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Resilient Modulus of Siliciclastic Unbound Granular Materials under Repeated Wheel Loading

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ABSTRACT

The Resilient Modulus (M_r) is a fundamental material property input in modern Mechanistic-Empirical (M-E) pavements structural design. Empirical pavement design methods have been in use over a long period during which large databases of four-days-soaked California Bearing Ratio (CBR) values at or near the Maximum Dry Density have been generated in the strength assessments for Unbound Granular Materials (UGMs). In the adoption of the M-E design approach researchers have so far attempted with various degrees of success to develop models to derive resilient modulus from the conventional CBR-based databases. This study provides an extensive laboratory experimental study to investigate the resilient modulus of siliciclastic unbound granular materials under cyclic loading. The study involved samples collected from twelve active roads construction borrow areas in Iringa Region in Tanzania. The materials were fully characterised at Tanzania National Roads Agency Central Materials Laboratory (TANROADS CML) to enable classification of the materials in the empirical approach to which a range of materials of CBR Grades 25 to 80 were defined. Further, the mineralogy of the samples was assessed by X-Ray Diffraction (XRD) using inXitu Bench top XRD 231 analyser at University of Dar es Salaam Geology Department. A servo-hydraulic Universal Testing Machine-130 at TANROADS CML was used to simulate Repeated Load Test on the multiple samples from which resilient modulus of the UGMs were determined. A soaked CBR - M_r prediction model was then developed which showed strong non-linear relationship and correlated well with existing databases. Based on this study, the developed model has shown better performance compared to other studies and gives a good estimate of M_r values without performing the Repeated Load Triaxial (RLT) test for M_r determination. In addition, estimates of M_r values for each class of siliciclastic UGMs has been achieved and tabulated using the developed model.

Key words: *resilient modulus; granular materials; siliciclastic materials; base course; sub base.*

INTRODUCTION

The stiffness of Unbound Granular Materials (UGMs) used in pavement sub-base and base course construction plays a significant role in the performance of flexible pavement structures subjected to repeated wheel loading. Reduced pavement life and higher pavement maintenance costs are expected whenever there is poor performance of UGMs which culminates to severe distresses such as rutting, depression and corrugation Cerni et al., (2015).

Similarly, mineralogical compositions of UGMs play a significant role on its performance under repeated wheel loading. Feldspar as the major rock forming mineral account for over 50% of the earth crust and Quartz being the second major Ineson, (1990). Siliciclastic UGMs are those made of 50% or more clastic fragments derived from pre-existing siliceous rock thus being rich in silica and feldspar minerals Murphy et al., (2017). Siliciclastic granular materials are non carbonaceous sediments that are broken from pre-existing rocks, transported, and re-deposited prior to forming other rocks Murphy et al., (2017).

Bilodeau et al.(2011); Cerni et al. (2015) and Haghighi et al. (2017) reported that UGM layers experience both elastic/resilient deformation and permanent/plastic deformation under repeated traffic loading, as seen in Figure 1 below. The elastic behaviour represents the recoverable part of the deformations characterized by elastic resilient modulus, M_r Araya (2011). M_r is a key parameter in structural designing of flexible pavements and prediction of its future performance under repeated traffic loading in Mechanistic Empirical Design Approach NCHRP, (2004).

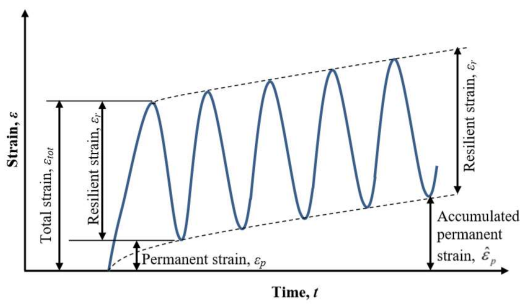

Figure 1: Strains in UGMs under repeated loading (Rahman, 2015)

M_r is affected by a number of factors Araya, (2011); Cary & Zapata, (2011) including; i) Stress levels, ii) Moisture content or degree of saturation, iii) Degree of compaction, iv)Frequency of loading and v) Type of materials. Arithmetically, the resilient modulus is the ratio of repeated deviator axial stress to the recoverable strain AASHTO (2017).

$$M_r = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

where

M_r = the resilient modulus
σ_d=repeated deviator axial stress
ε_r = recoverable strain

The Mechanistic Empirical (M-E) design procedure uses stresses, strains and displacements expected in the field under realistic traffic and environmental conditions NCHRP, (2004). Empirically, pavement design involves the California Bearing Ratio (CBR) test as a primary testing procedure MoWT, (1999).The CBR provides an indication of strength classification of unbound granular materials for sub base and base course layers. Materials with soaked CBR values greater than 25% and 45% after proctor compaction to 95% of their corresponding Maximum Dry Density(MDDs), classify as G25 and G45 respectively and soaked CBR values of greater than 60% and 80% after proctor compaction to 98% of their corresponding MDDs, classify as G60 and G80 respectively MoWT, (1999). The disadvantage of CBR testing procedure is that it cannot characterize the properties of UGMs on cyclic loading to simulate the actual loading mechanism occurring on the constructed pavement structures due to traffic loading. As such, the response of granular materials to cumulative traffic loading cannot be quantified on the basis of the CBR testing method alone Arshad, (2019); George & Kumar, (2018); Leung et al., 2013; NCHRP, (2001).Traffic loading on a pavement structure has two main components; the stress applied and the frequency of repetition of that stress(Araya, 2011). For pavement design purposes, the components are frequently simplified into the number of repeated standard axial load expressed in units of an equivalent standard axle Araya, (2011). However, the actual pavement loadings are complex and can be well described taking into consideration the duration, frequency and magnitude of stress applied which are always not constant throughout the pavement life Araya, (2011). In addition, the magnitude of stress varies with the magnitude of the traffic loads, properties and thickness of the overlaying pavement layer Gu et al., (2012); Wang et al., (2017).By taking into consideration the stress levels typically induced by a moving wheel load, elements in a pavement structure experience various combinations of horizontal (σ_h), vertical (σ_v) and shear (τ) stress with time as shown in Figure 2 below. Shear stress reverses as the tyre passes and as such, there is a rotation of the axis of the principal stress Gu et al., (2012; Wang et al.,(2017).

