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Resilient modulus of siliciclastic unbound granular materials under repeated wheel loading

Module résilient des matériaux granulaires siliciclastiques non liés sous des charges répétées de roue

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ABSTRACT: The stress – dependent elastic behaviour of materials under repeated wheel loading known as resilient modulus (M_r) is a primary input in modern Mechanistic–Empirical (M-E) structural design of pavements. This paper presents an extensive laboratory experimental study to investigate the resilient modulus of siliciclastic Unbound Granular Materials (UGMs) under cyclic loading simulating repeated wheel loading. Samples collected from twelve active road construction borrow areas in Iringa Region in Tanzania were fully characterised at Tanzania National Roads Agency Central Materials Laboratory (TANROADS CML) and University of Dar es Salaam 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 were assessed by X-Ray Diffraction then 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-linearity and validated well against existing databases.

RÉSUMÉ: Le comportement élastique dépendant de la contrainte des matériaux sous des charges répétées de roue, connu sous le nom de module résilient (M_r), est un élément principal de la conception structurelle mécaniste-empirique (M-E) des chaussées. Cet article présente une étude expérimentale approfondie en laboratoire pour étudier le module résilient des matériaux granulaires non liés siliciclastiques (UGM) sous chargement cyclique. Les échantillons collectés dans douze zones d'emprunt de construction de routes actives dans la région d'Iringa en Tanzanie ont été entièrement caractérisés au Laboratoire central des matériaux de l'Agence nationale des routes de Tanzanie (TANROADS CML) et de l'Université de Dar es Salaam pour permettre la classification des matériaux dans l'approche empirique à laquelle une gamme de matériaux de grades CBR 25 à 80 a été définie. En outre, la minéralogie des échantillons a été évaluée par diffraction des rayons X et une machine d'essai universelle servo-hydraulique 130 de TANROADS CML a été utilisée pour simuler un test de charge répétée sur les multiples échantillons à partir desquels le module élastique des UGM a été déterminé. Un modèle de prédiction CBR - M_r imbibé a ensuite été développé qui a montré une forte non-linéarité et bien validé par rapport aux bases de données existantes.

KEYWORDS: Resilient modulus, Granular materials, Siliciclastic materials, Base course, Sub-base

1 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 as the properties of the constituent minerals influence the whole properties of the UGMs. 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 & Vernik & Kachanov 2010). Bilodeau et al. (2011) reported that, UGM layers experience both elastic/resilient deformation and permanent/plastic deformation under repeated traffic loading. The elastic behaviour represents the recoverable part of the deformations characterized by elastic resilient modulus, M_r (Araya 2011) which 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.

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) Loading cycles and v) Type of materials. Arithmetically, the resilient modulus is the ratio of repeated deviator axial stress to the recoverable strain (AASHTO 2017).

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

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. This 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. Traffic loading on a pavement structure has two main components; the stress applied and the frequency of repetition of that stress. 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.

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 and 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). 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 as a baseline for Mechanistic – Empirical design approach for roads in Tanzania.

2 MATERIALS AND METHODS

2.1 *Materials*

Unbound Granular Materials (UGMs) from twelve (12) active borrow areas namely Chama, Igumbilo, Kanisani, Kitayawa, Lugalo, Lulanzi, Mapogolo, Msembe, Tosamaganga, TRM, Usokami 1 and Usokami 2 located across Iringa, Kilolo and Mufindi districts of Iringa region in Tanzania (Figure 1) were collected, transported and tested at Central Materials Laboratory (CML) to establish appropriate laboratory test results and data for analysis and validation purpose. Analysis of Mineralogical composition of the study materials was conducted at the University of Dar es Salaam Geology Laboratory.

2.2 *Methods*

2.2.1 *Analysis of mineralogical composition*

Laboratory mineralogy composition characterisation of the UGMs was done 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. Suryanarayana & Grant (1998) gives further details on specimen preparation and results interpretation.

2.2.2 *California Bearing Ratio*

The CBR test was originally developed by the California Division of Highway around 1930s to provide an assessment of the relative stability of fine crushed rock base material (AASHTO 2003). A corrected graph of load against penetration is plotted whereby the loads causing penetration of 2.5mm and 5.0mm are expressed as a percentage of two standard loads 13.2kN and 20.0kN; the higher percentage is taken as the CBR value (BSI 1990; Erlingsson 2011; MoWT 2000). It is generally acknowledged that the induced stresses experienced during CBR test, poorly represent the real stress state that pavements experience during traffic loading. The plunger penetration is sufficient to cause local complex high stress states in the material with probable permanent deformation as a consequence, which comprises many repetitive light loading cycles. For well graded compacted materials, where the aggregates are strong, the largest part due to 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. 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 resilient behaviour. In the current study, a compaction level corresponding to modified Proctor test 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).

