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Review Article

Performance of Terra Zyme for Soil Stabilization of Various Soil Groups

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Abstract - *The TerraZyme performance is evaluated by analyzing the changes in index and engineering properties for various stabilized soils classified according to IS Classification System (ISCS). The effect of enzyme dosages, curing period, and soil type on the properties of stabilized soils are investigated. The study also tries to correlate the effect of soils characteristics such as particle size distribution, consistency parameters, activity number, etc., on the degree of enzyme-based soil stabilization.*
The study attempts to showcase the maximum improvement for different treated soil groups that can be achieved for various index and engineering properties. It also expresses the comparative improvement status of various soil groups for the properties under consideration. The study also analyses the optimum enzyme doses and the duration of curing required to reach maximum improvement in various treated soil groups. Compared to all the soil groups, the CI-Soils exhibited the most prominent improvement in consistency limits, the maximum dry density, and Optimum Moisture Content, achieving a higher degree of stabilization. Clayey soils have shown maximum improvement in UCS values with curing duration. However, these soils require a higher curing duration to reach the maximum UCS value. MH-Soils attained maximum average percentage CBR value at comparatively smaller enzyme doses. The results of the finding are highlighted and discussed. The findings will be helpful for soil stabilization decisions using TerraZyme.

Keywords - *Soil Stabilization, TerraZyme, Soil Index properties, Engineering properties.*

1. Introduction

In soil stabilization, the soil is treated chemically or mechanically to improve its required engineering properties. Enzyme treatment is one of the non-traditional methods of soil stabilization.[1] The enzymes are proprietary, concentrated, nonbacterial, biodegradable preparations. They are supposed to minimize compaction efforts, increase the soil density and bearing capacity and thus lower the soil permeability.[2] The main advantages of these enzymes over other stabilizing additives are cost-effectiveness, eco-friendly, and convenience in use. They reduce environmental pollution due to carbon emission due to the use of common conventional soil stabilizers such as lime and cement.

TerraZyme is one of the frequently used enzymes. TerraZyme is an electrochemical enzyme product formulated to react with materials containing clay particles. The main ingredients of TerraZyme are nonionic surfactants and carbohydrates. It consists of fermented vegetable extract.

2. Literature Review

The enzyme stabilization is mostly based on empirical guidelines. The enzyme stabilization mechanism and conditions conducive to the stabilization are still not completely ascertained. Therefore, the correct stabilizer and material for stabilization must be chosen.[2] Enzymes' stabilizing performance would be expected to be very soil specific.[3] The fine organic matter and clay-sized particles are essential for bond formation and subsequent stabilization. As per the literature recommendations, the bio enzymes are effective for soils having a specified percentage of clay contents. Rauch et al. intimated that the soil should have clay minerals for reaction with other chemicals for effective bio enzyme stabilization. Enzymes are suitable for treating soils with high plasticity clays with an affinity for water and have some organic content for the enzymatic reaction.[4]

Bio-Enzyme treatment reduces compressibility and improves soil stability by optimizing consistency limits and indices with suitable enzyme doses and curing duration.[5] The degree of improvement in index and engineering properties of treated soils may be due to the reactivity of enzymes with soil chemical constituents with the Bio-Enzyme. So, it is recommended to examine the effect of Bio-Enzyme on soil in the laboratory before on-field applications.[6] The researchers suggested in several field applications that enzyme performance may have been negatively affected by the lack of clay content in the reclaimed layer.[7] However, literature also shows stabilization examples and improvements in SC, SM-GM, and SP-Soils with as low as 2% clay content. However, as Shankar et al. (2009***) observed,*** the enzyme is ineffective for soil with a higher percentage of cohesionless material.[4]

Several research studies are available on soil stabilization with TerraZyme. However, the experimental studies conducted to evaluate the enzyme's suitability as a soil stabilizer have revealed dissimilar performances. Hence, in this study, an attempt has been made to generalize the effects of the enzymes on the stabilization of different soils and evaluate the Performance of TerraZyme for stabilizing various soil groups.

3. Methodology

Published laboratory results of untreated and TerraZyme stabilized soils are compared to investigate the efficacy of enzyme stabilization with the following investigations,

1. Analysis of TerraZyme treated soil data to evaluate the performance of the enzymes with various soil types. The enzyme performance is investigated by analyzing the changes in index and engineering properties for various soil groups induced by enzyme stabilization compared to untreated soil.
2. Checking the effect of enzyme dosages, curing period (duration of treatment or ageing), and Soil type on the stabilized soil properties. The optimum enzyme doses required to stabilize the various soil groups are investigated. Also, the stabilization performance of TerraZyme achieved for the various soil groups is analyzed.

Various case studies of TerraZyme stabilized soils from the literature are analyzed. The case studies fulfilling the soil requirements for effective TerraZyme-based stabilization are selected for the study. The published data consisting of 34 soils belonging to distinct 11 soil groups in compliance with the enzyme application requirements is selected as shown in Table 2. Published literature consists of laboratory results of work carried out mostly to stabilize expansive soil and some examples of subgrade stabilization. The study includes an evaluation of stabilizing effect of TerraZyme with changes in doses, duration, and type of soil. The literature data consist of lots of parametric variations. In this study, the attempt was made to maintain the uniformity of representation to extend possible. Table 3. shows the average soil group characteristics of the untreated soils included in the study. The performance of stabilized soil in the index and engineering properties test can be considered an evaluation parameter for the effectivity of the degree of stabilization achieved. The effect of stabilization on soil index and engineering properties is analyzed and compared to conclude the effect of enzyme doses and curing duration for various soil groups.