M_r values being determined in laboratories through Repeated Load Triaxial (RLT) tests require sophisticated equipment and highly skilled personnel which makes them a costly parameter to evaluate routinely for road infrastructure design in developing countries Arshad, (2019); George & Kumar, (2018); Leung et al.,(2013). However, M_r can be predicted through correlations with other parameters like CBR, Resistance values, Plasticity indices (PI) or Shrinkage limit (SL)Makwana,(2019). Early model equations developed by different researchers to obtain M_r values from CBR values are presented in Table 1 below. This study aimed at evaluating M_r values and determining the relationship between M_r and CBR values of siliciclastic UGMs classes G25, G45, G60 and G80.

Table 1: Model equations to obtain M_r from CBR values

S/ No.	Organization	Equation	Reference
1	The Shell Oil	$M_r(MPa) = 10.35CBR$	(Dione et al., 2015; Makwana, 2019)
2	The U.S. Army corps of Engineers (USAGE)	$M_r(MPa) = 37.3CBR^{0.71}$	(Dione et al., 2015; Makwana, 2019)
3	The South African Council on Scientific and Industrial Research (CSIR)	$M_r(MPa) = 20.7CBR^{0.65}$	(Dione et al., 2015; Makwana, 2019)
4	The Transport and Road Research Laboratory (TRRL) model	$M_r(MPa) = 17.25CBR^{0.64}$	(Dione et al., 2015; Makwana, 2019)

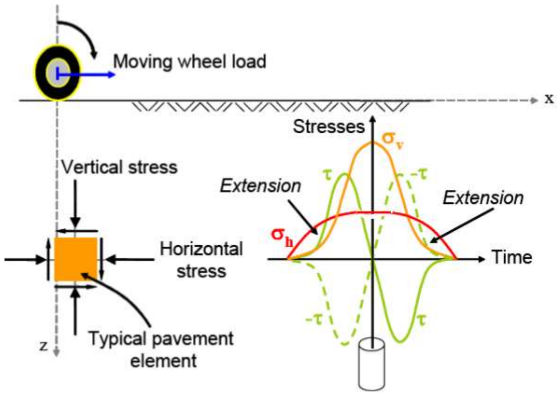

Figure 2: Stress regimes experienced by a pavement element under a moving wheel load (Gu et al., 2012; Wang et al., 2017)

MATERIALS AND METHODS

Descriptions of Materials

Unbound Granular Materials (UGMs) from twelve active borrow areas namely Chama, Igumbilo, Kanisani, Kitayawa, Lugalo, Lulanzi, Mapogolo, Msembe, Tosamaganga, TRM, Usokami 1 and Usokami 2 located in Iringa, Tanzania were collected, transported and tested at CML to establish data for the analysis and validation purpose. Figure 3 below presents the borrow areas locations for the materials used in the study and Figure 4 below shows pictorial descriptions of all the materials used in the study.

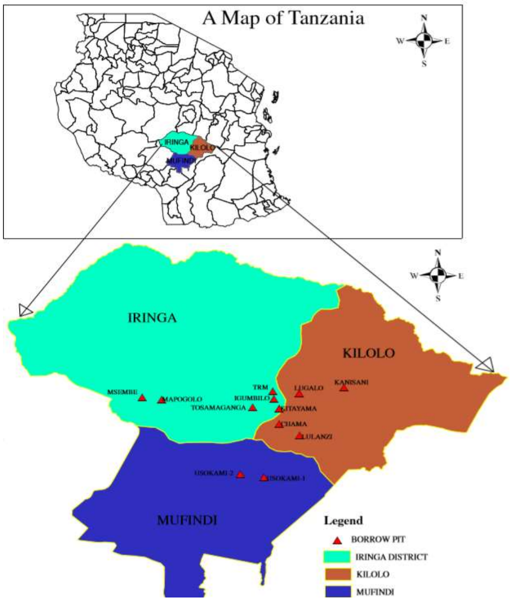

Figure 3: Map showing the twelve (12) borrow areas used for UGMs sampling for this study (Not to scale)