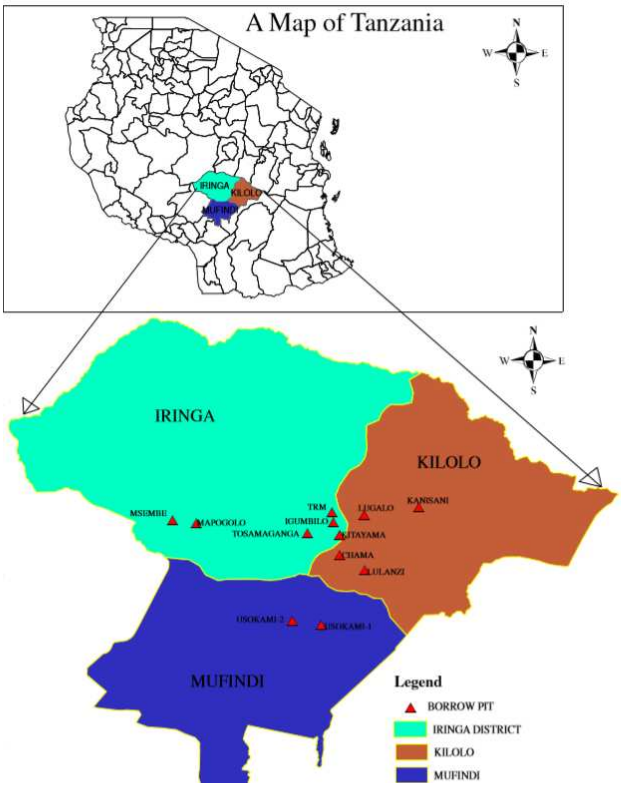

Figure 1. Not to scale map showing spatial distribution of the twelve (12) borrow areas used for UGMs sampling for this study. Iringa, Kilolo and Mufindi are the current districts of Iringa Region.

2.2.3 *The 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. 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. 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 150 mm x 305 mm which complied to the requirement of $h \geq 2d$ where h and d are height and diameter of the test specimen respectively (AASHTO, 2017). Figure 2 presents a UTM-130 set up for M_r testing. Data for load and deformation were captured for all the load applications over the entire loading sequence, however; the last five cycles that is the 96th to 100th cycles were used to work out the M_r. Computerized system using Linear Variable Displacement Transducers (LVDTs) incorporated in the M_r test equipment was used to capture deformation results (Mdzovela, 2020). Table 1 presents the test sequence followed in this study in accordance with AASHTO (2017). The test procedure adopted was a standard one with a conditioning sequence of 1000 repetitions of load applications followed by 15 next sequences at specified deviator stress and confining stress at 100 repetitions of load applications each as detailed under Table 1. The constant stress shown in the table represents the lateral confining pressure experienced by unbound materials in a constructed pavement layer when wheel load approaches/gets away the soil element. The stress experienced varies as the wheel load passes by. As such, AASHTO (2017) test protocol provides different sets of "constant stress" to depict the actual situation experienced by soil element in the constructed pavement structure.

Figure 2: The Universal Testing Machine UTM-130 set-up for M_r testing.

Table 1. Test sequence for granular Base/Sub base materials (AASHTO 2017).

S/N	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

3 RESULTS AND DISCUSSIONS

3.1 *Results*

3.1.1 *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 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, Table 2.

Table 2: XRD test results for mineralogical composition analysis of study materials

