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A Review Paper on Strength and Durability Properties of Stabilised Soils

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Abstract: With the advent of fast construction and development, the construction of road and building infrastructure has encountered enormous growth, especially since the last 3 decades. This rapid growth and large construction projects have led to the problem of scarcity of good quality natural metal aggregates which could be used in construction. One of the globally accepted methods is to replace the natural aggregates with locally available material by enhancing their characteristics and properties as per the requirements by use of stabilizers. Certain stabilisers have gained more strength than others in this field ad are being widely used around the globe in many countries. The strength is achieved by stabilisation but the durability in the long time frame for stabilised materials is still not being explored. This paper reports some of the recent and relevant work that has been done globally regarding the stabilised soils and its strength and durability characteristics.
Keywords: Soil strength; Durability of soil; Cement stabilisation; Stabilised soil; wet-dry test;

I. INTRODUCTION

Many codes have suggested that the scarcity of good material can be solved by the stabilising the locally available material. Most soils in their natural condition lack the strength, dimensional stability, and durability required for building construction. These inherent deficiencies may be overcome through a process of stabilisation by mechanical compaction and addition to the soil matrix of chemical binders, such as cement or lime, or waterproofing agents, such as bitumen [13]. Soil stabilisation is an alteration of the properties of existing soil to meet the specified engineering requirements. The main properties that may require to be altered by stabilisation are strength, volume stability, durability, and permeability. Several methods are available for stabilising clay soil in order to increase the strength properties and to reduce swelling or expansion behavior. Chemical stabilisation involves the formation of strong bonds between the clay minerals and other soil particles. Lime and PC are common among earlier chemical stabilisation [10]. Soil stabilization through mechanical and physical techniques can be done by decreasing the void rate through compacting or altering the grain size physically which also involves the particle size composition adjustment of the soil ASTM, 1992. The physical stabilisation does not provide adequate long term result since there is no change in the basic chemical properties of soil and thus is still susceptible to deterioration by climatic reaction with chemical thus chemical stabilisation is used which enhances both physical and chemical properties of soil. Chemical stabilisation includes the addition of additives such as lime, cement and fly ash. They cause a chemical reaction to occur in the soil-water system that stabilises the soil [6]. The reaction between chemical additives and particles of soil can bind the soil grains through a strong network, thus produce soil with better quality compared to mechanical and physical techniques, since higher strength, durability, and quality of soil can be achieved ASTM, 1992. Cement stabilisation is commonly used in practice because of high strength after a short period of stabilisation. The stabilisation is due to cementitious links between the calcium silicate and aluminate hydration products and the soil particles. The degree of improvement depends upon the quantity of the cement used and the type of soil. [6]

However, the cementation bond degrades with changes in the weather [5]. The stabilised soil must perform well in strength as well as durability criteria and thus the method durability test as per ASTM D 559-03(ASTM, 2003), Portland cement Association Handbook, IRC SP 89;2010 and IRC SP 89; 2018 suggest the Wetting-Drying and Freeze-Thaw test on stabilised soil for testing its durability. The durability of cement-treated or stabilized soils is another concern for the mix design of cement stabilization under wetting–drying or/and freezing-thawing cycles [14]. The durability of pavement can be defined as the ability of the material to retain stability and integrity over a number of years of exposure to the action of weathering [11]. [4] Defined durability as the ability of the materials to retain their stability and integrity and to maintain adequate long-term residual strength to provide sufficient resistance to climate conditions. [1] Indicated that the cyclic w-d cycles caused crack propagation, resulting in severe effects on the engineering properties of the materials, particularly in term of their residual strength and stability. Due to the long testing period of durability tests about six weeks, many state highway agencies currently require a minimum 7-day unconfined compressive strength UCS [14]**.** ASTM test is considered severe in comparison with actual field performance,' the suitability of a soil for cement stabilisation is, therefore, most likely to be determined by considerations of strength and shrinkage, rather than durability [13] The effect of cement on the stabilisation of clay soil is similar to the lime In the process of stabilisation of soil by cement, hydration of cement results in the rapid formation of calcium hydroxide and elevation of the pH of pore water. The products that are formed after a short period of ageing are largely gelatinous and amorphous. The lime that is released during hydration makes cementitious linkages between hydration products and soil particles.

II. MATERIALS USED

The details of the soil and agent used for stabilisation along with the quantity of stabiliser used and the proportions used have been presented in tabular form with the name of author and year of publication of research paper.

Table 1

Table representing soils, stabilisers, and proportions used by previous authors.

S NO	Author	Soil used (USCS)	Stabiliser used	proportion
1	[3] Dipti Ranjan et al., 2018	SW and GW	cement	2, 3, 4, 6, 8 and 10% by dry mass of the soil.
2	[14] Zhongjie Zhang and Mingjiang Tao, 2008	CL	cement water contents	2.5, 4.5, 6.5, 8.5, 10.5 15.5, 18.5, 21.5, and 24.5%
3	[9] Khoury & Zaman, 2007		cement kiln dust (CKD class C fly ash (CFA) fluidized bed ash (FBA)	15% 10% 10%
4	[5] Jeerapan et al., 2018	clayey gravel (GC)	melanin debris LS/MD cement (C)	60:40 & 80:20 (3% and 5%)
5	[6] Estabragha et al., 2012	clay soil with high plasticity (CH)	lime cement coal ash	5% and 10% 5%, 10% and 20% 5%, 10%, 15% and 20%
6	[7] Takeshi Kamei et al., 2013	Kaolin clay soil	type-B furnace slag cement recycled Bassanite	(C/S) ratios 5% and 10%, (B/S) ratios, 0, 10, 20 and 40,
7	[11] Shihata and Baghdadi, 2001	S1, S2, and S3 Soil samples	(sulfate-resistant) portland cement saline water immersion	5-7-9% 7, 90, 180, 270, and 360 days
8	[8] Apichit et al., 2013	clay soil with high plasticity (CH)	Calcium carbide residue (CCR) class F fly ash	5, 7, and 12% 5,10,15,20 25%
9	[2] Ahmeda & Issab, 2014	clay soil with high plasticity (CH)	furnace cement type-B and lime with recycled gypsum ratio1:1, 2:1, and 3:1	7.5, 15, and 22.5%
10	[12] Singh and Kalita, 2013	MI (silt of intermediate plasticity) & SP (poorly graded fine sand).	Ordinary Portland cement of 53 Grade Class F fly ash	1,2 & 3 % 10,20,35,50,65,90 & 100%
11	[13] P. J. Walker, 1995	clay soil and river sand	Clay soil and sand Ordinary portland cement	100% clay: 0% sand and 15% clay: 85% sand. 1: 10, 1: 15 and 1: 20 (cement : soil by dry volume),