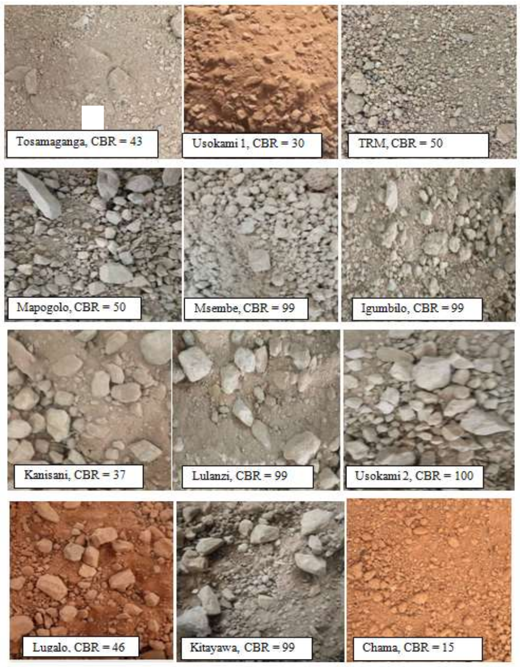

Figure 4: Pictorial presentation of UGMs used in this study

Methods

Analysis of Mineralogical Composition

Analysis of the mineralogical composition of the study materials was conducted at the University of Dar es Salaam Geology Laboratory and it was achieved by X-ray diffraction (XRD) using a Bench Top X-ray (BTX) SN 231 diffractometer. Six representative samples from the borrow areas namely Igumbilo, Kitayawa, Lulanzi, Mapogolo, Msembe and Usokami 1 were tested at University of Dar es salaam Geology laboratory. The BTX SN 231 is a portable bench top X-ray analyser which consists of three basic elements; an x-ray tube, a sample holder and, an x-ray detector. The equipment requires usage of powdery homogeneous specimen achieved by grinding and sieving to materials passing sieve No. 100 (150µm). Suryanarayana& Grant (1998) gives further details on specimen preparation and interpretation of results.

California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test is the most widely used test method to evaluate and classify the strength of materials used in constructing pavement structures for roads and airfields; the test being carried out on intact core sample from a pavement layer, samples compacted into a mould, or directly in-situ Erlingsson, (2011); Haghighi et al., (2017). The CBR values obtained in this test form an integral part of several flexible pavement design methods. A graph of load against penetration is plotted whereby the loads triggering penetration of 2.5mm and 5.0mm are presented as a percentage of two standard loads 13.2kN and 20.0kN. in Figure 5 below; the higher percentage is taken as the CBR value BSI, (1990); Erlingsson, (2011); MoWT, (2000). It is generally acknowledged that the resulting stresses during CBR test, are not representing the real stress state occurring to the pavements as a subsequently effect of traffic loading Erlingsson, (2011).

During CBR testing, the plunger penetration may lead into local complex high stress states to the material and this may result into permanent deformation, which comprises many repetitive light loading cycles. For well graded compacted materials, where the aggregates are strong, most of the deformation caused by a plunger penetration at the deformation of 2.54 mm is due to resilient response of the material and only a small extent being due to permanent deformation Erlingsson, (2011). As such, CBR-value can give some indications of the actual stiffness of the material Erlingsson, (2011). Subsequently, Fleming& Rogers (1995); Garg et al. (2009) and Haghighi et al. (2017) report that CBR values cannot characterize the UGMs performance under repeated wheel loading. Similarly, Leung et al. (2013)reports that CBR test method was introduced to give a bearing value in terms of strength and not a support value which describes the resilient behaviour as pointed out by Fleming & Rogers, (1995) and Garg et al., (2009). In this study, a compaction level corresponding to modified Proctor was employed using a standard CBR mould of 127mm height and 152mm diameter for CBR testing by three-point method and penetration was made after four days soaking of the test specimen as per BSI, (1990); MoWT, (2000).