The study includes an evaluation of the effects of TerraZyme stabilization on the properties of treated soils. Result analysis of Consistency Limits, Compaction Characteristics, California Bearing Ratio Test, Unconfined Compressive Strength (UCS) of enzyme-treated Soils, and other important properties such as permeability and consolidation parameters, including swelling characteristics. The laboratory test results from the literature are analyzed based on soil classification, enzyme doses, and duration of curing for various soil groups. The Average percentage variation in values, either positive (% increase) or negative (% decrease), are calculated for various soil attributes.

4. Soil Requirements for Enzyme Stabilization

Several factors such as soil type, enzyme doses, curing duration, and curing type affect the stabilization performance. The type of soil significantly affected the effectiveness of the treatments. The percentage of fines and the chemical and mineral composition are properties that affect the stabilization mechanism. Therefore, special attention should be paid to selecting the proper treatment for different soils.

Table 1. shows the soil suitability for effective TerraZyme-based stabilization as suggested by the manufacturer.[8**]** TerraZyme manufacturer uses Soil Sample Analysis Summary to guide the product application. It consists of an investigation of the type of the work, soils laboratory data for representative soil sample consisting of results of Sieve analysis, Liquid Limit (WL), Plastic Limit (PL), Plasticity Index (IP/PI), Soil pH, Optimum Moisture Content (OMC), Standard Proctor Test, California Bearing Ratio (CBR)-Unsoaked. Thus, these are the parameters used to assess enzyme stabilization's effectivity.

Table 1. Soil requirements for effective TerraZyme based stabilization

Liquid Limit	Particle Size	Clay content	pH	Temperature
< 30%	Passing 75micron >15%	>6% (minimum of 8% to 11% of cohesive fines)	4.5 to 9.5	>15 °C

Table 2. Details of the soils included in the study

No.	References	IS Soil Classification	
1	[9] Ramesh H.N.	CH	CH-Soil1
2	[10] Sweta Das et al.		CH-Soil2
3	[11] Usha Patel et al.		CH-Soil3
4	[12] Vinay Kumar et al.		CH-Soil4
5	[13] Nway Nway N.M. et al.		CH-Soil5
			CH-Soil6
			CH-Soil7
6	[14] Karnati Chakrapani et al.		CH-Soil8
7	[15] Joydeep		CH-Soil9
8	[9] Ramesh H.N.	CI	CI-Soil1
9	[16] Ishwarya S.D. et al.		CI-Soil2
10	[17] Khushbu Shah et al.		CI-Soil3

No.	References	IS Soil Classification	
11	[18] Nandini DN et al.	CL	CL-Soil1
12	[13] Nway Nway N.M. et al.		CL-Soil2
13	[19] Pradeep Singh et al.	CL-ML	CL-ML
14	[20] Nandini DN et al.	MH	MH-Soil1
15	[21] Akhilesh Kumar et al.		MH-Soil2
			MH-Soil3
16	[22] Priyanka M. S. et al.		MH-Soil4
			MH-Soil5
			MH-Soil6
17	[23] Tajamul Farooq et al.		MH-Soil7
18	[24] Basavaraj Akki et al.		MH-Soil8
19	[25] P. Jenith et al.		MH-Soil9

No.	References	IS Soil Classification	
20	[13] Nway Nway N.M. et al.	MH	MH-Soil10
21	[26] Venika	ML	ML-Soil
22	[5] S. Muguda et al.	SC	SC-Soil1
23	[22] Priyanka M. S. et al.		SC-Soil2
24	[27] C. Venkatasubramanian et al.	SP-SC	SP-SC
		SM	SM-Soil1
			SM-Soil2
25	[28] U. R. Shankar et al.	SM-GM	SM-GM
26	[29] Nandini DN et al.	SP	SP-Soil1
27	[30] Nandini DN et al.		SP-Soil2

Table 3. Average soil group characteristics of the untreated soils included in the study.

IS Soil Classification	CH	Cl	CL	CL-ML	MH	ML	SC	SP-SC	SM	SM-GM	SP
Gs	2.64	2.58	2.66	2.65	2.54	2.53	2.74	2.11	2.32	2.45	2.41
Clay Size (%)	36.82	32.25	39.40	59.00	54.95	15.65	10.50	8.00	16.25	2.00	1.73
Silt Size (%)	53.45	39.42	31.80	-	34.57	77.00	28.95	4.00	15.45	29.00	-
Sand Fraction (%)	19.74	28.33	44.00	41.00	12.43	7.35	60.05	82.00	54.50	50.00	71.25
Gravel fraction	3.28	-	1.40	0.00	2.01	0.00	1.00	6.00	13.80	19.00	26.63
WL (%)	63.18	43.41	28.30	21.81	59.46	27.00	34.85	28.00	38.00	35.00	49.50
PL (%)	27.59	23.65	12.95	15.17	36.33	23.21	21.98	22.00	32.50	25.00	28.00
PI (%)	35.59	19.76	15.35	6.64	23.13	3.79	12.88	6.00	5.50	10.00	21.50
Ws (%)	12.67	16.08	-	-	-	21.00	19.69	-	-	16.60	-
Shrinkage Index Is	53.22	27.33	-	-	-	6.00	15.16	-	-	18.40	-
Activity	1.40	0.72	0.83	0.11	0.49	0.24	0.46	0.75	0.35	-	-
MDD (kN/m^3)	15.51	16.63	19.37	19.03	22.49	17.90	18.34	14.03	15.70	19.32	16.68
OMC (%)	23.20	19.17	14.70	10.61	22.04	17.00	14.85	11.00	11.00	13.50	17.25

5. Laboratory Test on Enzyme-Treated Soils

Consistency test, Proctor Test, Unconfined Compression Strength (UCS) test, Soaked/Unsoaked California Bearing Ratio (CBR) tests are prominently specified for mapping stabilization performance of bio enzyme-treated soils.