III. LITERATURE REVIEW

A. Durability

Many researchers have tested different types of stabilised soils using various types and amount of stabilisers. In this section, the name of the author, year of publication, test methods adopted by the author, factors suggested by the author that affect durability and key findings by authors have been presented in tabular form for an easy overview for better understanding the previous research work done regarding the durability of stabilised soils.

Table 2.
Table representing an overview of previous research work done on durability of stabilised soils.

S no	Author	Soil	Durability criteria	Factors	Key findings
1	[3] Dipti Ranjan et al., 2018	SW and GW	Durability test was performed as per ASTM D559 (ASTM 1994).	cement percent increase	Mass loss % decrease
				UCS value	Non-linear power relationship
				w-d cycle	Linear up to 12^{th} cycle
2	[14] Zhongjie Zhang and Mingjiang Tao, 2008	CL	Maximum allowable soil-cement loss PCA	cement dosages	Decrease in Mass loss % maximum volumetric changes generally decreased
				increase of water-cement ratio	increase in Mass loss % maximum volumetric changes generally increased
3	[5] Jeerapan et al., 2018	clayey gravel (GC)	As per ASTM D 559-03(ASTM, 2003)	3% and 5% cement stabilised (without MD replacement)	samples fail after the 2nd w-d cycle
				MD replacement	The MD replacement can prolong the service life of the stabilised material by up to three cycles.
4	[6] Estabragha et al., 2012	clay soil with high plasticity (CH)	A new apparatus, similar to the one developed by Tripathy et al. (2002), was designed and fabricated to carry out wetting and drying tests	Increasing the number of cycles.	an irregular pattern of irreversible deformation occurred
				coal ash	Effect as a stabilising agent, is lost during the cycles of wetting and drying.
5	[7] Takeshi Kamei et al., 2011	Kaolin clay soil	procedure for wetting–drying cycles provided by the Japanese Highway Society (JHS, 2001)	the immersing of the dry samples in water during the wetting phase	a significant effect on the de-acceleration of the chemical reactions bonding which develops between the soil particles, produced by the chemical reactions, is reduced by the
				Increase in the. number of wetting–drying cycles,	Decrease in compressive strength, especially in the first three cycles. Afterward, this effect decreases with an increase in the number of wetting–

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					drying cycles
				After 3 cycles in this case,	The effect of an increasing number of cycles on the deterioration in strength is not significant.
				cement	has more potential to improve the strength of the tested soil than bassanite action of wetting–drying cycles has no significant effect on the durability
				samples stabilized with Bassanite-cement mixtures Bassanite–soil ratios cement–soil ratio of 10% increase in the Bassanite content to more than 10%,	achieved small durability compared to those samples treated with the same Bassanite–soil ratios at a cement–soil ratio of 5% Reduction in strength and durability was diminished.
6	[11] Shihata and Baghdadi, 2001	S1, S2, and S3 Soil samples	wetting and drying (ASTM D 550 1994) and by freezing and thawing (ASTM D 560 1994)	wet-dry and of the freeze-thaw tests amounts of fines (passing sieve	A linear relationship exists between the residual strength of the wet-dry and of the freeze-thaw tests with a good coefficient of determination: R2 = 0.884. Compressive strength started declining after about 90 days due to the application of the different freeze-thaw or wet-dry cycles. A descending linear relationship exists between the percent mass loss and URS for both the freeze-thaw and wet-dry tests
				#200)	Exhibit higher mass loss in the freeze-thaw test
				exposure to saline water	Shows that the mass loss in general increases sharply up to 90 days of exposure after which the rate of increase drops to almost a flat rate.

				Freeze-Thaw test	Mass loss in general increases sharply up to 90 days of exposure after which the rate of increase drops to almost a flat rate.
7	[8] Apichit et al., 2014	clay soil with high plasticity (CH)	wetting and drying test (ASTM D 559)	Number of cycles. (5% CCR sample cured for 28 days)	The strengths reduce significantly with All samples cured for 7 days cannot pass the recommendation after being subjected to only the first cycle
				The 7 and 12% CCR samples cured for 28 days	Can resist up to the second w-d cycle
				Increase in FA content for all curing times tested	The w-d cycle strengths increase remarkably also the durability against w-d cycles.
				unsoaked strength	Result indicates that the w-d cycle strength is dependent upon it.
				OMC) and maximum dry density (MDD)	Of a soil plays an important role in compaction as well as in strength and durability of the compacted soil.
8	[2] Ahmeda & Issab, 2014	clay soil with high plasticity (CH)		increasing soaking time	As expected, the durability index decreases significantly up to 15 days of soaking and then increases slightly or stays the same with different admixtures for all samples stabilised.
				Increased rate of water absorption.	The reduction in durability index or strength increases
				increase in the B–C admixture	is associated with an enhancement in durability
				increase in the admixture ratio is	Associated with a decrease in durability of both admixtures.
9	[13] P. J. Walker, 1995)	clay soil and river sand	ASTM standard D559	Increased cement content	durability was improved by increased
				reduced clay content	improved durability