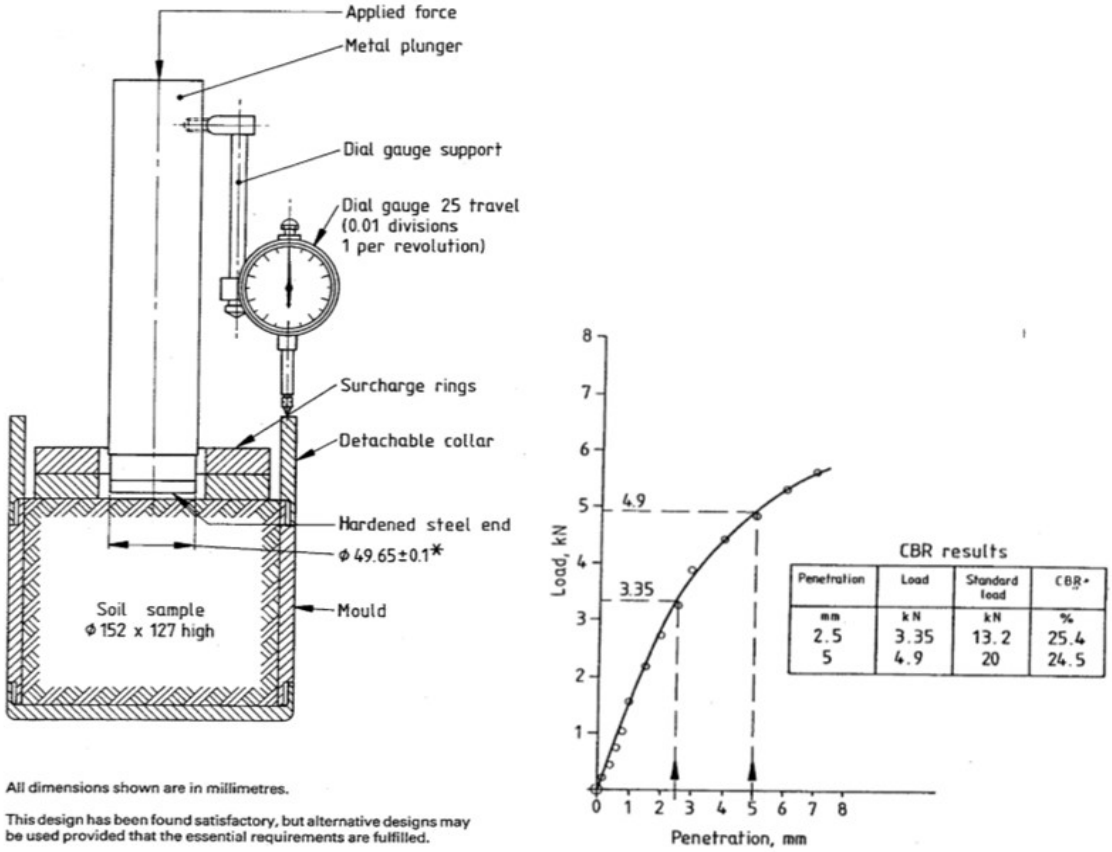

Figure 5: CBR test set-up and a schematic view of the evaluation of the CBR value (BSI, 1990)

Resilient Modulus (M_r)

Theories of elasticity suggest that the elastic property of materials is defined by the modulus of elasticity, *E*, and the Poisson's ratio, μ. With the UGMs, the modulus of elasticity, E is replaced by the resilient modulus (M_r) which describes the stress – dependent elastic behaviour of the materials under repeated wheel loading Araya, (2011). Hveem, as cited in Araya (2011) referred to the resilient behaviour of UGMs at first in the 1950's. It was then concluded that, the deformation of UGMs under transient loading is elastic in a way that it is recoverable. Subsequently, the concept of resilient modulus was introduced in 1960's during characterization of elastic response for sub grade soils in relation to fatigue failure noted in asphalt pavements (Seed et al., as cited in Araya, (2011)). In this study, Universal Testing Machine (UTM) – 130 available at CML which correspond to RLT test set-up with Constant Confining Pressure (CCP)was used for the laboratory determination of M_r of the UGMs and an impact compaction corresponding to Modified Proctor using a split mould of dimensions 150mm x 305mm which complied to the requirement of h≥2d where h and d are height and diameter of the test specimen respectively AASHTO, (2017). Figure 6 below presents a UTM-130 set up for M_r testing. The following testing procedures were involved in carrying out resilient modulus testing: specimen preparation, assembly of the triaxial cell, application of confining pressure, stress conditioning at a given stress state (stress sequence "zero" of Table 2), and load application for 15 further stress states. Conditioning was aimed at eliminating effects of imperfects during specimen preparation and reducing initial imperfect contact between the test specimen and the equipment. For this study, conditioning load cycles were allowed up to the maximum limit of 1000 cycles because further decrease in specimen height could be noted at the end of 500 cycles. Data for load and deformation were captured for all the load application over the entire sequence, and the last five cycles that is the 96^{th} to 100^{th} cycles were used to work out the M_r. Table 2 below presents test sequence followed in this study in accordance with AASHTO (2017) and Figure 7 below presents specimen preparation, instrumentation and loading of the triaxial cell with the test specimen into the UTM-30 equipment.

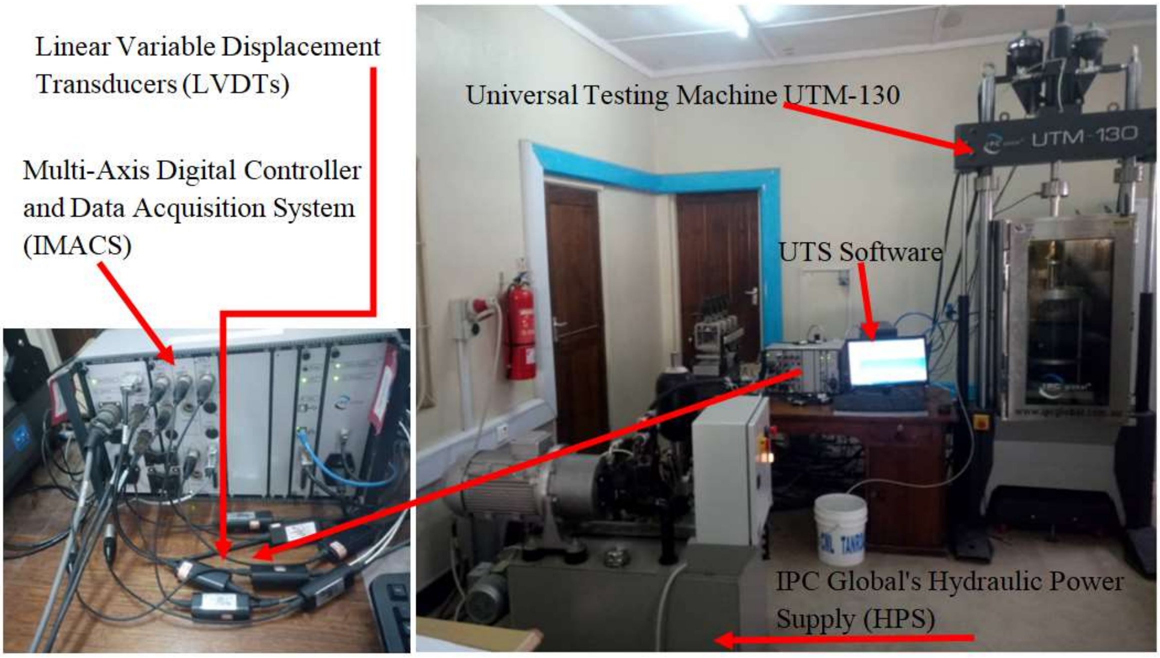

Figure 6: Universal Testing Machine UTM-130 set-up for M_r testing

Table 2 Test sequence for granular Base/Sub base materials AASHTO, (2017)