Quarry name	Mineral	% Weight
Usokami 2	Quartz [SiO_2]	64.9
	Antlerite [$Cu_3(SO_4)(OH)_4$]	6.5
	Brucite [$Mg(OH)_2$]	6.0
	Kaolinite [$Al_2Si_2O_5(OH)_4$]	11.2
	Gibbsite [$Al(OH)_3$]	11.4
Mapogolo	Quartz [SiO_2]	100.0
Msembe	Quartz [SiO_2]	44.1
	Albite [$NaAlSi_3O_8$]	55.9
Igumbilo	Quartz [SiO_2]	30.3
	Albite [$NaAlSi_3O_8$]	54.8
	Illite [$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$]	14.9
Lulanzi	Quartz [SiO_2]	70.8
	Cuprite [Cu_2O]	1.3
	Periclase [MgO]	5.0
	Antlerite [$Cu_3(SO_4)(OH)_4$]	6.9
	Dioptase [$Cu_6Si_6O_{18}\cdot 6H_2O$ or $CuSiO_2(OH)_2$]	5.6
	Gibbsite [$Al(OH)_3$]	10.4
Kitayawa	Quartz [SiO_2]	36.8
	Kaolinite [$Al_2Si_2O_5(OH)_4$]	10.6
	Periclase [MgO]	2.5
	Brucite [$Mg(OH)_2$]	4.5
	Muscovite-2M1 $KAl_2(AlSi_3O_{10})(F,OH)_2$, or $(KF)_2(Al_2O_3)_3(SiO_2)_6(H_2O)$	22.7
	Illite [$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$]	22.9

3.1.2 *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 against the observed measured values in this study, Figure 3. 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, Figure 4. 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, Table 3. The model whose CoV is smaller gives less dispersed predicted M_r values than the model with larger CoV. Again, the model whose mean value for predicted M_r to actual M_r values approaches 1.0, gives less dispersed predicted M_r values than the model with mean values are 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.

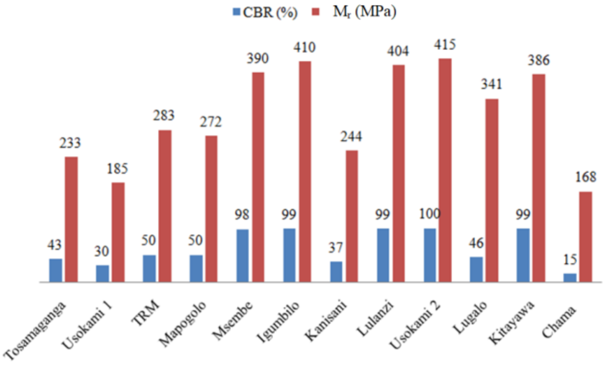

Figure 3: Ranges of CBR and M_r values for UGMs used in assessing prediction models and for development of improved model.

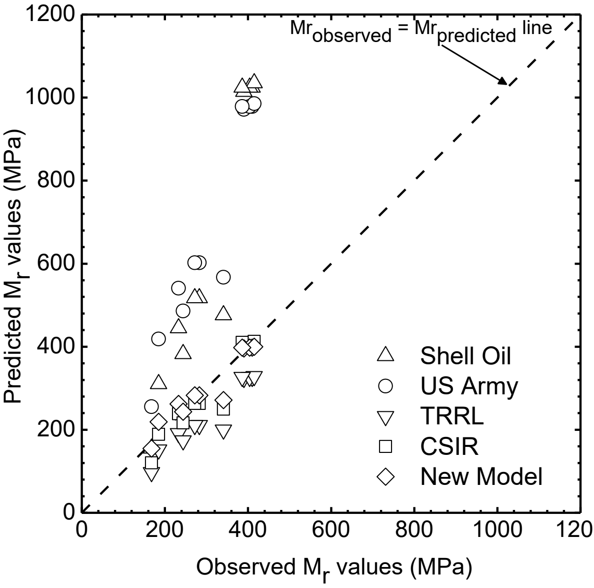

Figure 4: Assessment of suitability of selected existing CBR-based M_r prediction models.

Table 3. Comparison of existing models based on the Coefficient of Variation (CoV) and mean values for predicted to observed M_r ratios.

	Model Name			
$M_{r\ predicted}/M_{r\ actual}$	Shell Oil	U.S Army	CSIR	TRRL
Mean values	2.00	2.19	0.95	0.76
CoV	0.28	0.15	0.12	0.12

3.1.3 *Improvement of existing M_r – CBR models*

To develop an improved M_r – CBR model a general non-linear, power relationship of the form $M_r\ (\text{MPa}) = K * \text{CBR}^A$ has been adopted where the factor K and power A are dependent on the nature of the materials and CBR is the UGM's CBR grade. Regression analysis was applied to develop the improved M_r-CBR model and the 0.91 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 4 to Table 6. Table 5 presents the overall validity of the model using Analysis of Variance (ANOVA) from which it can be seen that significance F (p-value) is 1.93 x 10^{-06} which is much smaller than 0.05. Therefore, the model is significantly valid. Table 6 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 0.05 significance value set in the model (Mdzovela, 2020). This signifies that, M_r values can be well explained by CBR values.