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[3] Used SW and GW soils and tested for durability as per ASTM D559 (ASTM 1994). They used two different mechanism for brushing the samples i.e. hand brushing and mechanical brushing developed by Sampson (1988) the authors observed that, the stabilised samples of all three soils A, B and C having 2% cement could not sustain more than three cycles, five cycles and four cycles and all the soils having minimum 4% cement (except soil A) passed the limiting mass loss of 10% that is required for the structural layer of any pavement. A good relationship was observed between mass loss (%) and cement percentage for the studies of cement stabilised granular lateritic soil. Authors reported that Mass loss (%) has a non-linear power relationship (as fitted) with UCS values. minimum seven-day UCS of 2.97 MPa or seven-day soaked UCS of 1.08 MPa satisfies the mass loss criteria for cemented granular lateritic soil as per PCA guidelines. The mass loss increases linearly up to the 12^{th} cycle for 6% cement, however, as the cement percentage decreases, mass loss is more during initial cycles. Therefore, the initial mass loss may be considered to predict the total mass loss after 12 cycles. When mechanical brushing is done, the percentage mass loss should be suitably increased as the mass loss reported by hand brush was approximately 2.7 times of mass loss by mechanical brush.

[14] Found that not all the specimens were capable to survive 12 cycles of wetting–drying durability test. The soil-cement loss steadily decreased with the increase in cement dosages but increased with the increase of water–cement ratio. The greatest decrease of soil–cement loss happened when cement dosages were low from 2 to 4%.

[5] Reported that specimen with higher cement content had higher strength in the form of UCS value for the MD replacements. They also observed that the soil without MD blending had higher UCS strength for both cement dosages used but all the 3% and 5% C stabilised LS samples failed after the 3rd cycle and MD replacement improved the durability against w-d cycles. The w-d cycle test results directed that without MD replacement the 3% and 5% cement stabilised samples failed after the 2nd w-d cycle and the UCS was almost nil after the initial w-d cycle and thus the MD replacement was reported to prolong the service life of the stabilised material by up to three cycles.

[6] Designed and fabricated a new apparatus, similar to the one developed by Tripathy et al. (2002), to carry out wetting and drying tests

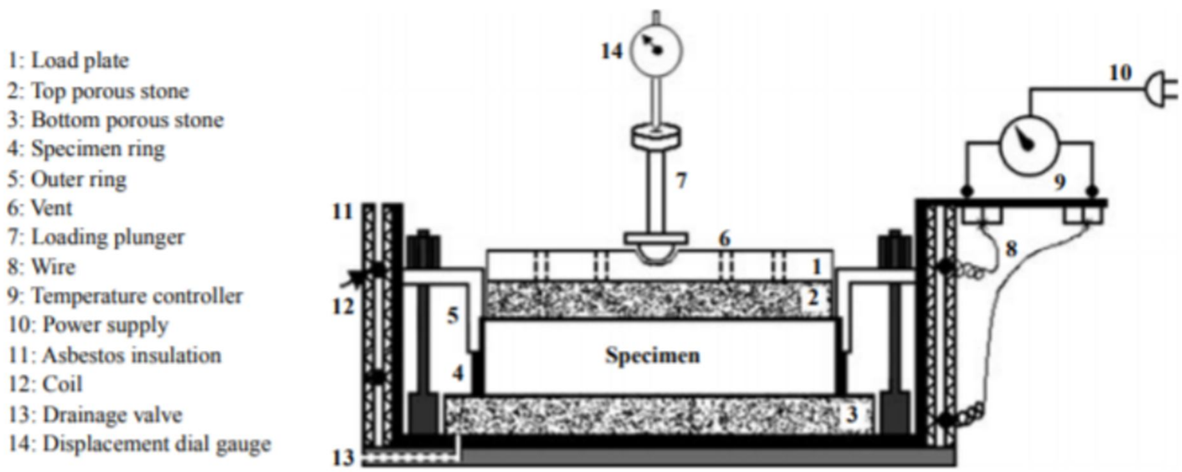

Figure 1. Apparatus Designed by [6] for wetting-Drying test.

Researchers also used conventional oedometer and modified it to allow tests to be conducted under controlled temperature and surcharge pressure. It was found that an irregular pattern of irreversible deformation occurred when the number of cycles increased. Results indicated that the effect of coal ash, as a stabilising agent, was lost during wetting and drying cycles. Authors stated that cyclic wetting and drying leads to the gradual destruction of the pozzolanic reaction of the coal ash-treated soil.

[7] Tested stabilized specimens soil for durability index which index is determined by dividing the ultimate compressive strength of a specimen after the desired number of wetting–drying cycles, by the ultimate compressive strength of an identical specimen, subjected to only 28 days of curing. They found that submergence of specimen during wetting phase has a substantial effect on the de-acceleration of the chemical reactions and the bond between the soil particles is reduced by the increase in the number of wetting–drying cycles also the decrease in compressive strength was observed due to wetting–drying cycles but After some specified number of wetting–drying cycle the effect of increasing number of cycles on the deterioration in strength was not significant. Cement has more potential to improve the strength of the tested soil than Bassanite because cement has a higher cementation property. The

durability in the case of samples stabilised with diverse Bassanite–soil ratios, at a cement–soil ratio of 10%, improved considerably after the third wetting–drying cycle. Wetting–drying cycles had no significant effect on changes in the water content or dry densities of the treated clay soil with Bassanite–furnace cement mixtures. Therefore, cycles of wetting–drying had no effect on changes in the volume of the soil specimens stabilized with the recycled Bassanite.

