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Predicting the Unconfined Compressive Strength of Stabilised Soils Sourced from Six Road Borrow Pits in Arusha region, Tanzania

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ABSTRACT: Soil stabilization is an important civil engineering applications such as sub-grade construction, road construction, backfill and foundation construction to improve the physical, mechanical and chemical properties of soil by admixtures. Therefore, the objective of this paper is to predict the unconfined compressive strength (UCS) of stabilised soils sourced from six road borrow pits in Arusha region, Tanzania using appropriate standard techniques including Dynamic Cone Penetration (DCP), Grading Modulus (GM), Dry Density and Plastic Index (PI) Tests. The UCS values of soils ranges from 0.62 to 2.59 MPa and DCP-DN values varies from 3.88 to 10.20 mm/blow. The grading modulus of soils varies between 1.99 and 2.71 whereas, PI values from 0% to 14% and the Maximum Dry Density (MDD) ranges from 1520 to 2106 kg/m^3. The analysis shows adequate model fit, indicating a significant relationship between UCS and DCP DN values (Average penetration rate in mm/blow). The developed relationship will be suitable in estimating in-place strength of soils and reduce some tests, cost and time for performing quality assurance and quality control on stabilization for road works.

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The strength parameters of pavement material are most essential for monitoring and assessment of the quality of pavement. The quality of stabilised material may be evaluated by performing a set of unconfined compression tests on the samples prepared in laboratory or cored from the in-situ, which is comparable to the procedure normally used for assessment of field concrete (Mueller, 2020). The in-situ strength of stabilised soils are only obtained by coring, then cores are tested in laboratory (Griffin and Tingle, 2009). The stabilised soils required to have a minimum compressive strength of 2.1 MPa prior to coring (ASTM:D6236-11, 2011) in order to prevent excessive breakage or other internal damage to the sample. It is expensive, tedious, difficult and time consuming to perform onsite compressive strength of stabilised layer less than 2.1 MPa once placed onsite. Because coring of low strength stabilized soil is not strong as concrete therefore, breakage or damage to the specimens typically occurs at a time of coring or

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extraction which may cause inconsistency of in place unconfined compressive strength (Mueller, 2020).

In Tanzanian practice common stabilised materials acquire a strength of 0.5 MPa (CM) ,1.0 MPa (C1) and 2.0 MPa (C2) (MoW, 2000; MoW, 1999) which may be tedious and difficult to core. In accordance with the Tanzania standard, the maximum particle size shall be two-third of compacted cemented layer thickness. The particle size on field remains naturally as occurring from borrow pit whereas preparation of stabilized samples for laboratory DN and UCS test require material passing 20 mm test sieve.

The procedure may result to unrealistic selection of material for road construction and overdesign of pavement layer caused by removing particles size larger than 20 mm result in increase of laboratory DN value and decrease of field DN value. Several researchers have attempted to develop correlations between the Unconfined Compressive Strength (UCS) and the Dynamic Cone Penetrometer (DCP) for several soil types, stabilizing agents, and testing conditions. Tables 1 and 2, reproduced from Baya and Lingwanda (2023), summarize these existing correlations, highlighting their equations, test methods, sample characteristics, stabilizing agents, coefficients of determination, limitations, and applicability. In this study, the regression analysis for the relationship between UCS and DCP developed from the results tested with the exactly the same procedures, compactive effort, water content, density, depth and diameter of sample.

In this study, standard compaction test was used and the compacted specimen for UCS and DCP prepared at predetermined water content and density at laboratory. This minimized variations and provided more uniformity results throughout sample production and, eventually, more consistent developed regression models.

Hence, the objective of this paper was to predict the unconfined compressive strength of stabilised soils sourced from six road borrow pits in Arusha region, Tanzania

MATERIAL AND METHODS

Material: The study was done in Arusha region, which falls under a moderate climatic zone characterized by an average annual rainfall of 1,180 mm.(MoWTC, 2016). The Arusha region is predominantly by sandy soils and clay of moderate to good drainage (MoW, 1999). In this study, six districts were selected from Arusha region for acquiring samples. The soils were collected from the road borrow pits of six selected locations.

Then, the samples were tested for Gradation, Atterberg Limits, Proctor, Unconfined Compressive Strength (UCS) and laboratory Dynamic Cone Penetration (DCP). The sampling techniques involves taking samples excavated from trial pits by excavator as per BS 1377- 1: 1990. In order to avoid contamination of samples, top soils and overburden were removed during sampling. The disturbance class for samples on the degree of the process of sampling, handling and transport until finally laboratory testing classified as Class 3 (MoW, 2003).

Sufficient sample quantities were collected to accurately represent the original source material, ensuring adequate amounts for conducting the required laboratory tests. The tests were carried out for stabilised and unstabilised samples except for the particle size distribution which was performed only to the unstabilised materials and the UCS which was performed only to stabilised samples. Testing methods and procedure for this research are presented in Table 1

Hydrated lime and Ordinary Portland Cement were used to stabilize soil. The additional of lime and cement to the soil samples were 4.0%, 6.0%, 8.0 % and 2.0%, 3.0%, 4.5%, respectively. The selection of the amount of chemical stabilizer were based from existing studies and MoW (1999).

The samples from the three locations were stabilized with cement and other three stabilized with lime. The selection of stabilizer agents was based on MoW (2000) guidance. A total of 162 soil tests were conducted prior to stabilization, with the average summary of three test results from each borrow pit provided in Table 2.

The soil samples were classified as silty or clayey gravel and sand, classification group A-2-4, A-2-5, A-2-6 and A-2-7 as per AASHTO. The soil samples classified according to USCS as Clayey Sand with Gravel (SC), well-graded sand with silt (SW-SM) and poorly graded gravel with silt (GP-GM).

Particle Size Distribution: The Particle Size Distribution were achieved on soils collected from the road borrow pits for each location before stabilization. The test conducted as per BS 1377- 2: 1990 and CML test method 1.7. The sample preparation carried out by determination of moisture content and soaking riffled fraction sample into the water for 12 hours to separate fine particles which sticked to course particle.

