APPLICATION OF THE CONTIGUOUS AGGREGATE PACKING PRINCIPLE TO PREDICT DENSITY POTENTIAL, CBR AND RESILIENT MODULUS OF UNTREATED GRANULAR MATERIALS

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ABSTRACT

Adherence to the Contiguous Aggregate Packing (CAP) principle on a granular material aggregate grading curve allows for the calculation of Rational Bailey Ratios (RBRs). RBRs enable calculation of porosity of such contiguous aggregate or fraction ranges along the grading curve. Previous work with asphalt aggregate packing showed RBRs can be related and correlated to porosity, density (through compaction indices), and permeability of asphalt mixes. Untreated granular materials (UGMs) also have grading curves, even though for lower quality UGMs, grading is not necessarily specified. Previous work done by Semmelink (1991) on developing a scientific basis for compaction determination of UGMs was revisited and the data base reworked. Semmelink (1991) succeeded in correlating Atterberg indicators, other material indicators such as loose bulk density and Optimum Moisture Content (OMC), with various methods and calculations of density. The original work by Semmelink had limited success in incorporating grading curve information in wide ranging correlation study with various methods of density determination and calculation. Acceptable correlation was also achieved with the universal material strength indicator, California Bearing Ratio (CBR), but was correctly criticised as an empirical strength indicator with significant variation.The Semmelink data set was reworked to "unpack" the wealth of "inherent properties" in the grading curve by calculating the RBRs. This was done through application of the CAP principle using RBRs of the obtained grading curves with the available Atterberg indicators and OMC for a variety of UGM quality materials. Very good correlations were obtained via these reworked correlation studies proving that the CAP principle and use of RBRs can also be used to improve prediction of density and strength of UGMs.

Keywords: Contiguous Aggregate Packing (CAP) principle, Untreated granular materials (UGMs), Atterberg indicators, Rational Bailey Ratios (RBRs), California Bearing Ratio (CBR), density.

1. INTRODUCTION

Well interlocked aggregate packing of freshly crushed hard rock aggregate is often viewed as the main contributor to asphalt stiffness under traffic loading in a variety of asphalt mix types (Al-Mosawe et al., 2015; Horak et al., 2017 & 2019, Komba et al 2019, Blaauw et al., 2019). The application and articulation of packing optimisation of discrete aggregate particles in asphalt mixes are based on the pioneering work presented and developed by the Bailey method (TRB, 2002; Vavrik et al., 2001). The Bailey method is currently included the South African asphalt mix design guideline TG 35 (SABITA, 2020) in support of achieving strength-optimised asphalt mix designs.

All discrete aggregate design methods rely on the principle that aggregates need to be densely packed. Such dense packing enables the aggregates to interlock with each other to give strength via the aggregate skeleton or matrix in the asphalt mix (Horak et al., 2021). Smit (2002) gives a good overview of the various aggregate packing models developed and an evaluation of the various models and methods. Relevant and recently developed aggregate packing methods have their fundamental basis in volumetric packing based on the theoretical study of spheres with various geometric three-dimensional packing configurations (Smit, 2002; Guerin, 2009; Chun, 2012). The volumetric packing strives to determine the ratio of the void size to the diameter of the same sized spheres that can fill the voids in between without disrupting the larger spheres (Yanqui, 2011). Smit (2002) indicate the original work by Lees (1971) was taken forward by Francken and Vanelstraete (1993) confirming the use of binary combinations of aggregate fractions can enable finding lowest porosity, therefore highest density packing. It confirmed the 0.22 diameter ratio of such binary aggregate combinations for optimised aggregate packing is validas utilised in the Bailey method (Vavrik et al., 2001).

Aggregate grading is described as using percentage passing by mass per sieve size and can be presented as a grading curve. The form of the grading curve gives very good basic information about the aggregate skeleton. Even with various mathematical descriptions of the grading curve form, such as those proposed by Fuller and Thompson (1907) and Talbot and Richart (1923), it still may tend to be a "blunt instrument" when used as a specification linked to strength and density achievable in strong durable asphalt mixes.