[11] Used numerous sets of test specimens and immersed them in the saline water for varying durations of 7, 90, 180, 270, and 360 days prior to conducting the wetting-drying cycles. The test results of the freeze-thaw and wet-dry durability in terms of mass losses were plotted against time of exposure to saline water reported that the mass loss increased sharply up to 90 days of exposure and after that, the rate of increase dropped to almost a flat rate. Also, the soils with smaller amounts of fines (passing sieve No. 200) exhibited a greater mass loss in the freeze-thaw test. A descending linear relationship existed between the percent mass loss and URS for both the freeze-thaw and wet-dry tests. As exposure duration increased the percent mass loss decreased when the URS increased. It was observed that the slope depends on the type of soil and the slope of the freeze-thaw test was steeper than that of the wet-dry test. The results of this study implied that the URS may be used to predict both the wet-dry and the freeze-thaw durability of soil-cement mixtures for paving purposes. The authors also performed Freeze-thaw test in addition to the wet-dry test and reported that mass loss in general increased sharply up to 90 days of exposure after which the rate of mass loss decreased to almost a flat rate. They also reported that a close linear correlation existed between the residual strengths of (both brushed and unbrushed samples) obtained from the wet-dry and freeze-thaw durability tests with a good coefficient of determination: R2 = 0.884 and a descending linear relationship existed between the mass loss percent and Unbrushed residual strength for both the freeze-thaw and wet-dry tests. Authors also observed that soils with lesser quantities of fines (passing sieve #200) displayed greater mass loss in the freeze-thaw test.

[8] Reported that the strengths reduce significantly with the number of cycles. In their test, all the samples cured for 7 days were not able to pass the recommended mass loss value after 1st cycle while 7 and 12% CCR samples cured for 28 days can resist up to the second w-d cycle. The increase in FA content caused a significant increase in strength for all the curing durations and researchers observed that the w-d cycle strength and durability both were dependent upon the unsoaked strength also the durability increased with increase in FA content. Researchers also reported that the OMC and MDD affect the compaction of the sample and thus effects the strength and durability.

[2] Reported that durability of B–L stabilised specimen was high compared to B–C admixture stabilised specimen and there was an association between an increase in the admixture ratio and decrease in durability of both admixtures. The durability index is defined as the ratio between the strength of the samples cured for 28 days and then subjected to a specified soaking time to the strength of the samples prior to soaking and it was observed that the durability index decreased with an increasing soaking time for all samples stabilised with different admixtures with a significant decreases up to 15 days of soaking and then slightly increased or stayed the same, they also found that early soaking time had a negative effect on the durability index and the cause for this behavior reported by authors was greater rate of water absorption for early soaking time than the later soaking time and reduction in durability index or strength increased with an increasing rate of water absorption. The structure of the stabilised specimens may rearrange again to accommodate to a new environment after 15 days. Increase in durability was observed after 15 days of soaking which may be due to the gain in additional curing time, the increase in the B–C admixture was associated with an improvement in durability. The use of low content of B–L admixture had a major and instant effect on the strength in comparison to the B–C admixture since lime has a greater potential than cement to absorb water. The increase in the proportion of admixture was associated with a decrease in durability for both admixtures

[13] Reported that durability increased by increasing cement content and reducing clay content. Durability requirements were improved by was generally fulfilled by the 10% and 6.7% cement content mixes, except for those with very high clay contents. The variation in observed results was attributed to the circumstances of the block surfaces earlier to testing. The author reported that high clay content required increased cement stabilisation and optimum cement amount was found to be 10%. The author concluded that since the ASTM test is considered severe in comparison with actual field performance the appropriateness of soil for cement stabilisation should be calculated by considering strength and shrinkage, rather than durability.

B. Unconfined Compressive Strength

The UCS test is performed for evaluation of the strength of the stabilsed samples. The various factors affecting the UCS strength, tests performed and the key findings reported by previous research has been presented in this section. A compiled information regarding previous findings related to UCS has been presented in tabular form.

TABLE 3
Table representing testing parameters, factors affecting and, key findings for ucs

S no	Author	Soil	Testing parameter	Factors affecting	Key findings
1	[3] Dipti Ranjan et al., 2018	SW and GW	CLS samples after 7-days and 28-days of curing. 4h soaked and unsoaked	relation between and UCS and durability	Mass loss (%) has a non-linear power relationship (as fitted) with UCS values.
2	[14] Zhongjie Zhang and Mingjiang Tao, 2008	CL clay with low plasticity	7-day UCS samples were submerged in water for 4 h before tested and on TS samples.	Cement content	UCS consistently increased with the increase in cement content
				Water cement ratio	the UCS decreased as the water-cement ratio increased
3	[5] Jeerapan et al., 2018	clayey gravel (GC)	UCS test on W-D tested sample after (3, 7, and 12 w-d cycles), by soaking the sample for 2h	Cement content	UCS consistently increased with the increase in cement content
					UCS increases with increasing curing time due to hydration
				Curing time	UCS of stabilised LS/MD blends decreases
				Increase in MD content	Results in higher water to cement ratio for the same cement content, hence the lower UCS.
				Increase in Optimum water content	The UCS of stabilised LS (without MD) is very low and close to zero after the first w-d cycle
				W-D Cycle	UCS values of 5% C samples are higher than those of 3% C for both 20% and 40%MD replacement for all N tested
4	[12] Estabragha et al., 2012	clay soil with high plasticity (CH)	Treated (with 20% coal ash, 20% cement and 10% lime) and untreated samples and the curing time of treated samples was 3 days.	Cement content	UCS consistently increased with the increase in cement content
5	[7] Takeshi Kamei et al., 2011	Kaolin clay soil	Unconfined compressive strength tests were conducted in accordance with ASTM D 2166-66 (Bowles, 1992)	number of wetting–drying cycles	The unconfined compressive strength decreases gradually.
				increase in the Bassanite	Reduction in strength and durability was diminished.
				cement content	UCS consistently increased with the increase in cement content

