	0.038
7	Indian Red Earth Soil	38	15	23	CL	1.67	17.8	0.281	0.038
8	C1 Type Soil	78	31	47	CH	8.85	wn = 70%	0.23	-0.074
9	C2 Type Soil	47	25	22	CI	9.05	wn = 62%	0.261	-0.235
10	C3 Type Soil	33	20	13	CL	9.44	wn = 53%	0.2	-0.003

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