5.1 Effect of TerraZyme Stabilization on Consistency Limits

With the addition of TerraZyme, both the liquid and plastic limits decrease and consequently decrease the plasticity index, thus signifying the decrease in plasticity characteristics and improved stability. Reduced plasticity is usually accompanied by the reduced potential for expansive soil swelling. Also, there is an increase in the Shrinkage Limit for the enzyme stabilized soil. The decrease in the plasticity index and the increase in shrinkage limit of enzyme stabilized soil with curing is more prominent, indicating the change in soil structure from relatively dispersed clayey fines to a relatively more flocculated material with better shear strength.[5] Also, the decreased shrinkage index (Is=Wp-Ws.) resulted in lesser compressibility and increased volumetric stability. It has been previously observed by Nagaraj [31] and Sridharan [32] that the compressibility of soil has a better correlation with shrinkage index (Is), and soils with lower shrinkage index have less compressibility. This indicates that enzyme-treated soils with clayey fines can be transformed into less compressible soil after curing.

The tabular data represents the average percentage variation ('+' sign indicates increase, '-' sign indicates decrease) in specified soil parametric values. Out of the available soils belonging to a particular group, the averaging of values is done for the soils having common treatment parameters of doses and curing period. The enzyme stabilization studies in the literature were carried out with different objectives, such as the effect of variation in enzyme doses or duration of curing on stabilization, etc. This has resulted in nonuniform discrete data. The fields marked with a dash ('-') indicate either data is not specified or unavailable hence not included. For CH-Soils (Table 4.), CI-Soils (Table 5.) Liquid limit, plastic limit, and plasticity index decreased (with some initial increase). In contrast, Shrinkage Limit increased for CH-Soils, decreased for CI-Soils for the higher TerraZyme doses, and increased curing duration (Table 6.). Overall signifying reduction in the expansion of the clayey soil.

Table 4. Average percentage variation in consistency limits for CH-Soils

CH-Soils	**Average % variation (+ increase, -ve decrease)**											
Doses ($200 ml/m^3$)	**LL**			**PL**				**PI**				
	1 week	**2 weeks**	**4 weeks.**	**0 Week**	**1 week**	**2 Weeks**	**4 Weeks**	**0 Week**	**1 week**	**2 Weeks**	**4 Weeks**	**8 Weeks**
13.2	-	-	-	-	-	-	-	-0.26	-15.6	-	-15.9	-
6.6	-	-	-	-	-	-	-	-0.26	-20.14	-	-13.85	-
3.5	-0.84	-2.40	-	-	0.00	0.00	-	-	-0.33	-3.04		-
3	1.2	-3.59	-7.89	-1.47	-6.25	-2.05	-21.88	-	7.53	-2.00	2.27	-
2.5	0.44	-4.07	-10.53	-3.56	-6.25	-4.07	-25.00	-	6.07	-2.00	0	-
2	-0.52	-5.39	**-14.47**	-5.21	-8.33	-7.25	**-28.13**	-	5.87	-2.00	-4.55	-
1.5	-0.92	-7.78	-11.84	-6.76	-8.33	-8.16	**-28.13**	-0.67	5.31	-5.13	0	**-24.00**
1	-	-	-	-	-	-	-	-0.29	-	-	-	-13.29

Table 5. Average percentage variation in consistency limits for CI-Soils

CI-Soils	**Average % variation (+ increase, -ve decrease)**											
	LL				**PL**				**PI**			
Doses ($200 ml/m^3$)	**0 Week**	**1 week**	**3 weeks**	**4 weeks**	**0 Week**	**1 week**	**3 weeks**	**4 weeks**	**0 Week**	**1 week**	**3 weeks**	**4 weeks**
13.2	-	-	-	-	-	-	-	-	-	-42.59	-	-58.33
6.6	-	-	-	-	-	-	-	-	-	-47.22	-	**-59.26**
4	-	6.41	-	-5.13	-	-4.55	-	-9.09	-	20.59	-	0.00
3.5	-	7.69	-	-7.69	-	-4.55	-	-11.36	-	23.53	-	-2.94
3	-	10.26	-	-7.69	-	-6.82	-	-13.64	-	32.35	-	0.00
2.5	-	11.54	-	-10.26	-	-9.09	-	-15.91	-	38.24	-	-2.94
1.7	-15.91	-	-67.53	-	46.40	-	-45.60	-	58.14	-	-39.53	-
0.8	-18.28	-	-67.74	-	40.00	-	-50.00	-	53.49	-	-44.19	-
0.6	-21.51	-	**-68.82**	-	34.00	-	**-50.00**	-	44.19	-	-44.19	-

Table 6. Average percentage variation in shrinkage limit for CH-Soils and CI-Soils

Doses (200ml/m^3)	Average % variation (+ increase, -ve decrease)				
	CH-Soils		CI-Soils		
	1 week	4Week	0 Week	1 week	4 Week
4	-	-	-	-5.56	-11.11
3.5	-	-	-	-5.56	-16.67
3	25.00	37.50	-	-11.11	-19.44
2.5	25.00	**50.00**	-	-11.11	-22.22
2	25.00	**50.00**	13.86	-	-
1.5	25.00	**50.00**	**25.38**	-	-

However, CI-Soils have shown a decrease in shrinkage limit. However, CH-Soils for high doses of 200ml/2m^3 and 200ml/1.5m^3 have shown an average percentage increase of 50% in shrinkage limit. The data on shrinkage limits for other soil types were not available. For MH-Soils (Table 7.) Liquid limit, plastic limit, and plasticity index decreased, whereas PI has increased for ML-Soil (Table 8.). For most cases, PI decreases with aging after an initial increase. For SM-GM Soils (Table 9.) Liquid limit, plastic limit, and plasticity index have shown decreased.