Sequence No.	Confining stress σ_3 (kPa)	Axial stress σ_d (kPa)	Cyclic stress (kPa)	Constant stress (kPa)	No. of load applications
0	103.4	103.4	93.1	10.3	1000
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

Figure 7: Preparation of specimen for M_r testing

RESULTS AND DISCUSSION

Results - Mineralogical Composition of the UGMs

Mineralogical composition of the UGMs used for this study was determined from six (6) representative samples; Igumbilo, Kitayawa, Lulanzi, Mapogolo, Msembe and Usokami 2. The XRD method results are presented on Table 3. From the analysis, it was revealed that quartz (SiO_2) and feldspars ($KAlSi_3O_8$ –$NaAlSi_3O_8$ – $CaAl_2Si_2O_8$) are the dominant minerals in the materials used for this study falling under the siliciclastic segments. M_r Values of UGMs

Determination of M_r was achieved in the laboratory through the use of the UTM-130 equipment and the determined M_r values ranged from 168 MPa to 415 MPa. Table 4 and Figure 8 below summarises the CBR and M_r values of the twelve UGMs sources.

Table 3: XRD Test Results for Mineralogical Composition Analysis

Sample No.	Sample Name	Mineral name	Chemical Formula	% Weight
2	Usokami 2	Quartz	SiO_2	64.80
		Antlerite	$Cu_3(SO_4)(OH)_4$	6.55
		Brucite	$Mg(OH)_2$	6.05
		Kaolinite	$Al_2Si_2O_5(OH)_4$	11.18
		Gibbsite	$Al(OH)_3$	11.42
4	Mapogolo	Quartz	SiO_2	100.00
5	Msembe	Quartz	SiO_2	44.14
		Albite	$NaAlSi_3O_8$	55.86
6	Igumbilo	Quartz	SiO_2	30.30
		Albite	$NaAlSi_3O_8$	54.81
		Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	14.89
8	Lulanzi	Quartz	SiO_2	70.85
		Cuprite	Cu_2O	1.34
		Periclase	MgO	5.00
		Antlerite	$Cu_3(SO_4)(OH)_4$	6.86
		Dioptase	$Cu_6Si_6O_{18}\cdot 6H_2O$ or $CuSiO_2(OH)_2)$	5.59
		Gibbsite	$Al(OH)_3$	10.35
11	Kitayawa	Quartz	SiO_2	36.76
		Kaolinite	$Al_2Si_2O_5(OH)_4$	10.58
		Periclase	MgO	2.49
		Brucite	$Mg(OH)_2$	4.53
		Muscovite-2M1	$KAl_2(AlSi_3O_{10})(F,OH)_2$, or $(KF)_2(Al_2O_3)_3(SiO_2)_6(H_2O)$	22.70
		Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	22.94
		Dominant minerals in the samples which are quartz and feldspar (siliciclastic)		

Table 4: M_r values for the siliciclastic UGMs sources

Sample No.	Borrow area	Class	MDD & DOC		OMC (%)	CBR %	M_r (MPa)
			MDD (kg/m^3)	DOC			
1	Tosamaganga	G25	2129	95%MDD	7.0	43	233
2	Usokami 1	G25	2160	95%MDD	8.5	30	185
3	TRM	G45	2023	95%MDD	8.0	50	283
4	Mapogolo	G45	2091	95%MDD	6.3	50	272
5	Msembe	G60	2133	100%MDD	6.2	98	390
6	Igumbilo	G60	2110	100%MDD	6.0	99	410
7	Kanisani	G25	2137	95%MDD	7.4	37	244
8	Lulanzi	G80	2119	100%MDD	7.8	99	404
9	Usokami 2	G80	2081	100%MDD	8.5	100	415
10	Lugalo	G45	2198	95%MDD	6.0	46	341
11	Kitayawa	G80	2070	100%MDD	8.0	99	386
12	Chama	G15	2108	95%MDD	7.2	15	168

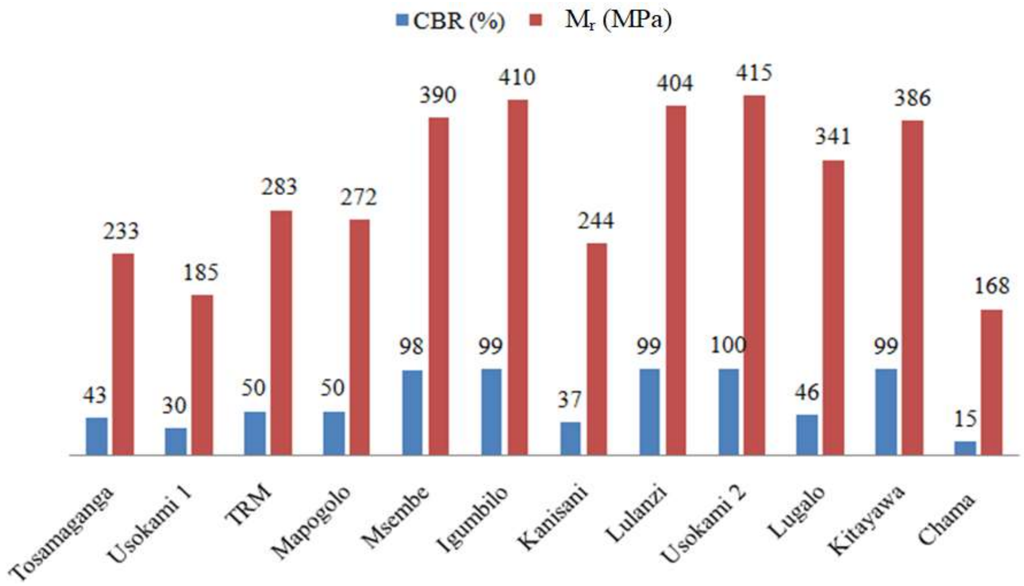

Figure 8: Ranges of CBR and M_r Values for UGMs used in assessing prediction models and for development of improved model