Table 1: Testing Methods and Procedures used in the Study

S/No.	Description of Test Method	Test Method and Code
	Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications	ASTM: D6951/D6951M :2015
	Unconfined Compressive Strength (UCS) of stabilized Materials	TMH1-1986, Method A14, CML Test Method 1.19 and 1.20
	In-situ tests	BS 1377- 9: 1990
	General requirement and sample preparation	BS 1377- 1: 1990
	Classification tests	BS 1377- 2: 1990
	Compaction-related tests	BS 1377- 4: 1990
	Test on soil and gravel	CML test method 1.1 – 1.4, 1.8-1.9 and 1.10-1.22
	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)	ASTM D 2487 – 06
	Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes	AASHTO M 145-91

Table 2: Summary of average three test results prior to stabilization

location			Muriet	Lodung'oro	Engorora	Laandarai	Njorieti	Kilimamoto
Grading	% Passing	4.750	60.39	32.93	64.41	62.07	65.48	68.8
		2.000	38.45	14.39	41.21	39.25	47.02	48.99
		0.425	16.83	9.10	21.15	27.34	30.10	27.88
		0.075	6.88	5.59	9.39	20.34	23.49	17.99
	Grading Coefficient		48.68	29.93	48.18	44.02	57.08	49.70
	Grading Modulus (GM)		2.38	2.71	2.28	2.13	1.99	2.05
LL	%		43	42	43	41	37	31
PL	%		40	38	35	21	18	23
PI	%		3	5	8	20	19	9
LS	%		1	1	11	11	8	3
SP			12	13	236	306	244	93
MDD	Kg/m3		1552	1713	1544	2093	2095	2134
OMC	%		12.8	12.7	13.5	8.7	8.5	7.47
Classification	AASHTO		A-2-5	A-2-5	A-2-5	A-2-7	A-2-6	A-2-4
	USCS		SW-SM	GP-GM	SW-M	SC	SC	SC

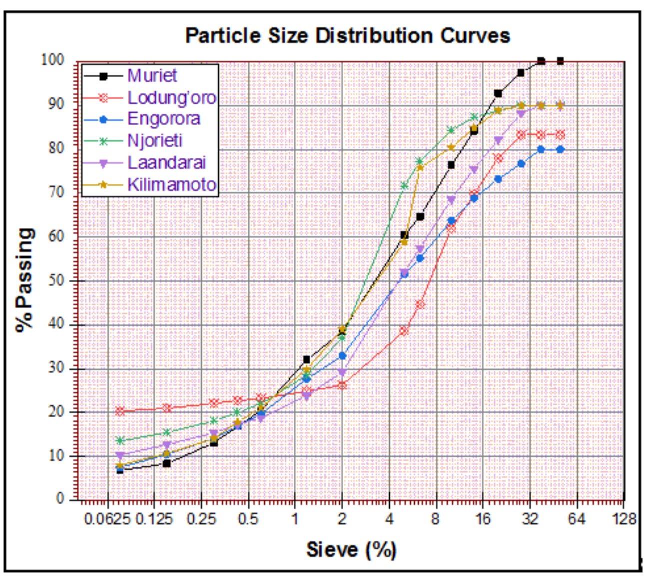
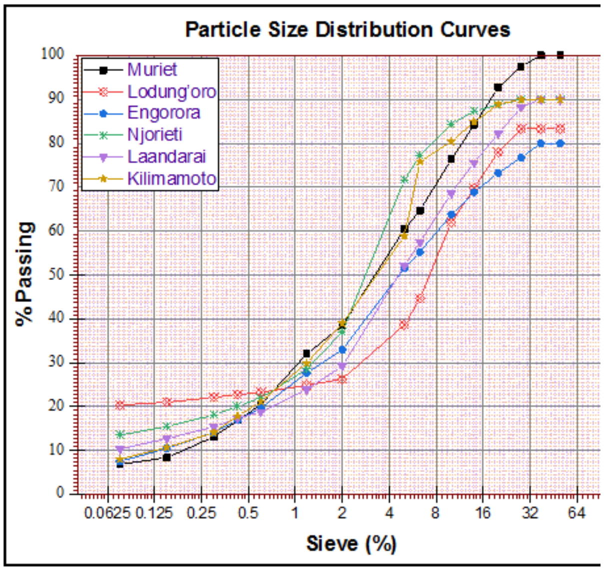


Fig. 1: Particle Sizes Distribution Curve of Soils

Then, the soaked sample were washed through 75µm sieve until water used for washing become clean to remove silt and clay sized particles. The samples retained on 75 µm sieve were dried in an oven at 105

℃ to 110 ℃ for 12 hours, any fines passing 75 µm after washing were measured and recorded. The dried samples were sieved through the appropriate BS sieves from 75 mm down to 75 µm and percentage passing each sieve were calculated.

The results of unstabilised soils samples for particle sizes distribution indicates that grading modulus ranges between 1.99 and 2.71. The plotted summary of average test results of distribution curve of particle sizes of this study is shown in Fig. *1*.



Atterberg's Limit Testing: Atterberg's limit tests conducted for the soil samples before stabilization collected from the borrow pits and after stabilization. The tests carried out as per BS 1377- 2: 1990, CML test method 1.2 and 1.3. The samples for Atterberg's limit tests of stabilized soil were obtained by blending soil and stabilizer content with water at OMC, then the samples were air dried prior to preparation for testing. All samples before and after stabilization were sieved through 425 µm sieve before testing. The tests covered determination of the liquid limit by cone penetrometer method, linear shrinkage and plastic limit. Liquid limit value of soil samples before stabilization ranging from 31% to 43%, while plastic limit value varies from 18% to 40%, and plasticity index values from 3 to 20. The soil classification plasticity chart of average test results before stabilization are shown in Fig. 2.