Table 7. Average percentage variation in consistency limits for MH-Soils

MH-Soils	Average percentage % variation (+ increase, -ve decrease)							
Doses (200ml/m^3)	LL		PL		PI			
	0 Week	2 weeks	0 Week	2 Week	0 Week	1 week	2 Week	4 Week
13.2	-	-	-	-	-	-12.50	-	0.00
6.6	-	-	-	-	-	30.36	-	**-16.52**
2.5	-17.7	-30.7	-25.7	-39.21	-5.81	5.88	-13.69	-
2	-19.55	**-35.44**	-30.2	**-53.61**	-5.81	11.76	-7.8	-
1.5	-13.98	-23.27	-33.28	-47.24	19.65	18.67	-	-
0.4	-	-	-6.32	-	-8.98	-	-	-
0.3	-	-	-12.84	-	-5.47	-	-	-
0.1	-	-	-18.42	-	-3.06	-	-	-

Table 8. Average percentage variation in consistency limits for ML-Soils

ML-Soil	Average % variation (+ increase, -ve decrease)					
Doses (200ml/m^3)	LL		PL		PI	
	1 Day	2 Days	1 Day	2 Days	1 Day	2 Days
3	-17.04	-25.93	-26.76	**-33.22**	42.48	18.73
2.5	-11.11	-22.22	-24.60	-31.06	**71.50**	31.93
2	-22.22	**-27.78**	-26.76	-31.06	5.54	**-7.65**
1.5	-3.70	-24.07	-26.32	-29.77	29.29	10.82

Table 9. Average percentage variation in consistency limits for SM-GM-Soils

SM-GM Soils	Average % variation (+ increase, -ve decrease)					
	LL		PL		PI	
Doses (200ml/m^3)	1 Day	4 Days	1 Day	4 Days	1 Day	4 Days
3.5	-14.29	-18.00	0.00	-0.40	-50.00	-62.00
3	-14.29	-18.57	0.00	-2.80	-50.00	-58.00
2.5	-14.57	-20.29	0.00	**-4.00**	-51.00	-61.00
2	-15.43	**-21.14**	0.00	**-4.00**	-54.00	**-63.30**

Table 10. shows that CI-Soils showed the most prominent variation in all consistency limits; however, there is significant variation in optimum enzyme doses and duration of curing required to achieve these improvements. Lesser average clay content (and thus lesser PI) of CI soils may be the reason for this improvement. The high increase in shrinkage limit for treated CH-Soil shows a higher degree of volume stability after treatment.

Table 10. Maximum average percentage variation in consistency limits for different soil groups.

Soils	**Maximum Average % variation (+ increase, -ve decrease)**			
	Liquid Limit	**Plastic Limit**	**Plasticity Index**	**Shrinkage Limit**
CH-Soils	-14.47 (200ml/2m^3, 4 weeks)	-28.13 (200ml/2m^3, 4 weeks)	-24.00 (200ml/1.5m^3, 8 weeks)	**50.00** (200ml/1.5m^3, 2m^3,2.5m^3, 4 weeks)
CI-Soils	**-68.82** (200ml/0.6m^3, 3 weeks)	**-50.00** (200ml/0.6m^3, 3 weeks)	**-59.26** (200ml/6.6m^3, 4 weeks)	**25.38** (200ml/1.5m^3, 0 weeks)
MH-Soils	-35.44 (200ml/2m^3, 2 weeks)	-53.61 (200ml/2m^3, 2 weeks)	-16.52 (200ml/6.6m^3, 4 weeks)	-
ML-Soil	-27.78 (200ml/2m^3, 2 Days)	-33.22 (200ml/3m^3, 2 Days)	-7.65 (200ml/2m^3, 2 Days)	-
SM-GM Soils	-21.14 (200ml/2m^3, 4 Days)	-4.00 (200ml/2m^3, 4 Days)	**-63.30** (200ml/2m^3, 4 Days)	-

5.2 Effect of TerraZyme Stabilization on Compaction Characteristics

The TerraZyme stabilization decreases the Optimum Moisture Content (OMC) and increases the maximum dry density (MDD) for the given soil. The closer packing decreases the voids between the soil particles, thus achieving greater compaction at minimal compaction effort and with lower water content. As the density increases, thereby increasing the shear strength of the soil.

For CH-Soils, the maximum average percentage increase in MDD after treating with optimal 200ml/1.5m^3 enzyme is 9.87 %, and the corresponding average percentage decrease of 11.30% in OMC. (Table 11.)

Table 11. Average percentage variation in OMC and MMD for CH-Soils

CH-Soils	**Average % variation (+ increase, -ve decrease)**		**CH-Soils**	**Average % variation (+ increase, -ve decrease)**	
Doses (200ml/m^3)	OMC	MDD	Doses (200ml/m^3)	OMC	MDD
	0 Week	0 Week		0 Week	0 Week
Untreated	0	-0.008	1.5	-11.30	**9.87**
3.5	0	0	0.5	-17.39	4.52
3	-1.3	4.4	0.25	**-17.39**	5.81
2.5	-8.48	3.91	0.15	-10.87	4.52
2	-9.78	6.72	0.0075	-4.35	3.23

Table 12. Average percentage variation in OMC and MMD for CI-Soils

CI-Soils	Average % variation (+ increase, -ve decrease)			
	OMC		MDD	
Doses (200ml/m^3)	Min	Max	Min	Max
	1 Week	6 Weeks	1 Week	6 Weeks
1.7	-0.38	-13.85	23.09	49.96
0.8	-3.85	-16.15	23.72	56.21
0.6	-7.69	**-68.71**	24.34	**68.71**

For CI-Soils (Table 12.), the maximum average percentage increase in MDD after treating with an optimal 200ml/0.6m^3 dose of the enzyme is 68.71 %, and the corresponding average percentage decrease is 68.71% in OMC.