Assessment of suitability of selected existing CBR-based M_r prediction models

In this study the suitability of four existing M_r-CBR models namely, the Shell Oil model, the U.S. Army corps of Engineers model, the South African Council on Scientific and Industrial Research (CSIR) model and the Transport and Road Research Laboratory (TRRL) model in predicting M_r values for siliciclastic UGMs was assessed. Actual M_r values from UGMs sources were compared to predicted M_r values using 4-days soaked CBR. A comparative graphical method was used in assessing how a model approximates the M_r values by comparing the laboratory determined M_r and the predicted M_r values, as shown in Figure 9 to 12 below. For a more accurate model, the scattering of the predicted M_r values was noted to be around the line of equality; for the less accurate model the predicted M_r values were noted to be far from the line of equality. Further, the mean and Coefficient of Variation (CoV) of the ratios of predicted to actual M_r values were used to statistically assess the prediction reliability of the four models, as shown in Table 5 below. The model whose Coven is smaller gives less dispersed predicted M_r values than the model with larger CoV. Again, the model whose mean value for predict to actual M_r values approaches 1.0, gives less dispersed predicted M_r values than the model with mean values lesser or higher than 1.0. Based on the results from the evaluation of the selected existing models, the Shell Oil and U. S. Army Corps of Engineers models showed poor performance by over predicting M_r values from CBR values. The TRRL model showed reasonable prediction though with under prediction of M_r values while CSIR model showed the best predictive reliability of the four models on the M_r values established from the siliciclastic UGMs from Tanzania borrow pits. The inconsistence in prediction of M_r values from CBR values for UGMs from Tanzania by the existing prediction models triggered developing an improved prediction model to suit the study materials.

Table 5: Comparison of existing models based on the Coefficient of Variation (CoV)and Mean values for predicted to actual M_r ratios ($M_{r(pred)}/M_{r(act)}$)

Model Name	Shell Oil	U.S Army	CSIR	TRRL
$M_{r\,(pred)}/M_{r(act)}$ Mean values	2.00	2.19	0.95	0.76
CoV	0.28	0.15	0.12	0.12

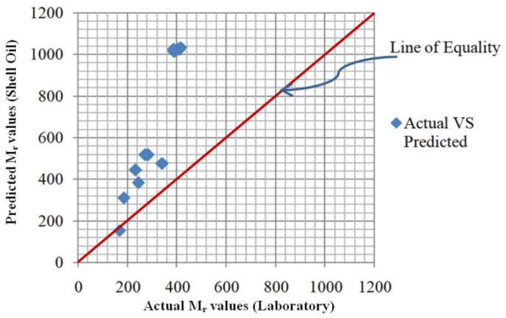

Figure 9: Shell Oil Model

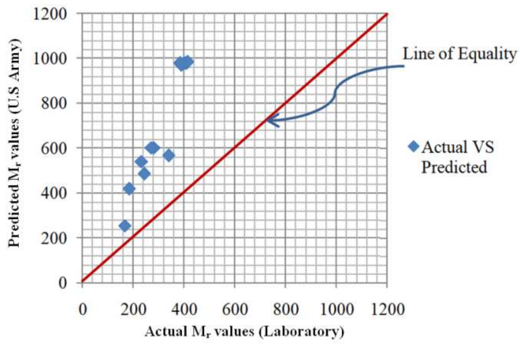

Figure 10: U.S. Army Model

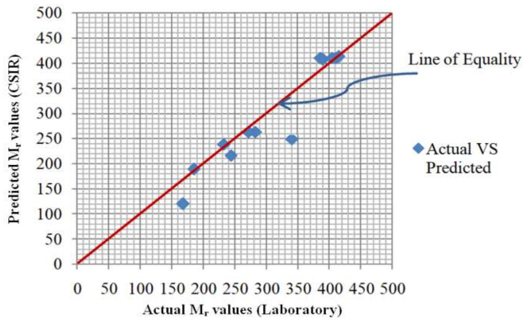

Figure 11: CSIR model

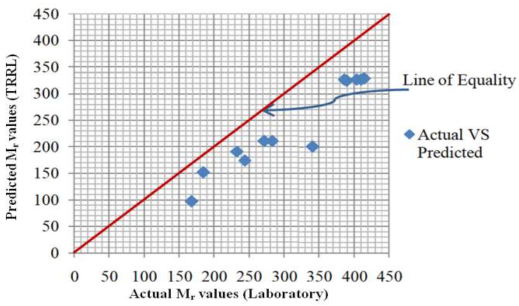

Figure 12: TRRL model

Improvement on the Existing M_r - CBR Models

Literature shows strong non-linear, power relationship between resilient modulus (M_r) and California Bearing Ratio (CBR). Therefore, an improved model of the general form of $M_r(MPa) = K * CBR^A$ has been adopted where the factor K and power A are dependent on the nature of the materials. Regression analysis was used to develop the improved M_r-CBR model and the 0.9056 coefficient of determination R^2 confirms that the model is strong, and the output of the regression analysis at confidence limits of 95% are presented in Table 6 to Table 8. Table 7 presents the overall validity of the model using Analysis of Variance (ANOVA) from which it can be seen that significance F (p-value) is 1.92x 10^{-06} which is much smaller than 0.05. Therefore, the model is significantly valid. Table 8 presents the validity of the model coefficients using ANOVA. It can be seen that p-value for the explanatory variable and intercept are both much smaller than the 0.05 significance value set in the model. This signifies that, M_r values can be well explained by CBR values. From Table 8 the fitted model is;

$$\ln M_r = 3.681 + 0.502 * \ln CBR \qquad (2)$$

This linear equation transforms to an equivalent power equation presented in equation 3.