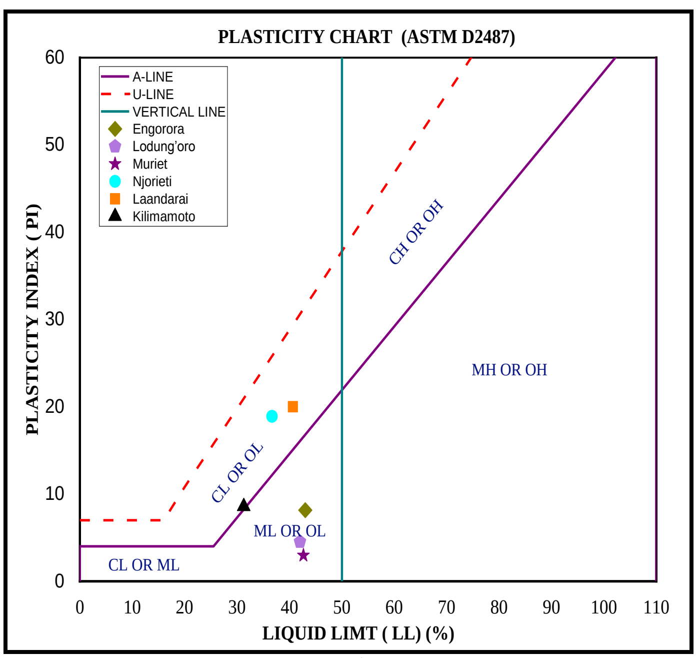


Fig. 2: Plasticity chart for average test results

Dry Density and Moisture Content: The unstabilised and stabilised soils of each stabilizer content were prepared and tested for compaction and moisture content as per BS 1377 and CML test method. The tests were performed to ensure the prepared samples for UCS and DCP are compacted at the same effort and mould size to the required OMC in order to achieve MDD for both stabilized and unstabilised samples. The stabilizers were admixed with soils before addition of water to the mixes. After additional of water, the mixtures were covered with plastic sample bags for about 4 hours. In order to make the mixtures consistent the covered mixtures were mixed every half an hour within 4 hours before compaction. The purpose of covering the mix with plastic bag was to avoid loss of moisture and mixing every half an hour within 4 hours before compaction aimed to make completely homogenous mixtures. The samples were compacted in a mould of 15.24 cm inner diameter and 12.7 cm inner height using 4.5 kg rammer with a drop of 45.0 cm by 62 blows per layer for 5 layers as compactive effort. The stabilizers were admixed with soils before water added. The samples for moisture content were taken for each specimen after compaction. The MDD for samples before stabilization varies from 1544 to 2134 kg/m^3 and OMC from 7.5 % to 13.5 %. The compaction curves of unstabilised soil which show the average MDD and OMC values are presented in Fig. 3.

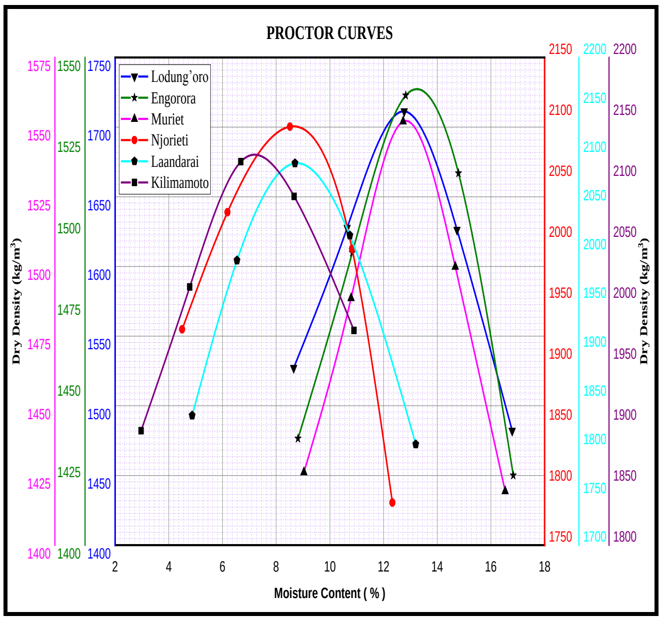


Fig. 3: Proctor Curves

Unconfined Compressive Strength (UCS): Unconfined Compressive Strength (UCS) test was achieved as per TMH1-1986, Method A14, CML Test Method 1.19 and 1.20. The soils from borrow pit were blended with specific percentage of stabilizer agent and then, water added to bring each material to Optimum Moisture Content (OMC). The amount of water added was the difference between the amount of water existing in the air-dry soil and that of the OMC. The blends were thoroughly mixed and covered in the same procedure as described for dry density. The mixed samples were compacted using 4.5 kg rammer with a drop of 45.0 cm in the CBR split mould of 15.24 cm inner diameter and height of 12.7 cm with 62 evenly spread blows to each of the 5 equally thick layers. The compacted samples were extracted from CBR split mould and cured for seven days in plastic bags immersed in water bath at a temperature of about 25℃. After seven days, the moulded samples were removed from water and plastic bags, then submerged in water for 4 hours and permitted to drain for at least 15 minutes, then placed to compression testing machine for crushing to total failure load. Nine specimens for each stabiliser content were made for compressive strength determination. The study shows the average UCS values varies from 1.23 to 2.11Mpa for lime at 4% to 8% and 0.62 to 2.59Mpa for cement at 2% to 4.5%.

Dynamic Cone Penetration (DCP): The DCP device used in the study comprises of a 16 mm diameter steel drive rod with a disposable 60 degree conical tip and a diameter at the base of 20 mm. The rod was topped with an anvil that was connected to a second steel rod. The top rod was used as a controller to permit an 8 kg hammer to be repeatedly raised and dropped to a fixed height of 57.5 cm. A vertical scale graduated by additions of 1.0 mm guided by sliding attachment was used for measuring penetration (ASTM:D6951, 2015). The procedure for determining the DN value of soils was same to that of the traditional UCS test except that a DCP was used to penetrate the moulded specimen in the CBR mould instead of the compression testing machine as indicated in Plate 1.

The laboratory DN test of stabilised soils were achieved on the samples prepared and compacted as per TMH1-1986, CML Test Method 1.19 and 1.20. To avoid a subsequent effect to the established correlations, the stabilised soil for laboratory DCP DN was compacted following exactly the same procedures used in the preparation and compaction of specimen for UCS test. Nine stabilised specimens of 15.24 cm diameter and height of 15.24 cm for each stabiliser content, 4 %, 6 % and 8 % for lime, and 1.5 %, 3 % and 4.5 % for cement expressed as the percentage by weight of dried soil were prepared for laboratory DN test. The specimens were cured for seven days in the sealed plastic bags immersed in the water bath at a maintained temperature of about 25℃ . After seven days the samples were removed from plastic bags and soaked in water of about 25 ℃ for 4 hours, then the specimen was placed in the in the BS steel CBR mould for laboratory DN test as described before.