For MH-Soil (Table 13.), the maximum average percentage increase in MDD after treating with optimal 200ml/0.3m^3 enzyme is 5.83%, and the corresponding average percentage decrease of 11.11% in OMC. Thus, the reduction in OMC indicates enzyme treatment has water reduction capacity, and high dry density can be obtained with minor compaction.

Table 14. shows that the ML-Soils attained a maximum average percentage increase of 5.03% with an enzyme dose of 200ml/2m^3 at the end of the 2nd week.

Table 13. Average percentage variation in OMC and MMD for MH-Soils

MH-Soil	Average % variation (+ increase, -ve decrease)	
Doses (200ml/m^3)	OMC	MDD
	(0 Week)	(0 Week)
0.4	-4.89	1.28
0.3	**-11.11**	**5.83**
0.1	-6.67	2.58

Table 14. Average percentage variation in OMC and MMD for ML-Soils

ML-Soil	Average % variation (+ increase, -ve decrease)			
	OMC		MDD	
Doses (200ml/m^3)	Min	Max	Min	Max
	1 Week	2 Week	1 Week	2 Week
3	-41.18	**-41.18**	0.00	0.56
2.5	-17.65	-11.76	2.12	4.47
2	-41.18	-17.65	1.84	**5.03**
1.5	-23.53	-17.65	1.12	2.79

A decrease in OMC maybe because of the effective cation exchange process due to enzymatic reaction. Table 15. shows the most prominent variation in compaction characteristics was shown by CI-Soils; thus, soils with intermediate clay contents show the best improvement in MDD value. CH-Soils require higher enzyme doses to achieve the maximum average percentage MMD value. However, there is significant variation in optimum enzyme doses and curing duration required to acquire the maximum average percentage MMD for different soils.

Table 15. Maximum average percentage variation in OMC and MMD for different soil groups

Soils		CH-Soils	CI-Soils	MH-Soils	ML-Soil
Maximum Average % variation (+increase/-decrease)	OMC	**-17.39** 00ml/0.25m3, 0 weeks)	**-68.71** (200ml/0.6m^3, 6 weeks)	**-11.11** (200ml/0.3m^3, 0 weeks)	**-41.18** (200ml/3m^3, 2 weeks)
	MDD	**9.87** (200ml/1.5m^3, 0 weeks)	**68.71** (200ml/0.6m^3, 6 weeks)	**5.83** (200ml/0.3m^3, 0 weeks)	**5.03** (200ml/2m^3, 2 weeks)

The improved MDD of enzyme-treated CI-Soils over CH soil cannot be justified clearly. The average soil group characteristics, as represented in Table 3. are quite similar for both untreated soils. Lesser average clay content (and thus lesser PI) of CI soils and comparatively balanced particle size gradation may have improved compaction characteristics. The least average clay size content (15.65%) and average PI (3.79%) among all soil groups may be the reason for ML-Soil showing improvement in OMC at a lesser enzyme dose of 200ml/3m$^{3.}$

5.3 California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of Soil

The results of enzyme-treated soils with specified doses were analyzed for the degree of improvements in index and engineering properties for various curing duration. For the particular curing duration, the percentage variation in values was averaged for the same soil group to show minimum and maximum percentage variation in properties with various enzyme doses. The minimum and maximum variation in property under consideration were observed for soils of a single soil group for a different duration. Thus, the average percentage variation column may show variation in duration for these minimum and maximum values as per the duration data from the literature. The duel fields of data for the same enzyme show the maximum variation (either positive or negative) of properties under consideration with the duration of curing. Some soils in the same soil group show minimum value after the first week, while others may show minimum value after the second week of curing. Thus, minimum or maximum values are represented for those two-corresponding duration.

Though the duration of aging to reach a minimum or maximum parametric value for various soils is different, this additional cueing duration shows the trend of variation of properties over time. It also highlights that the duration of curing required for stabilized soil to reach these values is variable, i.e., the duration of soil type and even the enzyme doses are the factors controlling the properties of stabilized soil.

5.3.1 Effect of TerraZyme Stabilization on California Bearing Ratio Test

With the addition of TerraZyme, a significant increase in both the soaked and unsoaked CBR values is observed. This may be because of the denser packing of soil particles compaction at decreased OMC values resulting in a stronger bond among the soil particles by reducing the void ratios. Similar findings were observed with compaction characteristics using the Proctor test.

The test results indicate that there is a continuous improvement in both unsoaked and soaked CBR values with an increase in enzyme dosages and duration. For CH-Soils (Table 16.), after 3 Weeks of curing average percentage increase in Unsoaked CBR value is 480 % for the CH-Soils treated with optimal 200ml/0.25m^3 enzyme. Whereas average percentage increase in soaked CBR value of 329.85% is obtained for the CH-Soils treated with optimal 200ml/ 0.75m^3 enzyme.