From Table 6 the fitted model becomes;

$$ln\ M_r = 3.689 + 0.502 * lnCBR \qquad (2)$$

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

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

Table 4. Summary output of regression statistics of M_r-CBR model.

Observations	Multiple R	R Square	Adjusted R Square	Standard Error of the Estimate
12	0.95	0.91	0.90	0.10

Table 5. F-Test ANOVA Overall validity of the model.

	Df	SS	MS	F	Significant F
Regression	1	1.02	1.02	95.89	1.93 E -06
Residual	10	0.11	0.01		
Total	11	1.13			

Table 6. t – Test Model Coefficient values.

	Coefficient	Standard Error	t-Stat	p-value	Lower 95%	Upper 95%
Intercept	3.689	0.21	17.71	7E-09	3.22	4.14
In CBR	0.50	0.05	9.79	1.93E-06	0.39	0.62

3.1.4 *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). 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 existing. The CoV and mean values of developed model were compared to 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 7. The results in Table 7 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 predicted M_r from 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 the newly developed model from a set of twenty CBR values from the results of the study carried out by Erlingsson (2011) were plotted and compared, Figure 5 to 9. 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.

4 CONCLUSION

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 which requires relatively specialised and costly equipment. 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. 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 power 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. 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 6). 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 if compared to Shell Oil, U. S. Army Corps of Engineers, CSIR and TRRL whose $M_{r\ (pred)}$ / $M_{r\ (act)}$ mean value 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 databases as evidenced by its better performance using M_r and CBR database from the study by Erlingsson (2011).

4. Further research is required in the performance of the model in siliciclastic UGMs with fines content (particles sizes < 75 microns) in excess of 20%.

Table 7. Comparison of new and existing models based on the Coefficient of Variation (CoV) and mean values for predicted to observed M_r ratios.

	Model Name				
$M_{r\ predicted}$ / $M_{r\ actual}$	**Modified Model**	**Shell Oil**	**U.S. Army**	**CSIR**	**TRRL**
Mean values	0.94	2.10	2.16	0.92	0.74
CoV	0.26	0.38	0.30	0.29	0.28

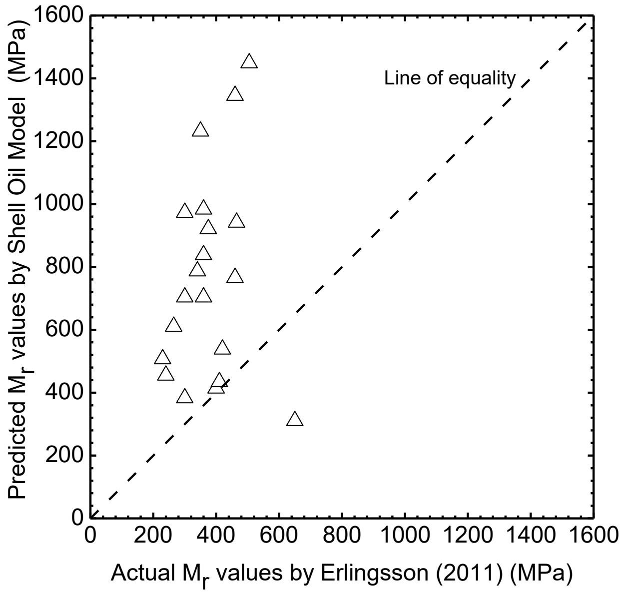

Figure 5: Assessment of suitability of Shell Oil CBR-based M_r prediction model against Erlingsson (2011) dataset.

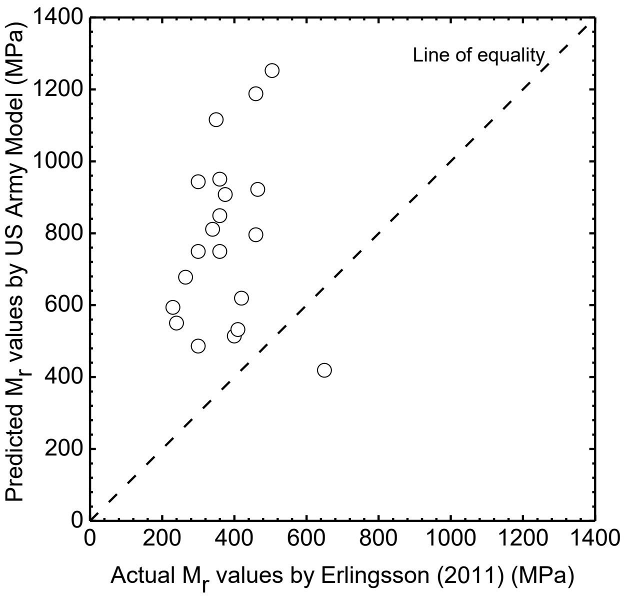

Figure 6: Assessment of suitability of US Army CBR-based M_r prediction model against Erlingsson (2011) dataset.