The CBR mould with the moulded specimen secured to the base plate and the mould placed on the hard levelled surface, and the surchage weight placed on upper of the mould. The height of the compacted sample inside the mould were measured to allow the test to stop just before the tip of the cone knockouts the mould base. An unfilled CBR mould was placed upside down next to the mould with compacted sample, as shown in Plate 1 to support and level the base of the ruler. The DCP cone tip located vertically in the middle top of the compacted sample in the mould, then hit down cautiously till 3 mm shoulder of the cone was levelled with the compacted sample at the top and recorded as zero reading. The penetration to the compacted sample on the DCP ruler after every 1 blow were recorded. Knocking the DCP cone into the compacted specimen continued until just before the tip of the cone touches the bottom of the compacted specimen and stopped to avoid blunting the cone.

Plate 1: Typical set-up of laboratory DN test

The DCP data set were analysed using AfCAP LVR - DCP v.103 software developed by Council for Scientific and Industrial Research (CSIR) of South Africa to obtain DN value. The software analyses DCP in-situ data from new and existing pavements, laboratory DCP data and assess imported soils as inputs for the design of the pavement layers. The effect of confinement in the steel CBR mould virtually increases the strength of the material compared with that of the in-situ (Pinard *et al*., 2020; MoTPW, 2020; MoWTC, 2016). Therefore, the obtained laboratory best fit DN values were adjusted to provide a correction to the field DN using data shown in Table 3.

Table 3: Relationship between required field DN and laboratory DCP DN values for materials *(MoWTC, 2016)*

Max. Field DN value (mm/bl)	19.0	14.0	9.0	8.0	6.0	5.9	4.6	4.0	3.2	2.6	2.5
Max. Laboratory DN value (mm/bl)	17.0	12.0	7.2	6.2	4.7	4.4	3.4	2.9	2.2	1.8	1.7

RESULTS AND DISCUSSION

The classification tests were conducted for both stabilised and unstabilised soil in order to allow prediction of the suitability of material before stabilization based on an assessment of the classification tests for comparison with the DN and UCS value. The results of this study shows that OMC, MDD, LS and PI are influenced by adding of cement or lime similar to the studies by Vakili *et al*. (2021), Asgari, *et. al*. (2013), and Holderby and Cerato (2011). The MDD of the lime stabilized soil was lower than the cement treated soil. However, the MDD of treated soils were lower than of the untreated soils, whereas the OMC of the stabilised soils were higher for the amount of lime than the similar amount of cement. Summary of test results after stabilization are shown in Table 4. The DCP and UCS results are discussed below in the following sub-sections.

DCP test results: The DCP data analyzed using AfCAP LVR - DCP v.103 software. The software inputs were depth of penetration and number of blows in Laboratory Project Type Module of AfCAP LVR - DCP v.103 software to get DCP-DN value. The laboratory DCP-DN value for the samples in this study were taken as the gradient of the best fit line from the central of the mould. The gradient calculated as the difference in penetration versus the difference in the number of blows. The best fit DN value is obtained through removing penetration of 15mm top and bottom with the corresponding blows. In the studies of Vakili *et al*. (2021), Uchaipichat (2019), Enayatpour *et al*. (2006), McElvaney and Bundadidjatnika (1991), Patel and Patel (2013), Patel and Patel (2011) and Patel *et al*. (2013) used weighted average DN values for regression analysis. However they conducted DCP and UCS in the laboratory, the DN values were not taken as the best fit. The laboratory DCP-DN values for analysis recommended to be taken as best fit. This is because the laboratory DCP-DN value in the top and bottom 1.5 cm of the sample in the mould regularly deviates from best fit due to deficiency of vertical confinement at the top and may be a higher density at the lowermost of the mould (Pinard *et al*., 2020; MoTPW, 2020; MoWTC, 2016). The laboratory DN value obtained in this study were adjusted to provide a correction to the field DN due to the effect of confinement in the steel CBR mould as indicated in Table 3. Vakili *et al*. (2021), Uchaipichat (2019), Enayatpour *et al*. (2006), McElvaney and Bundadidjatnika (1991), Patel and Patel (2013), Patel and Patel (2011) and Patel *et al*. (2013) in their researches the laboratory DCP-DN values were not adjusted for the effect of confinement in mould. The summary of the average results of laboratory DN value for three specimens with the similar compactive effort, moisture content and stabilizer content after stabilization are shown in Table 4. **Error! Reference source not found.**The DCP-DN value of stabilised soil samples obtained from the laboratory varies from 3.88 to 10.2 for lime at 4% to 8% and 2.85 to 10.20 for cement at 2% to 4.5%. The DCP-DN value decrease with increases of stabilizer content and UCS values. The DCP-DN value of cement stabilised soils are higher than the lime stabilised soils of the same content agreed with the study by Enayatapour *et al*. (2006). The adjusted laboratory DCP-DN values for correction to the field DN provide alternative methods of field compaction by evaluating the percentage of field and laboratory DN values.

UCS test results: The UCS and DCP tests were done at the similar moisture contents and densities. It was being observed that the average UCS values ranges from 1.23 to 2.11Mpa for lime at 4% to 8% and 0.62 to 2.59Mpa for cement at 2% to 4.5%. The test results shows that UCS value increases with stabilizer content and decrease DN values similarly to Vakili *et al*. (2021), Uchaipichat (2019), Enayatapour *et al*. (2006) McElvaney and Bundadidjatnika (1991). The UCS value influenced with plastic index and amount of stabilizer. The laboratory moulded stabilized specimens for UCS and DCP with cement content less than 2.0 were broken during curing and/or soaking. Similarly for the specimens with lime content less than 4.0% were damaged. The study found that soils with PI less than or equal 8 before stabilization requires more than 2% of cement and 4.0% of lime to mould specimens for UCS. This indicate that, the low plasticity soil requires lager amount of stabiliser initially to produce specimen for the UCS and DCP until it reaches optimum, then the increase of cement with plastic index of soil can cause cracks and consequently decrease of UCS (Vakil et. al, 2020). The study shows that Clayey Sand with Gravel (SC) soil needs minimum 4.0% lime to mould laboratory specimen for UCS and DCP, whereas well-graded sand with silt (SW-SM) requires cement content greater than 2.0%.