Table 16. Average percentage variation in CBR values for CH-Soils

CH-Soils	Average % increase						
	Unsoaked CBR				Soaked CBR		
Doses (200ml/m^3)	Min		Max		Min	Max	
	0 Week	1 Week	3 Weeks	4 Weeks	0 Week	4 Weeks	8 Weeks
13.2	-	121.26	-	155.59	117.78	154.82	-
6.6	-	128.64	-	147.36	131.85	194.07	-
3.5	59.92		-		-	-	-
3	-	10.92	-	337.82	-	-	-
2.5	-	40.34	-	353.78	-	-	-
2	-	76.28	-	346.59	-	-	-
1.5	-	68.07	-	**387.39**	-	-	-
1	-	-	-	-	71.64	-	229.10
0.75	-	-	-	-	71.64	-	**329.85**
0.25	207.72	-	**480.00**	-	-	-	-
Avg.	133.82	74.25	480.00	288.09	98.23	174.45	279.48

After 4 weeks of curing average percentage increase in unsoaked CBR value is 357.14% for the CL-Soils (Table 17.) treated with optimal 200ml/2.5m^3 enzyme. Whereas average percentage increase in soaked CBR value of 333.33% is obtained for the CL-Soils treated with optimal 200ml/6.6m^3 enzyme.

After 4 weeks of curing, for MH-Soil (Table 18.) average percentage increase in both unsoaked and soaked CBR values is 435.00% and 380%, respectively, for the MH-Soil treated with optimal 200ml/6.6m^3 enzyme.

Table 17. Average percentage variation in CBR values for CL-Soils

CL-Soils	Average % increase			
	Unsoaked CBR		Soaked CBR	
Doses (200ml/m^3)	Min	Max	Min	Max
	(1 week)	(4 weeks)	(1 week)	(4 weeks)
Untreated	-	-	4.36	-
13.2	63.64	72.73	216.67	266.67
6.6	172.73	218.18	216.67	**333.33**
3	28.57	214.28	-	-
2.5	71.42	**357.14**	-	-
2	-	-	11.07	-
1.5	-	-	7.58	-

Table 18. Average percentage variation in CBR values for MH-Soils

MH-Soil	Average % increase						
	Un-Soaked CBR			Soaked CBR			
Doses (200ml/m^3)	Min		Max	Min		Max	
	0 Week	1 Week	4 Weeks	0 Week	1 Week	3 Weeks	4 Weeks
13.2	-	310.00	300.00	-	180	-	260
6.6	-	415.00	**435.00**	-	300	-	**380**
3	2.83	-	49.43	19.09	-	-	345.45
2.5	5.66	-	50.75	26.36	100	307.18	368.18
2	9.03	-	55.04	19.46	182.05	391.54	347.64
1.5	11.04	-	57.62	24.13	136.16	351.28	360
1	15.29	-	59.8	17.6	76.81	184.15	333.6
0.75	-	-	-	-	122.52	247.65	-
0.5	17.06	-	63.73	20.80	-	-	343.20
Avg.	10.15	362.50	133.92	21.24	156.79	296.36	342.26

After 3 weeks of curing, the average percentage increase in unsoaked CBR value for ML-Soils (Table 19.) is 451.79%. Whereas average percentage increase in soaked CBR value at the end of the 2nd week is 200% for the ML-Soil treated with optimal 200ml/ 2m^3 enzyme.

Table 20. shows, the average percentage increase in unsoaked CBR value at the end of the 2nd week is 210% for the SM-GM soil treated with optimal 200ml/2m^3 enzyme

Table 19. Average percentage variation in CBR values for ML-Soils

ML-Soil	Average % increase			
	Un-Soaked CBR		Soaked CBR	
Doses (200ml/m^3)	Min	Max	Min	Max
	(1 Week)	(3 Week)	(1 Week)	(2Week)
3	207.50	272.68	94.92	150.00
2.5	170.71	439.46	124.58	154.23
2	200.71	**451.79**	158.47	**200.42**
1.5	153.57	436.96	133.05	162.71
Avg.	183.12	400.22	127.76	166.84

Table 20. Average percentage variation in CBR values for SM-GM Soils

SM-GM	Average % increase Un-Soaked CBR	
Doses (200ml/m^3)	Min (1 Week)	Max (4 Weeks)
3.5	70.00	130.00
3	100.00	170.00
2.5	130.00	190.00
2	**150.00**	**210.00**
Avg.	112.50	175.00

Table 21. Maximum average percentage variation in CBR for different soil groups

Soils	CH-Soils	CL-Soils	MH-Soils	ML-Soil	SM-GM Soils
Maximum Average % increase in Unsoaked CBR	480.00 (200ml/0.25m^3, 3 weeks)	357.14 (200ml/2.5m^3, 4 weeks)	435.00 (200ml/6.6m^3, 4 weeks)	451.79 (200ml/2m^3, 3 weeks)	210.00 (200ml/2m^3, 4 weeks)
Maximum Average % increase in Soaked CBR	329.85 (200ml/0.75m^3, 8 weeks)	333.33 (200ml/6.6m^3, 4 weeks)	380 (200ml/6.6m^3, 4 weeks)	200.42 (200ml/2m^3, 2 weeks)	-

Table 21. shows that both clayey and silty soils have shown maximum improvement in soaked and Unsoaked CBR values. For CH-Soils (Activity no.=1.4), higher doses are required to reach the maximum average percentage CBR value, whereas MH-Soils (Activity no.=0.49) reach the maximum average percentage CBR value at comparatively smaller enzyme doses. Whereas ML, SM-GM soils with lesser clay content (15.65% and 2%, respectively) reach to highest average performance at moderate enzyme dose. In general, the curing duration required to reach the maximum average percentage, CBR value decreases with clay contents.