Semmelink (1991) reported how Lees (1971) criticized singular reliance on the Talbot or Fuller curves for continuously graded asphalt mixes concluding that "*there can be no such thing as a unique ideal maximum grading curve*". It must be acknowledged this statement relates to the industry standard continuously graded aggregate in asphalt mixes. Other gradings, such as gap graded, single-sized, etc, do not adhere to such Talbot-type ideal grading curves and yet have succeeded in their own right. The grading curves of good quality and strong continuously graded asphalt mixes often vary from such prescribed ideal gradings and make it difficult to relate the grading curves, even within prescribed envelopes, to more fundamental material properties desired or to design for performance behaviour. Therefore, an aggregate grading as a design and analysis tool needs to be enhanced to improve its usefulness. In effect, the grading curves contain 'inherent properties' that need to be defined, ordered and 'unpacked' for articulation with a more objective evaluation versus strength and durability properties.

As already described, porosity is a fundamental engineering material indicator (Roque et al., 2006) of granular or aggregate mixes. Porosity can be linked to asphalt stiffness, rut resistance, and indirectly also can serve as an indicator of permeability potential (Al-Mosawe, 2016; Komba et al., 2019a & b; Horak et al., 2019; Horak et al., 2021). The calculation of porosity relies on the requirement that the range of aggregate fractions, for which porosity is calculated, must be contiguous (Roque et al., 2006; Green et al., 2014). Contiguous aggregates are adjacent (often consecutive) aggregate fractions and can collectively describe a typical aggregate grading curve segments or portions or in total ranging from the Nominal Maximum Aggregate/Particle Size (NMAS / NMPS) down to the filler size (0.075mm) sieve.

The Interstitial Components - Dominant Aggregate Size Range (IC-DASR) concept (Roque et al., 2006) has shown porosity calculations are possible for longer ranges of contiguous aggregate fractions on a grading curve that is associated with the main load bearing. Thus, adhering to the Contiguous Aggregate Packing (CAP) principle ensures or allows the calculation of the fundamental property of porosity of such aggregate combinations.

The original work by Furnas (1928 & 1931) on various aggregate combinations in binary pairs led to the development of the Binary Aggregate Packing (BAP) method for optimal concrete mixes (Mamirow, 2019). This concrete mix optimisation (density) was based on the porosity calculations (Lees, 1973; Baron and Sauterey, 1982) using BAP principles for binary contiguous aggregates. The BAP principles subsequently evolved into well-established asphalt mix design procedures (Francken & Vanelstraete, 1993; De Lerrard & Sedran, 1994; Perraton et al., 2007; Olard & Perraton, 2010; Olard, 2015).

The original Bailey method (Vavrik et al., 2001; TRB, 2002) calculated ratios of various aggregate fractions and ranges as indicators of strength contribution. These original Bailey method ratios did not consistently adhere to the required CAP principle as some of the aggregate fractions in the original Bailey Ratios overlapped. Thus, porosity could not be consistently calculated for such Bailey Ratios as fundamental basis or property.

Horak et al (2017, 2018, 2019, 2021 and 2022) developed the Rational Bailey Ratios (RBRs) based on the CAP principles to enable porosity-based aggregate grading ratios. Such RBRs could therefore be linked to porosity, interconnected voids (thus permeability), density and stiffness of asphalt mixes. The full range of RBRs describes a definite fundamental characteristic of the aggregate matrix and describes the grading curve in full in terms of various contiguous fraction combinations (Horak et al., 2022).

2. UNLOCKING GRADING CURVE INFORMATION

2.1 Bailey Method as Basis for Grading Curve Description

The grading description by Bailey (Vavrik et al., 2001; TRB, 2002) as applicable to asphalt mix design, is shown in Figure 1. Bailey descriptors of the grading curve are used as a framework or reference for an objective description of any grading curve. This grading curve description is used to describe the RBRs as contiguous aggregate fraction ranges on a grading curve.

The NMPS or NMAS is the starting point for such a grading curve description and analysis. The NMPS sieve size is, by definition, the one sieve size larger than the largest sieve to retain a minimum of 15% of the aggregate particles by mass (TG 35, 2020). As indicated above the original Bailey method descriptors of the rest of the control sieves follow the void to aggregate diameter ratio rule of 0.22 to define the Primary Control Sieve (PCS), the Secondary Control Sieve (SCS) and the Tertiary Control Sieve (TCS) (Vavrik et al., 2001). The sieve size closest to such calculations, following the NMPS sieve determination, is used to determine the PCS, SCS and TCS sieve sizes. The more sieve sizes are used in the grading analysis, the better it is for more accurate determination of PCS, SCS and TCS sieve sizes and subsequent CAP adhering ratios to be described.