Multiple regression mode of DCP-DN value, grading modulus, dry density and plastic index to predict UCS: In this study, multiple regression analysis was performed to predict whether the DN value, grading modulus, dry density and plastic index to predict the UCS value using IBM SPSS Statistics version 27 software. The selected variables for soil properties were in accordance with MoW(2000, 1999) requirements for materials in cemented layers. Vakili *et al*. (2021), Alshkane and Rashed (2020), Uchaipichat and Anuchit (2019), Patel and Patel (2011) established single power regression model to predict UCS value from DCP-DN value. Chukka and Chakravarthi (2012), and McElvaney and Bundadidjatnika (1991) developed single logarithmic regression model. Sisodia and Amin (2017) developed single linear regression model.

The multiple regression analysis is recommended to establish a reliable relationship (Baya and Lingwanda, 2023; Alshkane *et al*., 2020). Patel and Patel (2012), Holderby and Cerato (2011), Enayatapour *et al*. (2006) developed multiple variable regression analysis to predict UCS value from DCP-DN value and other soil properties.

Table 4: Summary of the stabilized test results

Location	Type of Stabilizer	Stabilizer Content	Sample No.	LL	PL	PI	LS	MDD	OMC	Corrected best fit DCP-DN Value		UCS Value	
				(%)	(%)	(%)	(%)	(Kg/m3)	(%)	Dry Density	mm/blow	Dry Density	Mpa
Muriet	Cement	2.0%	1	33	NP	NP	0	1548	13.2	1549	6.49	1549	1.12
			2	32	NP	NP	0	1547	13.2	1545	6.37	1549	1.13
			3	33	NP	NP	0	1552	13.2	1549	7.18	1549	1.18
	Cement	3.0%	1	38	NP	NP	0	1537	13.2	1538	4.27	1538	2.15
			2	39	NP	NP	0	1536	13.4	1539	4.27	1537	2.13
			3	39	NP	NP	0	1530	13.4	1532	4.26	1535	2.19
	Cement	4.5%	1	40	NP	NP	0	1520	14.0	1524	3.30	1521	2.58
			2	41	NP	NP	0	1523	13.8	1524	3.39	1524	2.55
			3	42	NP	NP	0	1522	13.8	1525	3.35	1520	2.59
Lodung'oro	Cement	2.0%	1	41	NP	NP	0	1690	16.6	1697	10.20	1687	0.62
			2	42	NP	NP	0	1693	16.8	1698	10.17	1686	0.64
			3	41	NP	NP	0	1692	16.7	1698	9.91	1683	0.62
	Cement	3.0%	1	42	NP	NP	0	1685	17.0	1684	7.52	1683	0.85
			2	43	NP	NP	0	1683	17.3	1684	7.56	1683	0.88
			3	39	NP	NP	0	1680	17.1	1684	7.43	1683	0.86
	Cement	4.5%	1	46	NP	NP	0	1674	17.2	1668	5.87	1668	1.37
			2	45	NP	NP	0	1670	17.3	1671	5.87	1664	1.36
			3	44	NP	NP	0	1668	17.4	1670	6.04	1671	1.34
Engorora	Cement	2.0%	1	43	NP	NP	2	1542	13.0	1544	6.06	1543	1.21
			2	43	NP	NP	2	1540	13.5	1541	6.04	1542	1.21
			3	43	NP	NP	2	1545	13.5	1539	6.11	1545	1.20
	Cement	3.0%	1	42	NP	NP	1	1532	16.2	1532	4.28	1530	1.61
			2	43	NP	NP	1	1533	16.3	1531	4.49	1535	1.60
			3	42	NP	NP	1	1530	16.6	1535	4.08	1527	1.59
	Cement	4.5%	1	40	NP	NP	1	1525	16.8	1522	2.99	1528	2.38
			2	39	NP	NP	1	1520	17.0	1522	2.85	1523	2.35
			3	40	NP	NP	1	1524	16.6	1524	2.92	1522	2.43
Laandarai	Lime	4.0%	1	39	26	14	7	2080	12.0	2080	5.35	2081	1.26
			2	40	27	13	6	2081	12.1	2080	5.29	2080	1.27
			3	39	25	14	7	2078	12.2	2078	5.12	2076	1.27
	Lime	6.0%	1	37	28	10	5	2074	14.6	2077	5.19	2074	1.72
			2	38	28	11	5	2071	14.7	2073	5.12	2072	1.70
			3	38	28	10	5	2075	14.4	2077	4.98	2073	1.76
	Lime	8.0%	1	40	31	9	4	2060	16.2	2061	4.09	2060	2.05
			2	40	30	10	4	2061	15.8	2061	4.43	2061	2.04
			3	38	30	8	4	2062	15.7	2062	4.39	2062	2.04
Njorieti	Lime	4.0%	1	34	26	8	4	2082	9.2	2081	10.09	2082	1.38
			2	35	27	8	4	2085	9.3	2085	9.95	2083	1.39
			3	34	26	8	4	2086	9.5	2083	10.20	2084	1.40
	Lime	6.0%	1	31	26	5	1	2075	10.2	2073	7.43	2076	1.51
			2	31	26	5	2	2078	10.4	2075	7.80	2076	1.52
			3	31	26	5	2	2078	10.5	2076	7.44	2076	1.51
	Lime	8.0%	1	28	25	3	1	2060	11.2	2061	5.91	2061	1.79
			2	28	25	3	1	2063	11.6	2063	5.88	2062	1.82
			3	28	26	2	1	2060	11.7	2061	5.92	2060	1.80
Kilimamoto	Lime	4.0%	1	33	26	8	4	2106	7.6	2105	5.20	2105	1.23
			2	33	25	9	4	2105	7.5	2105	5.49	2107	1.39
			3	32	24	8	4	2104	7.8	2106	5.25	2107	1.33
	Lime	6.0%	1	31	24	6	3	2096	8.0	2093	4.42	2097	1.62
			2	31	25	7	3	2094	8.1	2093	4.58	2095	1.61
			3	30	23	7	3	2095	8.2	2096	4.46	2094	1.62
	Lime	8.0%	1	30	25	5	2	2080	8.8	2081	3.88	2085	2.09
			2	30	26	4	2	2084	8.5	2083	4.05	2084	2.09
			3	30	25	5	2	2082	8.5	2084	4.13	2082	2.11