The soaked CBR test requires a comparatively higher curing duration to reach to maximum average percentage CBR value. This increased curing duration for soaked CBR may be required to achieve greater strength and higher penetration resistance to minimize the leaching effect of the enzyme during 96 hours of soaking of specimen done during the soaked CBR test.

5.3.2 Effect of TerraZyme Stabilization on Unconfined Compressive Strength (UCS) of Soil

The treatment with enzyme showed a considerable increase in the shear strength of the soil. Unconfined Compression Test is observed for CH-Soil (Table 22.) treated with optimal 200ml/2m^3 enzyme, and the unconfined strength increases more than 493.43% compared to virgin soil. This increase in strength may be due to an enzymatic reaction with clay minerals.

Table 22. Average percentage variation in UCS values for CH-Soil

CH-Soil	UCS Average % increase			
Doses (200ml/m^3)	Min		Max	
	0 Week	1 Week	4 weeks	8 weeks
3.5	35.21	-	-	215.49
13.2	-	10.74	35.69	-
6.6	-	16.07	41.49	-
3	23.55	-	96.03	420.87
2.5	30.52	-	119.26	446.07
2	38.62	-	144.48	**493.43**
1.5	43.67	-	150.99	485.59
1	6.25	-	-	197.60
0.75	4.33	-	-	151.92
Average	26.02	13.41	127.69	344.42

For Unconfined Compression Test (Table 23.) shows that for CI-Soil treated with optimal 200ml/2.5m^3 enzyme, the UCS increases more than 493.36% compared to untreated soil.

Table 23. Average percentage variation in UCS values for CI-Soil

CI-Soil	UCS Average % increase	
Doses (200ml/m^3)	Min	Max
	(0 Week)	(8 Weeks)
4	7.73	457.01
3.5	11.35	468.24
3	12.08	491.19
2.5	12.56	**493.36**
Avg	10.93	477.45

For UCS Test for CL- ML Soil (Table 24.) treated with optimal 200ml/0.5m^{3}enzyme, the average % UCS increases is more than 375.00% compared to virgin soil.

Table 24. Average percentage variation in UCS values for CL-ML-Soil

CL-ML*	UCS Average % increase	
Doses (200ml/m^3)	Min	Max
	0 Week	4 Week
1.5	0	258.33
1	0	300.00
0.5	0	**375.00**
AVG	0	311.11
* Single Soil sample		

Table 25. Average percentage variation in UCS values for MH-Soils

MH-Soil	UCS Average % increase			
Doses (200ml/m^3)	Min		Max	
	0 Week	2 Weeks	3 Weeks	4 Weeks
13.2	-	2.61	-	18.61
6.6	-	8.70	-	76.52
3	7.02	-	-	1.15
2.5	10.35	71.09	72.22	60
2	13.7	71.4	**102.99**	70
1.5	23.82	37.07	85.53	58.88
1	17.95	-	-	54.31
0.5	30.90	-	-	73.33
Avg.	17.29	38.17	86.91	51.60

For the UCS test for MH-Soil (Table 25.) treated with optimal 200ml/2m^{3}enzyme, the average % UCS increases is 102.99% compared to virgin soil.

SP soil gives less UCS average percentage increase as compared to other soils. The enzyme is not effective for soil with a higher percentage of cohesionless material. It was also observed in the case studies by Shankar et al. (2009).[28]
For UCS Test for SP -Soil (Table 26.) treated with optimal 200ml/2m^3 enzyme, the average % UCS increases is more than 98.01% compared to virgin soil at the end of the 2nd week. However, an example of [24] where SP soil has shown a UCS average increase of 440.89%. This may be due to the cementation of grain particles due presence of cementing material in the soil.

Table 26. Average percentage variation in UCS values for SP-Soil

SP-Soil	UCS Average % increase	
Doses (200ml/m^3)	Min	Max
	(0 Week)	(2 Weeks)
3	2.59	69.40
2.5	7.25	85.31
2	23.25	**98.01**
Avg	11.03	84.24
* Single Soil sample		

Table 27. shows that clayey soils (CH, CI, CL-ML) have shown maximum improvement in UCS values with aging. CH, CI soils with the highest improvements in UCS values over almost similar enzyme doses and curing duration are with 36.82% and 32.25% clay size particles, respectively. For CH, MH and SP-Soils reach maximum average percentage UCS value at a moderate enzyme dose of 200ml/2m$^{3;}$ however, clayey soil requires a higher curing duration to reach maximum value. As clay contents decrease, the time required to attend maximum value also decreases. The CL-ML Soils require a higher enzyme dose of 200ml/0.5m^3 and moderate duration to attend the maximum average percentage UCS value.

Table 27. Maximum average percentage variation in UCS for different soil groups

Soils	CH-Soils	CI-Soils	CL-ML Soils	MH-Soils	SP-Soils
UCS Avg % increase	**493.43** 200ml/2m^3, 8 weeks	**493.36** 200ml/2.5m^3, 8 weeks	**375.00** 200ml/0.5m^3, 4 weeks	**102.99** 200ml/2m^3, 3 weeks	**98.01** 200ml/2m^3, 2 weeks

Apart from the test observations from consistency limits, CBR, and UCS on enzyme stabilized soils, the literature also discussed the improvements in other soil properties such as permeability, consolidation parameters such as compression index, and Coefficient of consolidation percentage swell pressure.