6	[11] Shihata and Baghdadi, 2001	S1, S2, and S3 Soil samples	Unconfined compressive strength tests for 7 and 28 days cured were conducted after soaking in fresh water for 4 h and 90 and 180 day specimen in saline water	curing period	Compressive strength increases sharply throughout a curing period. Compressive strength started declining after about 90 days due to the application of the different freeze-thaw or wet-dry cycles.
			Brushed residual strength (BRS) & Unbrushed residual strength (URS).	Brushing	URS is larger than BRS by approximately 20%,
				Residual UCS W-D & Residual UCS Freeze-Thaw	The figure shows that a linear relationship exists between the residual strength of the wet-dry and of the freeze-thaw tests with a good coefficient of determination: R2 = 0.884
7	[8] Apichit et al., 2014	clay soil with high plasticity (CH)	(UCS) of stabilised test specimens was determined using a Hounsfield testing machine for without the cured specimens being subjected to soaking in water.	CCR content	the compressive strength of samples without w-d cycle increases with increasing CCR content
				Curing time (28 days to 56 days)	The strength generally decreased from 28 days to 56 days of curing, at both stabiliser dosages for all methods of calculating the initial compaction water input.
				Fly Ash	Increases the maximum dry unit weight (densification) of the stabilized clay
8	[2] Ahmeda & Issab, 2014	clay soil with high plasticity (CH)	The specimens were soaked in water for different interval times of 0, 4, 7, 15, 30, and 60 days. Unconfined compressive tests were carried out in accordance with ASTM 2166-66 (ASTM, 2007)	Soaking time increase	Strength ratio increases significantly with an increase in soaking time up to 30 days, especially for samples subjected to curing times of 3 and 7 days
				samples cured for 28 days and then subjected to soaking	the strength ratio decreases with the increasing soaking time up to 15 days, whereas the increase in the soaking time after 15 days does not exhibit a significant effect on the strength ratio
				cement or lime increase	Increase in strength

[3] Tested UCS for 2 curing periods of 7 days and 28 days. 2 specimens were tested from which one was tested after 4 hr soaking in water and named as soaked UCS and the other as unsoaked UCS. The relation between UCS and Mass loss % revealed that UCS had a non-linear power relationship UCS values. Authors also reported that seven-day soaked UCS and mass loss have a better fit compared as compared to seven-day UCS.

[14] Found that there was an increase in UCS with the increase in cement content they also reported that the initial molding moisture contents also affect the UCS values as the UCS decreased with increase in water-cement ratio.

[5] Tested specimens for soaked UCS after varying cycles of wet-dry test. Authors observed an increase in UCS with an increase in cement content and time of curing and decrease in UCS with the increase in MD content due to higher water absorption of MD. Authors stated that this reduction in UCS maybe attributed to the decrease in MDD of the specimen. They also reported that higher optimum water content causes an increase in the water-cement ratio for the same cement content and thus causes a reduction in UCS value. An exponential relationship between UCS and MDD was observed for 3% cement stabilised sample while a linear relationship was observed for 5% cement stabilised sample. Authors reported that the usage of low C and high MD contents was appropriate as the UCS marginally reduced while MDD significantly reduced with increasing MD replacement, they also found that cementitious products decreased with an increase in MD replacement and thus reduction in UCS was observed.

Residual UCS; The UCS of stabilised LS (without MD) was very low and near to zero after the 1st w-d cycle which indicates low durability even when high UCS strength is obtained for both C = 3% and 5%. The UCS of cement stabilised MD/LS blends for both 3% and 5% C increased with an increase in the number of wet-dry cycles up to 3 and then decreases for wet-dry cycle greater than 3.

[6] Also reported that cementation and hardening processes of clay soil and additive materials are time-dependent.

[7] Reported a decreases in the unconfined compressive strength with an increase in the number of wet-dry cycles for different specimens studied, also the sustained compressive strength for the samples treated with 10% cement after the application of the wet-dry cycles was greater as compared to the samples treated with 5% cement. The wet-dry cycles caused a major effect on the percent decrease in unconfined compressive strength. The sustained strength of 10% of cement treated samples was better as compared to 5% cement samples.

[11] Tested compressive strength after soaking in the saline water for 4hrs using three different procedures in the first procedure the specimens were exposed to wet-dry or freeze-thaw cycles, brushed according to the suitable ASTM standard procedure then tested for compressive strength after soaking in saline water for 4 h at room temperature. The compressive strength obtained was categorized as the brushed residual strength (BRS). In the second procedure the samples were not brushed and the compressive strength obtained was categorized as unbrushed residual strength (URS), for the third and last procedure, new sets of specimens were molded and tested for 7-day unconfined compressive strength as per the standard of (ASTM D 1633). At the end of curing, the samples were soaked in water for 4 h before testing for compressive strength. The 7 and 28 days cured samples were mixed with fresh water and the 90 and 180 days samples were mixed with saline water. An increase in residual strength was observed with the increase in exposure period up to 90 days after which residual strength decreased significantly until about 270 days after which the rate in the decrease of strength was minimal. Residual compressive strength after 270 days of exposure was considered as a long-term strength. The ratio of the long-term to the residual strength for 7 days of exposure was governed by the soil properties. The ratios for three tested soils S1, S2, and S3 were 0.58, 1.0, and 0.65 respectively. Similar results were observed for the specimens tested for freeze-thaw durability. Unbrushed strength was greater than brushed strength by approximately 20%, which depicts the effect of brushing. Increase in compressive strength was observed throughout the curing period of 28 days after which the rate of increase reduces while the total increase in strength from 7 to 28 days was found to be more than 200%.

[8] Found that for all the CCR contents, the compressive strength of the CCR stabilized samples without undergoing w-d cycle increased with increase in curing time and. CCR content. The strength of 7 and 12% CCR samples were basically the identical because the CCR contents were in the inert zone and thus the natural pozzolanic reaction of clay was not enough to react. It was also observed that for the same input of FA, the 12% CCR samples depicted a little greater strength than the 7% CCR samples. The input FA caused an increase in the densification of the stabilized clay. Hounsfield testing machine was used for determination of UCS. The UCS was determined without the cured specimens being subjected to soaking in water. Overall results revealed that strength increased with increase in stabiliser from 10% to 20% and with increasing curing period from 7 to 28 to 56 days for all methods of calculating the compaction moisture content. Nevertheless, the strength magnitudes are lower for PC-GGBS system as compared to the lime-GGBS system for both curing periods. The increased amount of stabiliser dosage resulted in increased UCS with increasing curing period for LOC-PFA target materials, except for when lime alone was used as stabiliser. Overall results thus reveal that lime alone is not suitable for use as stabiliser.