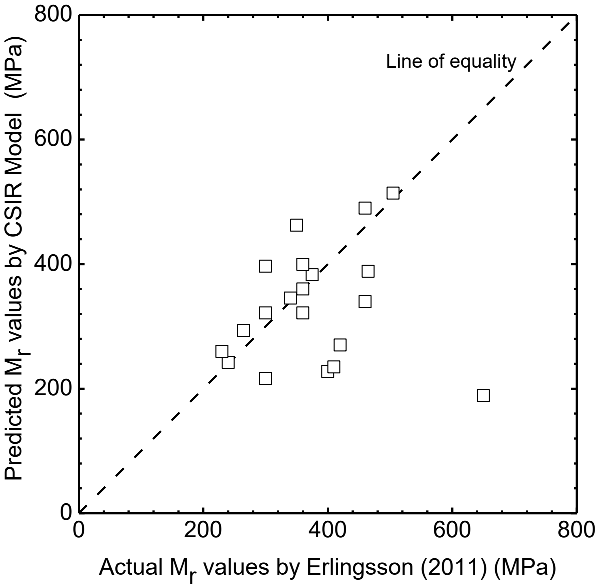

Figure 7: Assessment of suitability of CSIR CBR-based M_r prediction model against Erlingsson (2011) dataset

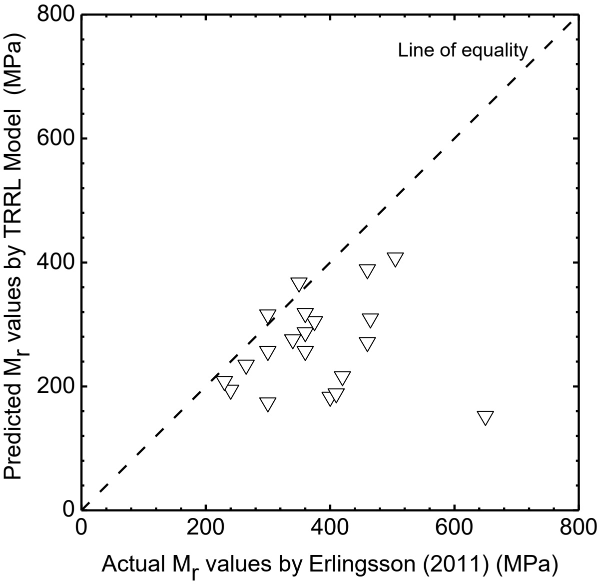

Figure 8: Assessment of suitability of TRRL CBR-based M_r prediction model against Erlingsson (2011) dataset

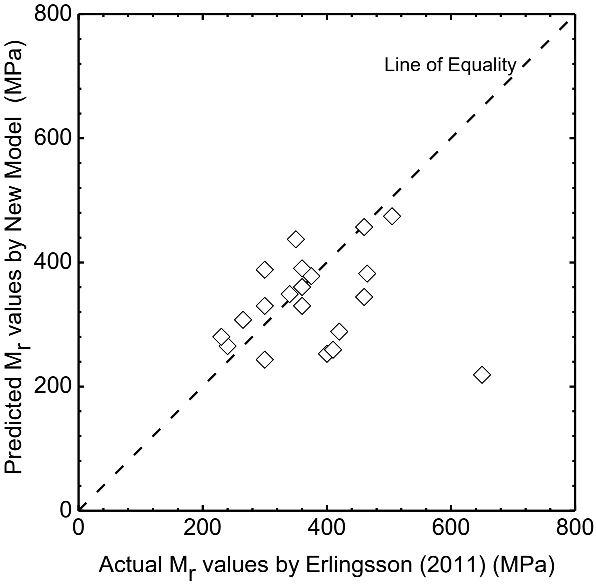

Figure 9: Assessment of suitability of the newly developed CBR-based M_r prediction model against Erlingsson (2011) dataset

5 ACKNOWLEDGEMENT

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