Aggregates larger than the PCS are defined as the macro range in the aggregate matrix or grading curve (See column 1 in Table 2). The coarse fraction can be further described in terms of two distinct fraction ranges: The Interceptors (I) (between Half Size (HS) and PCS) and the Pluggers (P) (larger than HS). Horak et al. (2019) refined this Plugger range by describing the Pluggers Normal range (PN) as between HS and NMPS and Pluggers Oversize range (PO) as aggregates larger than NMPS. Aggregates smaller than PCS sizes up to SCS are described as the meso range fraction.

The original Bailey Method description of the fine fraction is here subdivided into a meso range and a micro range to help refine the contiguous aggregate fraction combinations. The meso range includes the fine fraction range Coarse of Fine (CF) between PCS and SCS sieve sizes. This meso range identification is largely based on the work by Al-Mosawe et al (2015) and Al-Mosawe (2016) which identified these meso range RBRs as highly influential in rut and stiffness prediction in asphalt mixes. The fines smaller than SCS as well as TCS are described as the micro range. Horak et al. (2019) subdivided the micro range into Medium of Fine (MF) between SCS and TCS and Fine of Fine (FF) which are smaller than TCS. This latter distinction was largely based on the focus on permeability and linkage to interconnected voids in the general fines aggregate range by Horak et al. (2019). The filler size is described as the smallest size fines normally depicted by the 0.075mm sieve size.

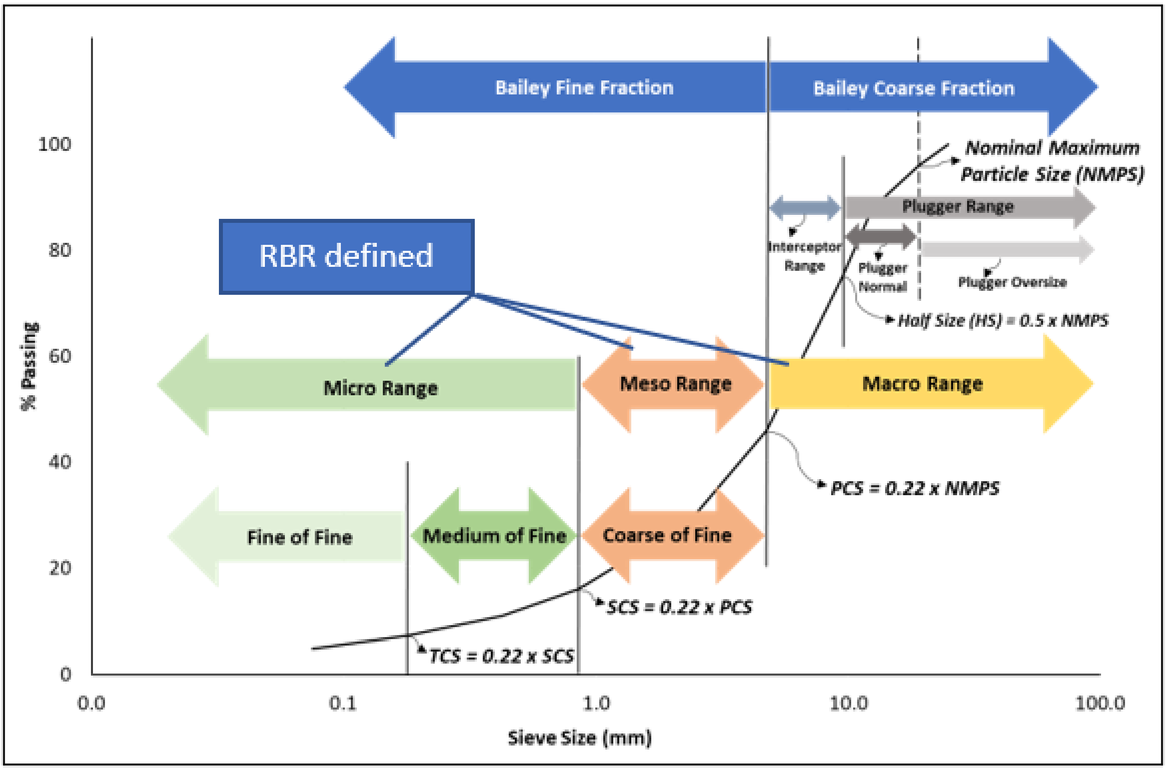

Figure 1: Bailey method framework description of grading curve and control sieves