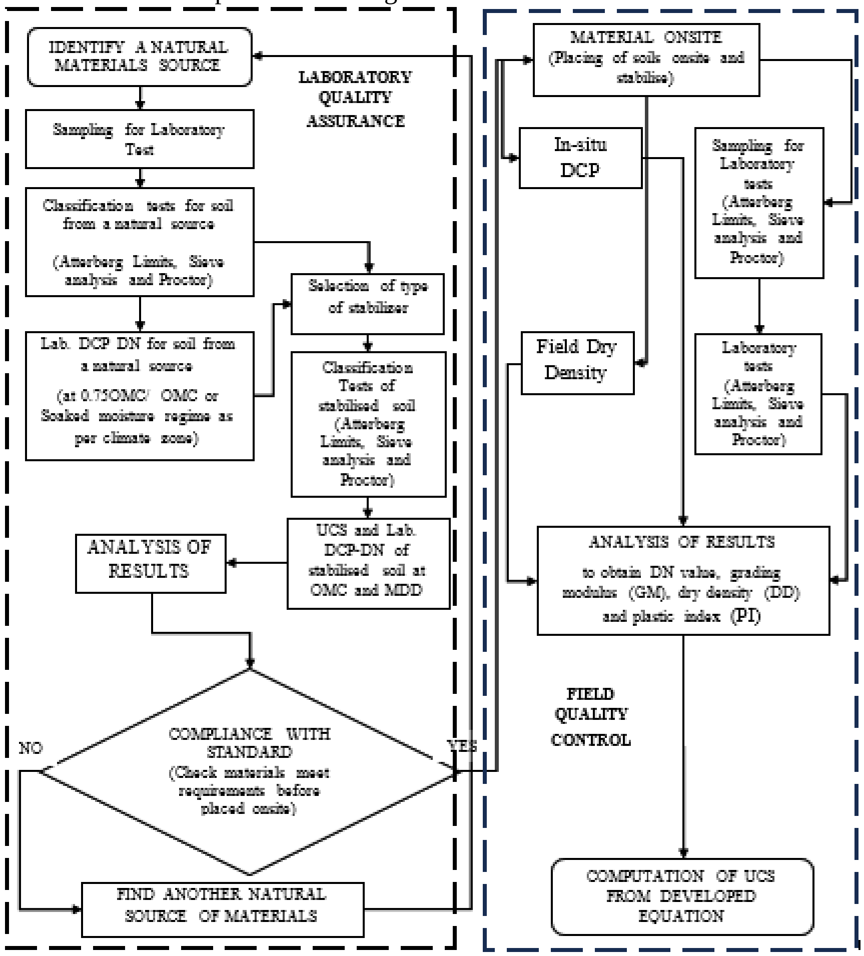


Fig. 4: The flow chart presentation of the application of developed equation

$$UCS_{value} = 4.415 - 0.174\, DN_{\ value} - 0.784GM + 3.444x10^{-5}\, DD - 0.031PI \qquad (1)$$

Holderby and Cerato (2011), and Enayatapour *et al*. (2006) developed equation to predict UCS value from the field DCP-DN value, chemical stabilizer content and curing time. Patel and Patel (2012), developed relationship from multiple regression analysis to predict UCS from DCP-DN value, maximum dry density (MDD), modified liquid limit (WLM) and optimum moisture content (OMC) of subgrades from experimental investigations of soils in soaked conditions. The variables used in the developed relationship by Enayatapour *et al*. (2006), Holderby and Cerato (2011) and, Patel and Patel (2012) were not related to the standard specification for road works (MoW, 2000; MoW, 1999). Therefore, they may not be suitable for estimation of strength for quality control and assurance of cemented pavement layers commonly used in Tanzania. Patel and Patel (2013), Patel *et al*. (2013), Patel and Patel (2011), Enayatpour *et al*. (2006), and McElvaney and Bundadidjatnika (1991) suitable for DCP-DN values larger than 20 (Baya and Lingwanda, 2023; Alshkane *et al*., 2020). In this study, the developed Equation 1 elucidates the coefficient of determination, $R^2 = 0.657$, indicating a reasonably good model fit and a significant relationship between the variables. (Hair *et al*., 2011; Chin, 1998; Falk and Miller, 1992). From developed Equation 1 the DCP-DN value (DN_{value}) decreases UCS value (UCS_{value}) likewise grading modulus (GM) and plastic index (PI) decreases UCS value. Dry density (DD) slightly increases UCS value (UCS_{value}) This is because samples were prepared on predetermined density and moisture at laboratory (at OMC and MDD). Which cause the variations of MDD for stabilised soil slightly differs with the stabiliser content. The DCP-DN value highly influenced by dry density (DD), its effect merged in DCP-DN value.

This indicate that even if better soils not compacted properly will be insignificance to the UCS and DCP-DN value. There is always a minor difference in the dry densities of samples compacted with the similar effort and moisture content (Pinard *et al*., 2020).

Application of developed correlation: The developed mode will be useful in assessing strength of soils for performing laboratory quality assurance and field quality control for the stabilisation of road works. The initial procedure is to identify natural source of material to be used for construction of stabilized road.

Then, sampling of the soil from the natural source for Atterberg limits, particles size distribution, proctor and laboratory DN test. The laboratory DN test will be tested according to the anticipated long term moisture regime and climatic zone of the site as per MoW (1999). The percentage passing 75 µm and plasticity index test results will enable the selection of the type of stabilizer in accordance with the type of soil as per MoW (2000). After selection of type of stabiliser, the soil samples will be tested for Atterberg limits, proctor, laboratory DN and UCS test at different stabilizer content to obtain optimum binder content and stabilization class. Then, the test results analysis will be conducted on condition that, the soil from the natural source comply with the standard of the stabilization class as per MoW (2000). Provided the source meets the requirement will be approved for the permanent stabilisation works onsite unless another source shall be identified. The soil from approved source will be paced on the road for construction. The sampling will be done on fresh mixed soils onsite with their insitu stabilizer content and OMC attained from the laboratory. The samples will be tested for grading modulus (GM) and plastic index (PI) tests. The insitu DCP test, moisture content (MC) at DCP penetration and field dry density (DD) tests will be performed after seven days on the same location on compacted insitu stabilised layer on road. Lastly, the analysis of laboratory and field test results will be done to get inputs of the developed Equation 1 for the estimation of insitu UCS. The graphical presentation of the developed equation and its application for quality assurance and quality control is presented in Fig 4**Error! Reference source not found.**.