5.4 Effect of Enzyme Treatments on Permeability

The permeability of TerraZyme treated soil decreases noticeably with enzyme stabilization. Bio-enzymes improve strength, reduce compaction effort, and increase density, thus reducing permeability [28]. The Coefficient of Permeability of SM-GM has shown a reduction of 41.81% at enzyme doses of 200ml/2.5m^3 and 2m^3 for 4 weeks of curing.

5.5 Effect of Enzyme Treatments on Consolidation Parameters

The Coefficient Of consolidation (Cv) measures the compressibility of soil, whereas the compression index (Cc) is used to predict soil compressibility. The effect of enzyme treatments on expansive soil is summarized in Table 28.
Ramesh et al. show TerraZyme treated black cotton soil has shown a drastic reduction in Free Swell Index with drying.[9] Also, Sureka Naagesh et al. show that the consolidation test on bio enzyme-treated expansive (CH) soil reduces percentage swell and swell pressures.[33]

Table 28. Effect of enzyme treatments on consolidation parameters

References	Coefficient of consolidation (Cv)	Compression index (Cc)	Free Swell Index	Swell Pressure
K. Chakrapani et al. [14] CH-Soil	-98.28% (200ml/2.5 m^3 /30 days)	-82.35% (200ml/2.5 m^3 /30 days)	-	-71.11% (200ml/2.5 m^3 /30 days)
Ramesh et al. [9] CH-Soil	-	-18.62% (200ml/2m^3)	-77.12% (200ml/2m^3.)	-
Khushbu et al. [17] CH-Soil	-	-	-56.08% (200ml/2m^3, 3 weeks)	-
Priyanka et al. [22] MH-Soil	-	-	-15.77% Avg. (200ml/0.75m^3, 3 weeks)	-
Priyanka et al. [22] SC-Soil	-	-	-4% (200ml/0.75m^3, 3 weeks)	-

Thus, the enzyme treatment effectively reduces swelling activity and consolidation activities.

Enzyme treatments also affect the specific gravity of soil. Venika et al. [26] for ML soil have indicated a 3.95% increase (200ml/2m^3) and an average percentage increase of 2.02% in specific gravity at the end of the first week. Also, there was a 13.44% increase (200ml/2.5m^3) and an average percentage increase of 10.54% in specific gravity at the end of the second week.

6. Result and Discussion

Following are the important findings of the research,

1. The most prominent variation in all consistency limits was shown by CI-Soils, which may be due to lesser average clay content (and thus lesser PI).
2. Among all clayey and silty soil groups, the CI-Soils with intermediate clay contents have shown the maximum increase in MDD and maximum decrease in OMC value.
3. ML-Soil with lesser clay size particle and PI value showing comparatively higher improvement in OMC at lesser enzyme dose indicates clay size content and plasticity index of the soil have a major bearing on enzyme dose requirement.
4. A similar observation of MH-Soils (Activity no.=0.49) achieving maximum average percentage CBR value at comparatively smaller enzyme doses highlights the same relation.
5. In general, the curing duration required to reach the maximum average percentage, CBR value decreases with clay contents. The soaked CBR test requires a comparatively higher curing duration to reach to maximum average percentage CBR value.
6. Clayey soils (CH, CI, CL-ML) have shown maximum improvement in UCS values with curing duration. Clayey soil requires a higher curing duration to reach the maximum UCS value.
7. TerraZyme treated black cotton soil (in general CH-soils) has dramatically reduced the Coefficient of Permeability, Free Swell Index, and swell pressures. The enzyme treatment has shown improvement in specific gravity.

There is significant variation in enzyme doses and duration of curing required to reach the maximum improvement in index and engineering properties of various soil groups. Different soils have reached the maximum parametric value with the different enzyme doses and the curing duration. This indicates the variation in the degree of stabilization of different soils with changes in enzyme doses and curing duration.

- When the individual soil classified under the same group is compared shows inconsistent trends of variation in values of soil properties. Such large variation is unexpected for a few soils and falls out of general group trends. The results' variation may be due to changes in the standard procedure of sample preparation or laboratory testing conditions. Such cases need further investigation as the testing results with limited specimen also hinders the causes for such unexpected results.
- It's also a common observation that the optimum value of enzyme dose giving the maximum improvement in each engineering property is variable. Thus, the same enzyme dose shows a variable effect on various soil properties stabilized for different soil groups and the different soils classified under the same group.
- Enzyme treatments show no consistent improvements in the soil properties. There is either insignificant or inconsistent improvement in soil engineering properties in many individual cases. Though few soil cases have shown significant improvement in soil properties, there are no definite trends in the enzyme doses and the curing duration required to achieve the best performance.

The inconsistent variation in the properties of stabilized soils may be due to the following reasons.

- The samples may be cured in air-dry conditions and a sealed container. In air-dry curing, the samples were allowed to dry at room temperature, whereas in a sealed container, the moisture was preserved in the samples during the curing time. The method of curing affects the performance of stabilization. For many of the literature data, the distinction between desiccator curing and air-dry curing is not specifically mentioned making it difficult to conclude the effect of the curing method on soil properties. The air-dry curing conditions are quite similar to field conditions. As per the literature, there is a need for initial moisture content for initiation and effectiveness of enzymatic action. However, lower values of desiccator cured laboratory specimens- compared to air dry curing cannot be explained based on curing conditions only.
- Controlled untreated samples must be prepared to account for any strength gain due to thixotropy or aging. Also, the part of the substantial improvement in UCS/CBR could have been due to moisture loss because the moisture content at the time of the sample preparation and testing was not mentioned in many studies.

This study highlights the need to carry out a large-scale, systematic study on micro characterization of different soils, enzyme characterization, and the effect of enzyme doses and curing duration to better understand the effect of enzyme stabilization.

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