2.2 Rational Bailey Ratios Definition

The CAP principle allows the definition and calculation of a set of RBRs shown in Table 1 using equations 1 to 7. The Bailey grading curve descriptors of the sieve sizes are used as best or common descriptors in these equations. These RBRs are based on the Bailey

Method description of the grading curve, which is defined or limited by the sieve sizes used in South Africa. The sieve sizes in South Africa tend to increase or decrease by a factor of two, e.g. 40mm, 20mm, 10mm, 5mm, etc. There is often more than one aggregate fraction size placed between some of these sieve sizes. Horak et al. (2019) showed the Binary Aggregate Packing (BAP) principle allows the evaluation of the contribution of binary contiguous aggregate fractions if they can be defined by separate sieve sizes.

Table 1: Rational Bailey Ratios based on contiguous aggregate fractions defined by Bailey grading curve descriptors (Horak et al., 2020)

Matrix Level	Rational Bailey Ratios
Macro	$\frac{PN}{PO} = \frac{(\%\mathrm{NMPS}-\%\mathrm{HS})}{(\%100-\%\mathrm{NMPS})} = \frac{\%\mathrm{Pluggers(PN)}}{\%\mathrm{Oversize\ or\ Pluggers\ (PO)}}$ ***Equation 1***
	$\mathrm{CA} = \frac{(\%\ \mathrm{HS}-\%\mathrm{PCS})}{(\%\ 100-\%\mathrm{HS})} = \frac{\%\ \mathrm{Interceptors}}{\%\ \mathrm{All\ pluggers}}$ ***Equation 2***
	$\frac{\mathrm{I}}{\mathrm{PN}} = \frac{(\%\mathrm{HS}-\ \%\mathrm{PCS})}{(\%\mathrm{NMPS}-\%\mathrm{HS})} = \frac{\%\mathrm{Interceptors}}{\%\mathrm{Pluggers\ (PN)}}$ ***Equation 3***
Meso	$\frac{C_f}{F_c} = \frac{(\%PCS-\%SCS)}{(\%HS-\%PCS)} = \frac{\%\mathrm{Coarse\ portion\ of\ fines}}{\%\mathrm{Interceptors}}$ ***Equation 4***
	$\frac{F}{C} = \frac{(\%\mathrm{PCS})}{(\%\mathrm{NMPS}-\ \%\mathrm{PCS})} = \frac{\%\mathrm{Fines}}{\%(\mathrm{Plugger\ (PN)+Interceptors})}$ ***Equation 5***
Micro	$FA_{cm} = \frac{(\%\mathrm{SCS}-\%\mathrm{TCS})}{(\%\mathrm{PCS}-\%\mathrm{SCS})} = \frac{\%\mathrm{Medium\ fine\ of\ fines}}{\%\mathrm{Coarse\ of\ \ fines}}$ ***Equation 6***
	$FA_{mf} = \frac{(\%\mathrm{TCS}-\%\mathrm{Filler}}{(\%\mathrm{SCS}-\%\mathrm{TCS})} = \frac{\%\mathrm{Fine\ of\ fines}}{\%\mathrm{Medium\ fine\ of\ fines}}$ ***Equation 7***

The matrix level descriptors in Column 1 of Table 1 are to facilitate the concept or even visualization of successive aggregate ranges that fit into each other's voids like the Matryoshka dolls (Olard, 2015). These ranges of macro, meso and micro levels, shown in Figure 1, are ranging respectively from maximum size sieve to PCS, from PCS to SCS, from SCS to the finest bottom of the grading curve as illustrated in Figure 1. Micro range is again using the original subdivision defined by the Bailey method to describe three sub-ranges: coarse of fine, medium of fine and fine of fine. These matrix level descriptors are not rigidly defined as typically changes in NMPS (e.g. 20mm or 40mm or 50mm) may cause a shift of some of the control sieves linked to the actual asphalt mix type or change in maximum aggregate size being used (See Tables 45, 46 and 47 in Appendix A of TG35, 2020). For G1 to G4 type UGMs, the NMPS may typically be 26.5mm as aggregate gradings stretch from a maximum aggregate size of 50mm down to 0.075mm as the minimum sieve size.