Conclusion: The aim of this study is to predict UCS from DCP of stabilised soils. Performing insitu UCS test in the pavement layer can be difficult, time consuming and rarely attempted but not reliable in Tanzania. This is because common cemented layers as per Tanzania specification for road works classified as CM, C1 and C2 which are difficult to core. Instead, the samples with moisture content about OMC are usually taken for laboratory testing when stabilization works onsite is on progress. The laboratory UCS attained from the in-situ wet samples tested at laboratory are taken as insitu UCS. This method cannot accurately represent the actual site conditions because the compaction procedures in the field are not exact to those in the laboratory. Laboratory compaction is higher than field due to the controlled testing conditions. Likewise, the strength of stabilised pavement layer is highly influenced by the field condition rather than laboratory.

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Data Availability Statement: Data are available upon request from the corresponding author.

REFERENCES

Abdulrahman, HM (2015). The Dynamic Cone Penetration Test: A Review of Its Correlations and Applications. *Internl. Confr. Adv. Civl. Environ. Eng*.

Al-Amoudi, OB; Khan, K; Al-Kahtani, NS (2010). Stabilization of a Saudi calcareous marl soil. *Constr. Buildg. Materials.* 24 1848–1854. DOI: https://doi.org/10.1016/j.conbuildmat.2010.04.019

Alshkane, YM; Rashed, KA; Daoud, HS (2020). Unconfined Compressive Strength (UCS) and Compressibility Indices Predictions from Dynamic Cone Penetrometer Index (DCP) for Cohesive Soil in Kurdistan Region/Iraq. *Geotech. Geol. Eng.* 38:3683–3695

Amadi, AA; Sadiku, S; Abdullahi, M; Danyaya, HA (2018). Case study of construction quality control monitoring and strength evaluation of a lateritic pavement using the dynamic cone penetrometer. *Internl. J. Pvnt. Res. and Technol.* 11: 530–539. DOI: https://doi.org/doi.org/10.1016/j.ijprt.2018.07.001

Amena, S; Tsige, D; Quezon, PT (2021). Modelling unconfined compressive strength of fine-grained soils: Application of dynamic cone penetration to predict foundation soil strength. *Appl. J. Environ. Eng. Sci.* 7(4) 348-359.

Amini, F (2003). Potential Applications of the Static and Dynamic Cone Penetrometers in MDOT Pavement Design and Construction. Jackson State University, Department of Civil Engineering, Mississippi Department of Transportation and U.S. Department of Transportation Federal Highway Administration, Mississippi, Jackson, MS 39217-0168.

Arumugam, RA; Rashid. A; AS; Yaacob, H; Noor, NM (2014). Correlation between Liquidity Index (LI) and Unconfined Compressive Strength of Stabilized Silty Clay. *Astrn J. B. Appl. Sci.* 7(10): 450-454.

Asgari, MR; Dezfuli, AB; Bayat, M (2013). Experimental study on stabilization of a low plasticity clayey soil with cement/lime. *Arab J Geosci.* DOI: https://doi.org/10.1007/s12517-013-1173-1

ASTM: D2166 – 06. (2007, January). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. Designation: D2166 – 06.

ASTM: D6236-11 (2011, February). Standard Guide for Coring and Logging Soil-Cement or Lime-Stabilized Soil. Designation: D6236 − 11.

ASTM: D6951 (2015, May). Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications. Designation: D6951/D6951M − 09.

Azmi, H (1996). The Effects of Material Parameters on Dynamic Cone Penetrometer Results for Fine-Grained Soils and Granular Materials. Oklahoma State University, Stillwater, Oklahoma.

Baya, LB; Lingwanda, MI (2023). Review of Correlations between Unconfined Compressive Strength (UCS) Values and Dynamic Cone Penetrometer (DCP–DN) Values of Stabilized Soils. *MUST J. Res. Dev.* II (5), 613-626.

Chatterjee, S; Hadi, AS (2012). Regression Analysis by Example (5th ed.). New York, United States of America: A John Wiley and Sons, INC.

Chin, WW (1998). The partial least squares approach to structural equation modelling. (G. A. Marcoulides, Ed.) Modern methods for business research.

Chukka, D; Chakravarthi, VK (2012). Evaluation of Properties of Soil Subgrade Using Dynamic Cone Penetration Index: A Case Study. *Internl. J. Eng. Res. Dev*, 4(4), 07-15.

Dirriba, A; Teferra, A (2017). Developing Correlation between Dynamic Cone Penetration Index (DCPI) and Unconfined Compression Strength (UCS) of the Soils in Alem Gena Town. Addis Ababa Institute of Technology, Department of Civil and Environmental Engineering.

Edil, TB; Benson, CH (2005). Investigation of the DCP and the SSG as Alternative Methods to Determine Subgrade Stability. University of Wisconsin-Madison, Department of Civil and Environmental Engineering, Madison, WI 53706.

Enayatpour, S; Puppala, AJ; Vasudevan, H (2006). Dynamic Cone Penetrometer to Evaluate Unconfined Compressive Strength of Stabilised Soils. *S. Geom. Charatn.* (GSP 149), 285 - 292.

Falk, RF; Miller, NB (1992). A primer for soft modelling. University of Akron Press. Griffin, J. R., and Tingle, J. S. (2009). In Situ Evaluation of Unsurfaced Portland Cement-Stabilized Soil Airfields.

Hahs-Vaughn, DL (2017). Applied Multivariate Statistical Concepts. New York, United States of America: Routledge, 711 Third Avenue, New York, NY 10017.

Hair, JF; Ringle, CM; Sarste, M (2011, March). PLS-SEM: Indeed, a silver bullet. *J. Markt Thry Pract*. 19(2), 139–151. DOI: https://doi.org/10.2753/MTP1069-6679190202

Holderby, E; Cerato, AB (2011). Field Verification of Stabilized Soil Strength. *Geo-Frontrs 2011 © ASCE 2011, 2454 - 2463.*

Livneh, M; Ishai, I; Livneh, NA (1995). The effect of vertical confinement on the DCP strength values in pavement and subgrade evaluation. Transportation Research Board (1473).