$$\text{Predicted } M_r(MPa) = 40 * CBR^{0.5} \qquad (3)$$

Table 6: Summary output of regression statistics of M_r-CBR model

Observations	Multiple R	R Square	Adjusted R Square	Standard Error of the Estmate
12	0.9516	0.9056	0.8961	0.1032

Table 7: F-Test ANOVA Overall validity of the model

	Df	SS	MS	F	Significant F
Regression	1	1.0222	1.0222	95.894	1.92566E-06
Residual	10	0.1066	0.0106		
Total	11	1.1288			

Table 8: t – Test Model Coefficient values

	Coefficient	Standard Error	t-Stat	p-value	Lower 95%	Upper 95%
Intercept	3.681	0.208	17.71	7E-09	3.218	4.144
In CBR	0.502	0.051	9.79	1.93E-06	0.388	0.617

Table 9: Comparison of models based on the Coefficient of Variation (CoV) Mean values for predicted to actual M_r ratios ($M_{r(pred)}$ /$M_{r(act)}$)

Model Name	Modified Model	Shell Oil	U.S. Army	CSIR	TRRL
$M_{r\,(pred)}$/$M_{r(act)}$ Mean values	0.94	2.10	2.16	0.92	0.74
CoV	0.26	0.38	0.30	0.29	0.28

Validation of the Improved Model

For validation of the improved model, a database of twenty (20) CBR and M_r test results was extracted from Erlingsson (2011), as seen in Figure 13 below. The study represented the most comprehensive independent and accessible data set that could be used for the validation of the improved model. Again, both graphical method and statistical methods were used to compare the performance of the improved model to the existing ones. The CoV and mean values of developed model were compared to those of the published models. The CoV and mean values for siliciclastic UGMs to each model under study was determined and the results of the assessment are summarized in Table 9 below. The results in Table 9 indicate that the developed model for siliciclastic UGMs is closely predicting M_r values than the selected published models that were analysed in this study. To compare the predicted M_r from the actual M_r values for respective models under the study, graphs showing predicted M_r values for the published models that were analysed in this study and a newly developed model from a set of twenty CBR values from the results of the study carried out by Erlingsson (2011) presented in Figure 13 were plotted and compared. The results of the analysis are presented in Figure 14 to Figure 18 below. From the analysis it can be concluded that the developed model provides a stronger approximation of the M_r from CBR than the rest of the models under this study.

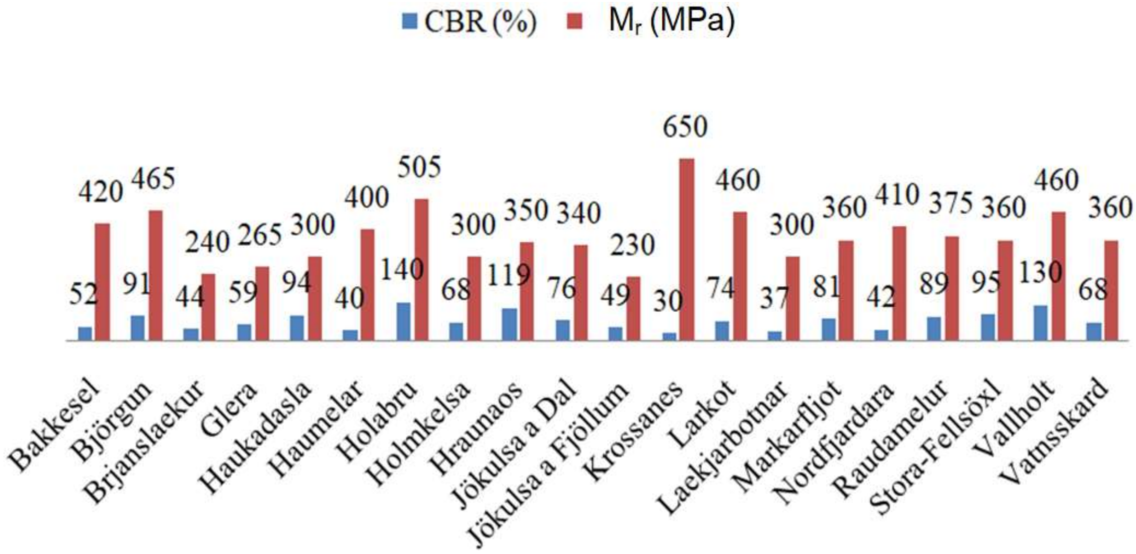

Figure 13: Ranges of CBR and M_r values of UGMs used for Discussion of Results (Erlingsson, (2011)