3. ARTICULATION OF RBRS WITH UNTREATED GRANULAR MATERIALS

3.1 Introduction

Untreated Aggregate Mixes (UGMs) are mixes of pure aggregate or stone and soil particles. UGMs are used as base, subbase and the other support layers in flexible pavement structures. The main difference between UGMs and asphalt aggregate mixes is that there is no binder (bitumen) in UGMs. If bitumen is added hot or warm, it is defined as an asphalt premix designed according to TG 35 (SABITA, 2020). If the bitumen is added in situ via recyclers (e.g. emulsion or foamed) to UGMs, the resulting mix is defined as Bitumen Stabilised Material (BSM). BSMs are typically designed according to Technical Guideline TG 2 (SABITA, 2020). UGMs may also be stabilised using cement or lime to form more rigid stabilised materials as described in SAPEM (SANRAL, 2014).

Smit (2002) indicate Francken and Valenstratet (1993) acknowledge the need for further definition of the filler size by reference and use of the Rigden voids (Rigden, 1947). Tunniclif (1960) also investigated the importance of size distribution, shape and surface texture results on the stiffening of asphalt mastics based on the concept of 'fractional voids' in building on the work of Rigden (1947) . This aspect is of particular interest in the voids in the filler range taken up as the mastic (Horak & Mukandila, 2008), but here the focus is on the need for a finer definition of the minus 0.075 mm filler fraction. It should be noted in asphalt mixes in addition the bitumen binder has selective disperiosn as it specifically adheres to fines fraction. Although the UGMcould with optimum compaction achieve a matrix in its most dense form, when it is stabilised with bitumen, the resultant mastic inhibits ideal packing leading to additional voids.

The common aspect is that UGMs, even as a stabilised material, still require an aggregate grading to describe the structural matrix compacted in its most dense form. Most stabilisation of UGMs covers natural gravels while the use of freshly crushed hard rock aggregates would lead to better quality stabilised materials, at an increased cost. Semmelink (1991) stated regarding the grading of UGMs that "*the particle size distribution (ie grading) of untreated roadbuilding materials has an effect on nearly all the other roadbuilding parameters. What is even more stunning is the fact that these same basic principles are also applicable to treated materials such as asphalt mixes and portland cement concrete in that the particle size distribution also determines the <u>amount of voids available</u> and thus the allowable binder content or OMC for concrete and thus the optimum amount of cement* …." (Underline for emphasis only).

UGMs cover the whole range of materials from freshly crushed hard rock to natural materials and gravels. A G1 quality material is defined as a graded crushed stone, usually obtained from crushing solid un-weathered quarried or mined rock or boulders. G2 and G3 quality material are obtained by the same process as a G1 quality material, but may contain natural fines not derived from crushing the parent rock. G1 to G3 crushed rock have specific grading envelopes and high density requirements.

Medium quality materials (G4, G5 and G6) are defined by the TRH 14 (DoT, 1985) and subsequently in SAPEM (SANRAL, 2014) as natural gravel or a mixture of natural gravel and boulders that may require crushing. Their grading specification envelopes are less restrictive and density requirements are lower with California Bearing Ratio (CBR) requirements added. Any of these materials may be modified using cement, lime, bitumen or polymers to enhance certain strength characteristics of the material. Lower quality materials (G7, G8, G9 and G10) are defined as gravel-soil in TRH 14 (DoT, 1985;

SANRAL, 2014). Their density requirements are lower and they do not have grading envelope requirements, but do have related indicators , eg Grading Modulus (GM) that provides control of the ratios of the between combined fractions. They do have CBR ranges specified linked to densities.