Lomax, RG; Hahs-Vaughn, DL (2012). An introduction to statistical concepts (3rd ed.). New York, United States of America: Taylor and Francis Group.

MacRobert, CJ; Bernstein, GS; Nchabeleng, MM (2019). Dynamic Cone Penetrometer (DCP) Relative Density Correlations for Sands. Soils and Rocks, Sao Paulo, 42(2): 201-207. DOI: https://doi.org/10.28927/SR.422201

McElvaney, J; Bunadidjatnika, I (1991). Strength Evaluation of Lime - Stabilised Pavement Foundation Using the Dynamic Cone Penetration. *Austr. Rd Res.*

McLaughlin, JB (2017). Evaluation of Methods to Assess the Strength of Soil Cement Base. Master Thesis, Auburn University, Department of Civil Engineering, Auburn, Alabama.

MoTPW (2020). Low Volume Roads Manual (Vol. 1). Pretoria, South Africa: Tshwane University of Technology.

MoW (1999). Pavement and Materials Design Manual. Dar Es Salaam, Tanzania: Allkopi AS, Oslo Norway.

MoW (2000). Laboratory Testing Manual. Dar Es Salaam, Tanzania/Dar Es Salaam: Novum Grafisk AS, Skjetten Norway.

MoW (2000). Standard Specifications for Road Works. Dar Es Salaam, Tanzania: Novum Grafisk AS, Skjetten, Norway.

MoW;TANROADS (2003). Field Testing Manual, Central Materials Laboratory (CML). Dar es Salaam, Tanzania: Elanders Novum AS, Oslo Norway.

MoWTC (2016). Low Volume Roads Manual. Dar es Salaam, Tanzania: Goldprints.

Mueller, E. E. (2020). Development of Implementation Guidelines to Assess the Strength of Soil Cement Base in Alabama. Auburn University, Department of Civil Engineering, Alabama.

Paige-Green, P; Plessis, LD (2009). The use and interpretation of the dynamic cone penetrometer (DCP) test. CSIR Built Environment.

Paige-Green, P; Van Zyl, GD (2019). A Review of the DCP-DN Pavement Design Method for Low Volume Sealed Roads: *Dev. Appl. J. Transt. Technol.* (2160-0473), 397- 422.

Patel, MA; Patel, HS (2011). Experimental Investigation on Cement - Fly ash Stabilised Soil to Formulate Correlation between DCP and PBT, UCS and CBR Test Results. *Intern. J. Adv. Eng. Technol.*, 2(3). *666-678*

Patel, MA; Patel, HS (2012). Experimental Study to Correlate the Test Results of PBT, UCS, and CBR with DCP on Various soils in soaked condition. *Inter. J. Eng. (IJE)*, 6(5).

Patel, MA; Patel, HS (2013). Laboratory Assessment to Correlate Strength Parameter from Physical properties of Subgrade. Non-Circuit Branches of the 3rd Nirma University *Internl. Cnfnce on Eng.* (NUiCONE 2012), 200-209. DOI: https://doi.org/10.1016/j.proeng.2013.01.029

Patel, MA; Patel, HS; Dadhich, G (2013). Prediction of Subgrade Strength Parameters from Dynamic Cone Penetrometer Index, Modified Liquid Limit and Moisture Content.

Pedhazur, EJ(1997). Multiple Regression in Behavioural Research, Explanation and prediction (3rd ed.). (E. McPeek, Ed.) New York, Brooklyn, United States of America: Christopher P. Klein.

Pinard, MI; Hongve, J; Infra Africa (Pty) Ltd. (2020). Pavement Design of Low Volume Roads using the DCP-DN Method. London: ReCAP for UK aid.

Pituch, KA; Stevens, JP (2016). Applied Multivariate Statistics for the Social Sciences (6th ed.). New York, United States of America: Routledge.

Rolt, J; Michael, IP (2016). Designing low-volume roads using the dynamic cone penetrometer. Developing countries/pavement design/roads and highways, 169(TR3), 163 - 172.

Salgado, R; Yoon, S (2003). Dynamic Cone Penetration Test (DCPT) for Subgrade Assessment. Purdue University, Joint Transportation Research Program, Indiana Department of Transportation and U.S. Department of Transportation Federal Highway Administration, West Lafayette, Indiana.

Samuel, P; Done, S; TRL (2005). DCP analysis and design of low volume roads by new TRL software UK DCP. Seminar: Sustainable Access and Local Resource Solutions.

Siekmeier, J; Pinta, C; Merth, S; Jensen, J; Davich, P; Camargo, F; Beyer, M (2009). Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance. Minnesota Department of Transportation, Maplewood, Minnesota 55109.

Sisodia, EM; Amin, AA (2017). Sub-Grade Soil Assessment Using Correlation between Dynamic Cone Penetration Indexes (DCPI) and Unconfined Compressive Strength (UCS). *Internl. J. Res. Appl. Sci. Eng. Technol.* 5(8), 45 - 49. DOI: https://doi.org/10.222214/ijraset.2017.8008

Tingle, JS; Jersey, SR (2007). Evaluation of In Situ Pavement Layers with the Dynamic Cone Penetrometer (DCP). *U.S. Army Eng. Res. Dev. Ctr*, 1-24.

TMH1 (1986). Standard Methods of Testing Road Construction Materials. (2, Ed.) Technical Methods for Highways.

Uchaipichat, A (2019). Correlation between Unconfined Compressive Strength and Penetration Index Obtained from DCP Tests for Cemented Lateritic Soils. *Eng. Mtrls.* 814(1662-9795), 399 - 403.

Vakili, AH; Salimi, M; Shamsi, M (2021). Application of the dynamic cone penetrometer test for determining the geotechnical characteristics of marl soils treated by lime. *Heliyon* 7 (2021) e08062, 1-7. DOI: https://doi.org/https://doi.org/10.1016/j.heliyon.2021.e08062

Yong, RN; Ouhadi, VR. (2006). Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils. *Appl. Cly. Sci.* 35: 238–249.