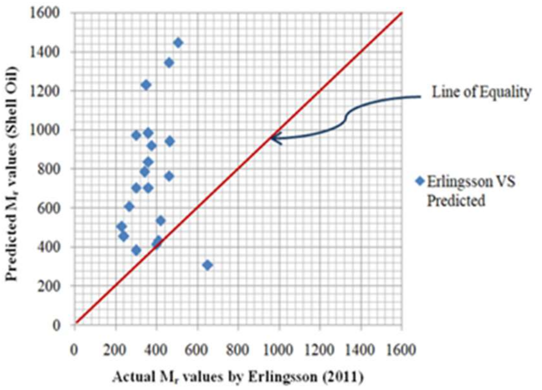

Figure 14: Shell Oil Model

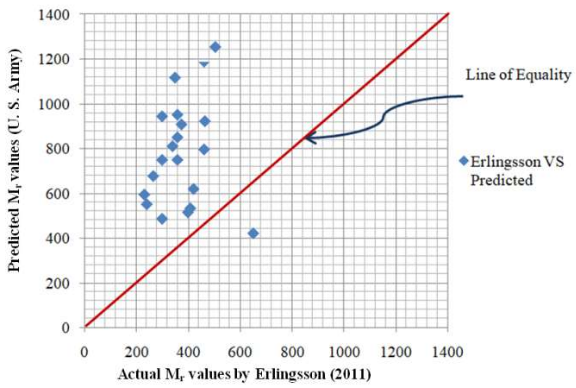

Figure 15: TRRL Model

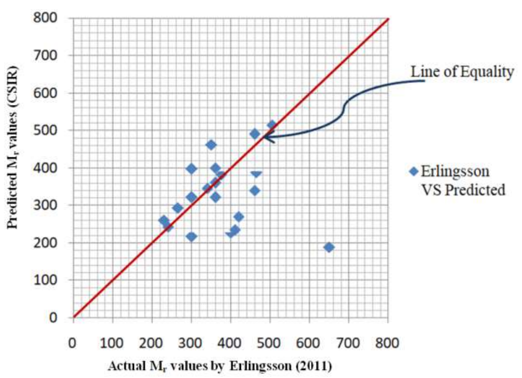

Figure 16: CSIR Model

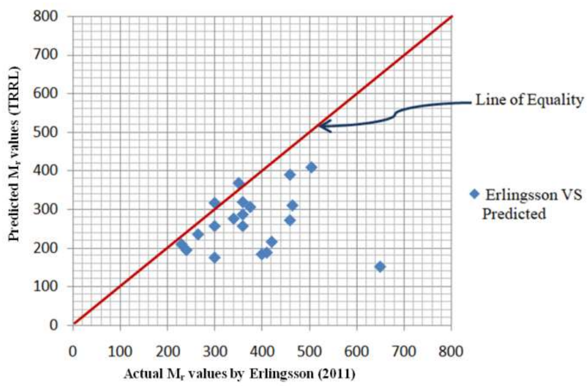

Figure 17: TRRL Model

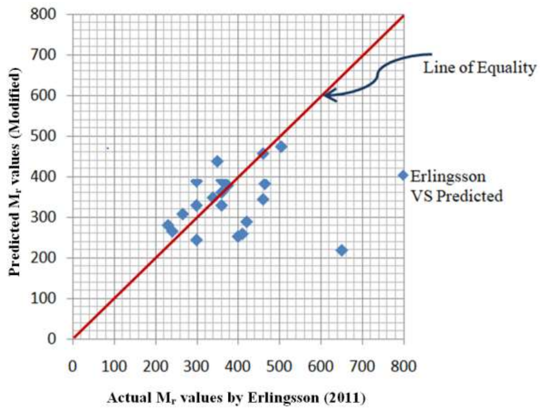

Figure 18: Newly improved Model

CONCLUSIONS

In Mechanistic-Empirical pavement design approach, the resilient modulus (M_r) is a significant parameter to achieve designs. Conventionally, the M_r is determined in the laboratory through a RLT test method. RLT testing requires such special and sophisticated equipment which is costly. Besides, specimen preparation, instrumentation and conducting tests require special skills and knowledge. Thus, laboratory determination of M_r remains suited for research purposes with simplified prediction models being employed to estimate M_r values from physical properties of soil or soil strength parameters like the CBR Haghighi et al., (2017). The prediction model developed from this study could be judiciously used for estimating M_r values from soaked CBR values for siliciclastic UGMs. The model is simple and it gives fairly good estimate of M_r values.

In this regards the following conclusions can be drawn from the results of this study:

1. There is strong non-linear relationship between M_r and soaked CBR values evidenced by a Coefficient of Determination of 91%.
2. The improved model has shown better performance in predicting M_r values for the study materials. This is evidenced by nearly equal predicted M_r to actual M_r values (Figure 18). Besides, the model gives smaller dispersion of the predicted values evidenced by smaller value of CoV of 0.26 in comparison to the reviewed existing models for Shell Oil, U. S. Army Corps of Engineers, CSIR and TRRL whose values of CoV are 0.38, 0.30, 0.29 and 0.28 respectively (Table 9). Additionally, the modified model has a mean $M_{r\ (pred)}$ / $M_{r\ (act)}$ value of 0.94 implying that there is an error of only 6% in predicting M_r values, this mean value is reasonable compared to Shell Oil, U. S. Army Corps of Engineers', CSIR's and TRRL's whose $M_{r\ (pred)}$ / $M_{r\ (act)}$ mean values are 2.1, 2.16, 0.92 and 0.76 respectively (Table 9). The model is therefore suited for prediction of M_r from CBR values for the study materials.
3. The newly developed model validates well against the existing data evinced by its better performance using M_r and CBR data base from the study by Erlingsson (2011).
4. The use of the improved model is limited to siliciclastic materials' electronic components size that will utilize less power compared to the existing ones.

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