Shear strength of UGMs had been used as primary design criteria for unbound granular pavement layers (Theyse et al., 2007) but Theyse and Kannemeyer (2019) states that such shear characteristics were only indirectly addressed via grading and Atterberg indicators, particularly for the G1 to G3. Theyse and Kannemeyer (2019) state that the Grading Modulus (GM) specified for G5 and G6 materials is not adequate as an indicator to ensure shear strength is obtained in such materials. As mentioned above, lower quality UGMs such as G7 down to G10 tend to not have any real grading prescription and gradings vary considerably. A significant weight in terms of their classification ultimately depends on their CBR values. The use or reference to CBR as strength indicator is currently questioned and under review to move towards more fundamentally correct shear and strength indicators.

The focus of the current SANRAL research on UGMs is on the use of triaxial testing to determine not only basic shear characteristics like internal angle of friction and apparent cohesion, but also via repeated loading the resilient modulus (M_R). However, in this paper the data set developed by Semmelink (1991) was analysed to evaluate the possible correlation of density with the RBRs of UGMs as well as determine to what extent CBR as strength indicator could also be correlated with the RBRs of UGMs.

3.2 Porosity as Fundamental Characteristic of Untreated Granular Materials

Semmelink (1991) quoted Lees (1971) as a pioneer in asphalt mix design optimisation who looked at voids in the 'coarse' and 'fine' aggregates as the main criteria to achieve the most dense aggregate packing. Lees (1971) used this approach to determine the percentage of fine aggregate which should be added to the coarse aggregate to give the lowest void content. This can be expressed as porosity of the mix.

This is basically the principle on which the Bailey method developed later (Vavrik et al., 2001). The Bailey principle states the ratio of the voids diameter between the diameter of larger aggregate combination is 0.22. This ratio provides the size of aggregate fines that would theoretically fill the voids optimally.

According to Semmelink (1991) the American Society for Testing and Materials (ASTM) normally specify density of a granular mixture in terms of relative density, where the relative density (D_d) is normally defined as below in Equation 8:

$$D_d = \frac{\gamma_{max}(\gamma-\gamma_{min})}{\gamma(\gamma_{max}-\gamma_{min})} \times 100 \tag{8}$$

Where D_d = relative density (%)

γ_{min} = Minimum density (kg/m^3)

γ_{max} = Maximum density for specific compactive effort (kg/m^3)

γ = Measured density (kg/m^3)

Semmelink also indicated density can be expressed as per ASTM in terms of void content (porosity is directly linked) as follows in equation 9.

$$D_d = \frac{e_{max} - e}{(e_{max} - e_{min})} \times 100 \tag{9}$$

Where,

e_{max} = Maximum void content at minimum density γ_{min}
e_{min} = Minimum void content at maximum density γ_{max}
e = Actual void content at maximum density γ

This expression in terms of voids or porosity, as per equation 9, is not often used, but in effect, confirms porosity is as much a fundamental property as the density of compacted granular materials.

4. UGM DATA GRADING CURVE ANALYSIS

4.1 Introduction

The data from a published source of UGM material information was mined and reworked. Semmelink (1991) did a large study on a range of UGMs to determine the effect of measured material qualities on their compactability. This data set provided grading curves of a variety of UGMs from which RBRs could be calculated to describe the grading curve in full. The data sets also had Atterberg indicators, density and strength indicators such as CBR. The data sets were reworked to determine to what extent the RBR description of the grading curve improves multiple correlation analyses with strength or engineering design values. The van Aswegen (2013) and the Theyse & Kannemeyer (2019) data sets provided resilient modulus (M_R) values for various UGMs, their grading curves, normal Atterberg Indicators and optimum moisture content (OMC) and maximum dry density (MDD) values. These latter two data sets provided opportunity for correlation of the RBRs with more fundamental M_R as UGM strength indicator.

4.2 Density Correlation With RBRs

4.2.1 Semmelink Data Set

The Semmelink (1991) investigation on the compactability of UGMs was to determine the effect of measured material qualities on the density of UGMs. The material properties of the UGMs measured included grading, Atterberg limits, linear shrinkage, shake down bulk density (SBD), loose bulk density (LBD), shape factor (SF) and specific rugosity (S_{rv}). A sample size of 21 different UGMs ranging from a G9 to a G1 (see TRH14, 1986) were tested. Regression analyses were done to correlate various expressions of density (eg % of Solid density and Mod AASHTO) with these materials in terms of grading, Atterberg limits, linear shrinkage, SBD and SF.