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[2] Defines the strength ratio as the ratio of the strength of the sample subjected to a specified soaking time to the strength of an identical sample prior to soaking. The authors found increases in strength ratio with an increase in time of soaking up to 30 days, especially for samples cured for 3 and 7 days. For 28 days cured samples when subjected to soaking, the strength ratio decreased with the increase in soaking time up to 15 days, whereas the increase in the soaking time after 15 days does not display any major effect on the strength ratio. Thus the increased cement or lime content in the soil-gypsum mixture is related with increased strength. Acceptable admixture ratio that could stop solubility and decrease the percentage of soil deterioration for soil–gypsum mix was found to be greater than 3:1. After the 28 days of curing, the stabilised specimen approximately attained the dry state. Afterward, the expose of the dry specimens to soaking caused destruction of the bond between the soil particles causing decreased strength.

C. Alternative for Durability Test

The time required to conduct durability test is very long which becomes impractical in case of time bound projects and thus many authors have proposed alternatives to predict the suitable durability of different soil types. In this section, an overview of the alternatives provided by previous researchers has been given.

[3] Reported that mass loss corresponding to both soaked and unsoaked UCS vary in a considerable range and thus initial mass loss may be considered to predict the total mass loss after 12 cycles. The linear regression analysis of mass loss obtained by hand brushing and machine brushing resulted in equation$Mh = 2.7 \times Mm$. Based on the chart obtained between UCS and mass loss, the upper envelope is used to propose a design chart for predicting the value of mass loss based on 7 day soaked and unsoaked UCS

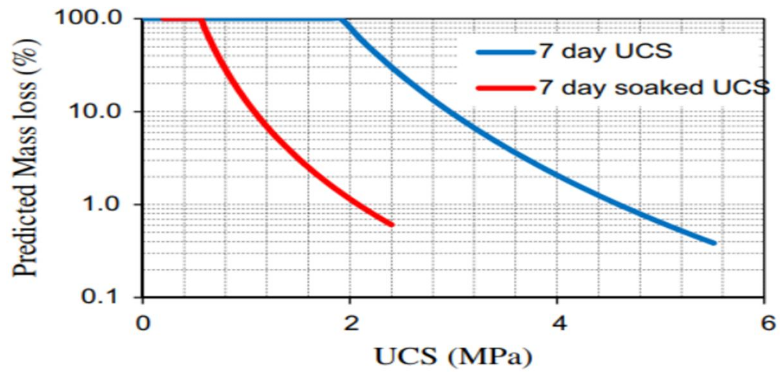

Figure2. Prediction chart proposed by [3].

The authors reported that a minimum seven-day UCS of 2.97 MPa or seven-day soaked UCS of 1.08 MPa satisfies the mass loss criteria for cemented granular lateritic soil based on PCA guidelines., Higher 7-day UCSs usually corresponded to lower soil-cement loss and volumetric changes, and thus good durability.

[14] The authors proposed two alternatives for prediction of durability based on maximum 7% soil-cement mass loss criterion for cement-stabilized CL soil

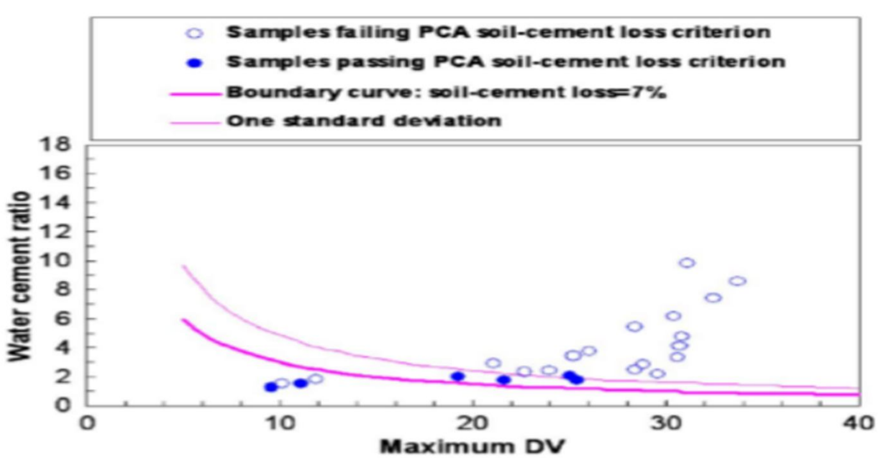

Figure. 3. Prediction chart developed by [14] for soil cement mass loss based on water cement ratio and maximum DV.

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Authors state that due to the variability in test data, the curve which is one standard deviation away from the boundary curve can give a feasible division among the test data. Authors also state that statistically rigorous prediction charts can be developed using the maximum DV or 7-day UCS if different sources of CL soils are tested and plotted in the charts. Authors state that two modified parameters can be used for predicting the durability of cement-stabilized soils. For the TS test, the parameter is the amplified maximum DV and for the UCS test, the parameter that can be used is the reciprocal of 7-day UCS.

[9] provided a wide-ranging model to predict resilient modulus based on results obtained and due to the fact that Mr is a function of stresses, a regression model correlating the variation of resilient modulus with the aforementioned stabilizing and aggregate properties, stress levels and W-D cycles was developed using the stepwise method at a 0.15 level.

It was statistically established that the final model developed for prediction of Mr was a function of W-D cycles, the quantity of free lime, a quantity of SAF, stress levels and physical properties of the mixture. The final developed equation was

$M_r = A \times B^{WDC} \times C^{CSAFR} \times D^{DMR} \times E^{\sigma 3} \times F^{\sigma d}$ …. Equation developed by [9]

Where,

WDC = Number of W-D cycles.

CSAFR = Ratio of free lime to SAF.

DMR = Ratio of MDD (in kN/m3) to the OMC (in %).

σ3 and σd (in kPa) and A, B, C, D, E, and F are model coefficients. R^2 The value was 0.67 and the F value was 289 with a Pr, 0.0001, which shows that the model can be considered statistically significant for prediction of Mr variation values with stress level, stabilization, and WD cycles.

[11] tested three soil samples for both wet-dry and freeze-thaw durability test and finally concluded that unbrushed residual strength of samples soaked for varying periods can be used to predict the mass loss percentage and hence durability based on both wet-dry and freeze-thaw test for their use as a pavement material.

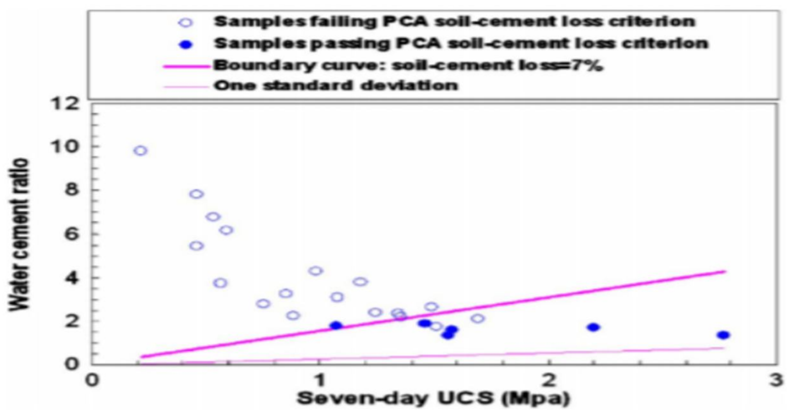

Figure 4. Prediction chart developed by [14] for soil cement mass loss based on water cement ratio and 7 day UCS.

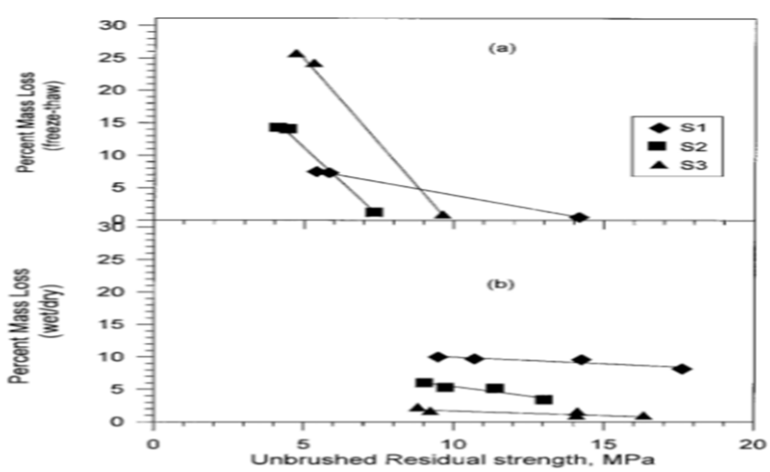

Figure. 5 Mass loss percent for three soils tested based on wet-dry and freeze-thaw durability test given by [11].

[8] Found that the strength after any number of w-d cycle is directly associated with the unsoaked strength, regardless of the CCR and FA contents. Therefore, it is possible to develop a relationship between generalized strength and number of w-d cycles.

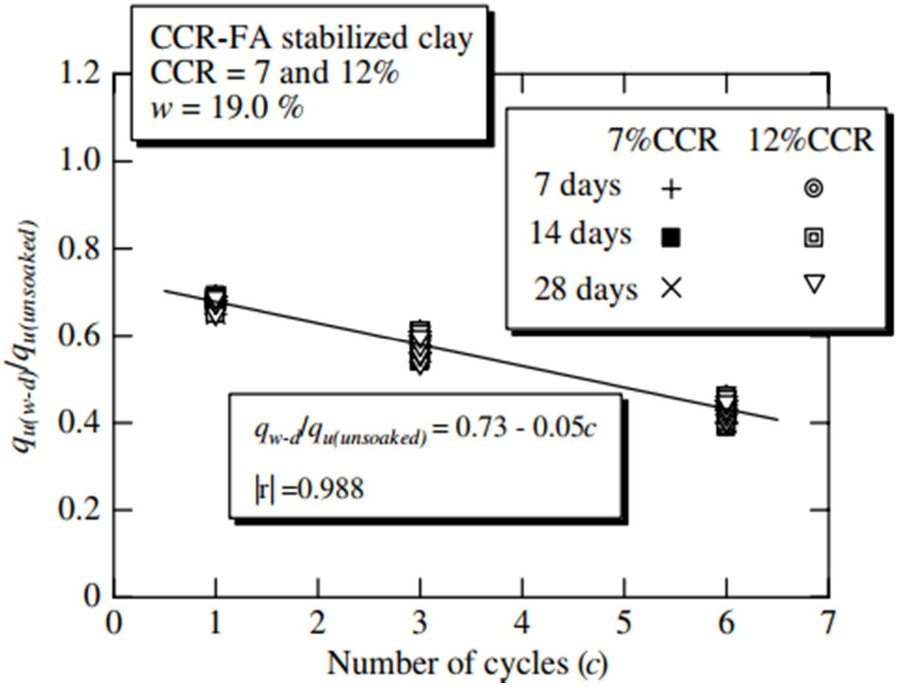

Figure. 6 Relationship between generalized strength and number of w-d cycles observed by [8].

The relationship between the generalized strength and number of w-d cycles was not linear. However, for w-d cycles between 1 and 6, the linear relationship exists and thus the author suggested a new mix design procedure for stabilised soil to provide required strength and durability based on findings of tests conducted by the author.

IV. DISCUSSION

The review of literatures provides an insight regarding the tests used and factors influencing the durability of stabilised soil which has been presented in this section.

A. The increase in cement content causes a decrease in the mass loss percentage and thus increases the durability of the stabilised soil regardless of the type of soil used for stabilisation and also helps in decreasing the value of maximum volumetric change caused by progressive wet-dry or freeze-thaw cycles. Cement also proves to be a better stabilizing agent than bassanite, lime, and other stabilisers tested.

B. Unconfined Compressive Strength can be used as a good indicator of durability. The relation of UCS with durability was different based on the different soil type, curing period and soaking of the specimen prior to testing for UCS but overall it was found that prediction charts based on the UCS of various samples tested can be used for prediction of mass loss percentage and hence durability.

C. Increase in water cement ratio causes an increase in the mass loss percent thus reducing the durability. It also increases the effect of maximum volumetric change weakening the soil structure even further.

D. With the increase in the number of wet-dry cycles, irregular pattern of irreversible deformation was observed, the compressive strength of stabilsed samples also decline significantly with the increase in the number of wet-dry cycles but after a certain number of cycles, the effect on the deterioration in strength is not significant. It was also found that the strengths reduced significantly with an increase in w-d cycle for all samples regardless of the time of curing adopted for sample preparation.

E. With an increase in soaking time, the durability index decreases significantly in initial soaking periods and then increases slightly or stays the same with different admixtures for all samples stabilised. The soaking of the specimen during the wetting phase in the wet-dry cycle also causes a significant effect on the de-acceleration of the chemical reactions bonding which is developed between the soil particles, produced by the chemical reactions.

V. CONCLUSIONS

This paper was based on the review of various papers on the durability and strength characteristics of soil-cement stabilised blends and to get an overview and understand the different procedures adopted, tests conducted, materials used for stabilisation, the effect of different parameters on the durability and strength criteria. It was found that durability can be predicted on the basis of certain other properties of soil such as & day UCS(Soaked and Unsoaked), Dielectric value of stabilised samples, OMC-MDD and water-cement ratio. The interrelationship between these parameters and durability in terms of mass loss percent can be used for prediction of durability of soil without performing 12 wet-dry cycles.

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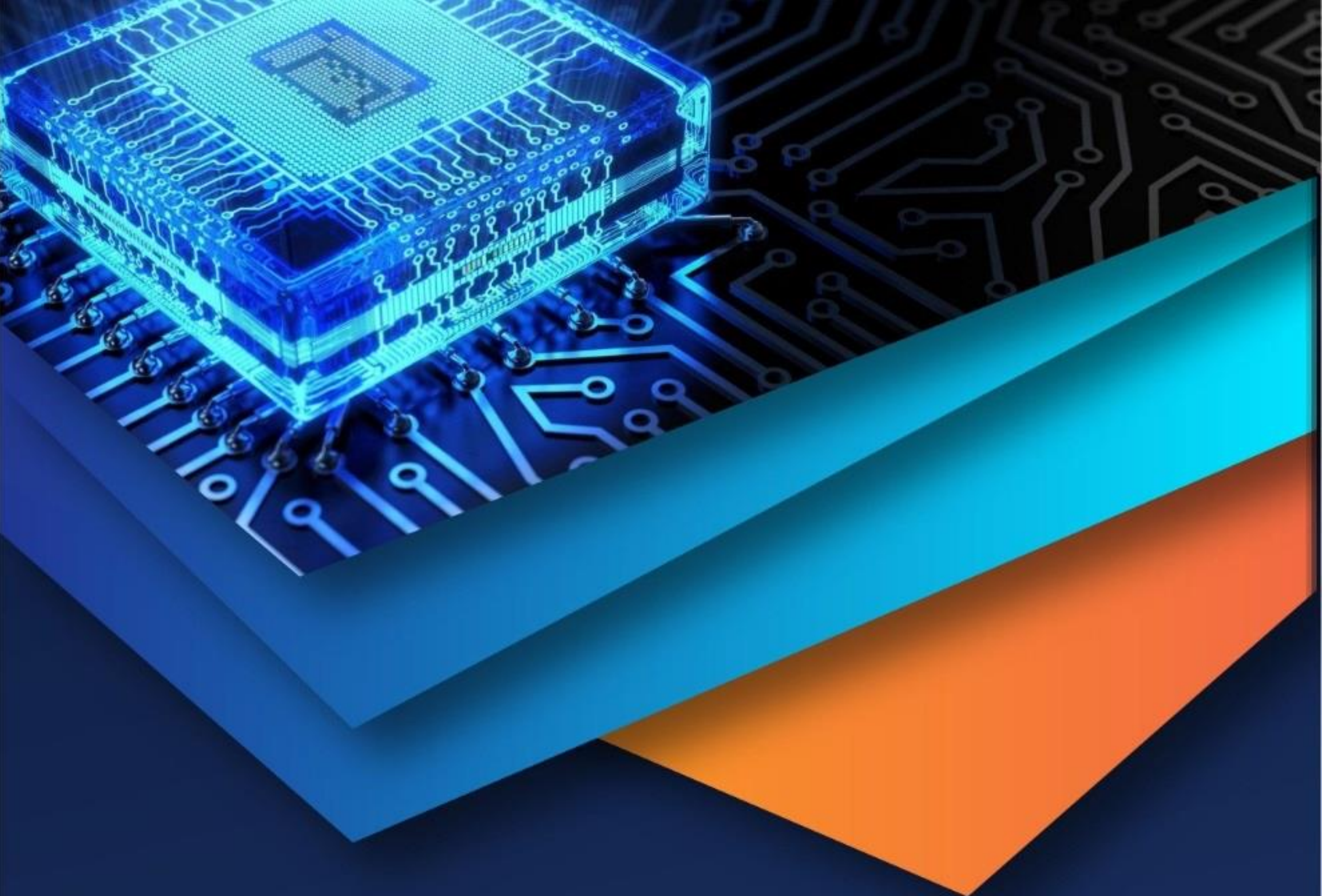

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