The focus of the work by Semmelink (1991) was the introduction of the vibratory table for sample compaction versus Mod AASHTO density sample preparation. The vibratory compaction method was then still experimental and Semmelink (1991) helped to establish the laboratory method. This vibratory table method of sample preparation is currently used in the SANRAL UGM research on the resilient modulus (M_R) via triaxial and repeated load triaxial tests of samples that vary from 150mm to 300mm in diameter. The correlation relationship developed for density at the optimum or critical moisture content (related to vibratory table characteristics) of the Grading Factor (GF), a combined fines content and Liquid Limit (LL) factor (C, see equation 10), and the same fines content linked to Linear Shrinkage (LS) expressed as factor Q (See equation 11) .

By definition, they are :

GF = is grading factor, =sum of (percentage passing sieve size /nominal sieve size (mm)/100 for 75mm, 53mm, 37,5mm, 26,5mm 19mm, 13.2mm, 4.75mm and 2mm sieve sizes)

C = Liquid Limit factor = (percentage passing 0.425mm sieve/100)* $(LL/100)^{0.1}$ (10)

Q = Linear Shrinkage factor = (percentage passing 0.425mm sieve /100)*(LS) (11)

It is clear the grading information as utilised by Semmelink (1991) only rely on the fines portion (<0.425mm) of the grading as factors C and Q where they are combined with two Atterberg indicators, LL and LS. In this study by Semmelink (1991) limited distinctive grading information was actually used and may be defined as under utilised even for compactibility determination.

4.2.2 Density and CBR Data Analysis

The grading sourced and sample identification for the various samples from the Semmelink thesis (1991) are presented in Table 2. The NMPS, as defined before are indicated in yellow highlight. Samples are also identified where not enough sieve sizes up to the 0.075 filler sieve size are available (sandy and clayey materials). Their sample names are highlighted in orange/brown. These samples had to be discarded in the further RBR analysis as RBRs cannot be calculated.

Table 2: Grading information of data set of samples from Semmelink (1991)

	% Passing by mass										
	Sieve size (mm)										
sample	75	63	53	37,5	26,5	19	13,2	4,75	2	0,425	0,075
BAB	100	100	100	100	100	100	100	100	99,3	97	79
SPR2	100	100	100	100	100	99,3	93,7	87,2	76,3	65,9	42,1
SPR1	100	100	100	100	100	100	99,7	90,4	77,6	58,3	23,4
LabLEN	100	100	100	100	100	99,8	99,8	99,5	97,4	81	42,2
LabDEW	100	100	100	100	100	100	100	99,7	99,5	58,3	9
OFS1	100	100	100	100	100	100	100	100	100	99,4	8,2
NPAB	100	100	100	93	87	79	73	52	46	30	20
SIL	100	100	100	100	100	100	98	94	93	77	28
LABD1	100	100	100	100	100	99,3	95	72,7	60,2	48,3	30,8
TPA3	100	100	100	91	85	78	72	55	42	30	19
TPA1	100	100	100	91	85	79	78	69	56	21	7
CPA1	100	100	100	100	93	82	67	46	30	15	8
DENS7	100	100	100	100	100	98,8	77,8	46,1	34,9	24,8	18,2
TPA2	100	100	100	96	92	88	84	62	40	14	4
NPAE	100	100	100	100	99,1	96,2	87,5	50,9	29,6	13,6	2,8
FERR1	100	100	100	99,7	96,5	85,4	71,2	41	25,3	12,4	1,8
OFS2	100	100	100	99,6	97,6	96	91,6	54,5	27,6	10,3	3,5
NPAA	100	100	100	99	88	76	67	43	34	17	7
POSS1	100	100	100	99	83	73	65	48	34	15	6
DENS8	100	100	100	100	100	97,1	85,1	54,6	43,5	31,6	27,2
OFS3	100	100	100	100	99	97	83	36	15	5	2
Key		NMPS									
		Samples where NMPS has not enough sieves sizes to do RBRS									

The data set presented in Table 3 were used to do multiple regression analysis of the RBRs calculated with the Excel data analyser software add-in. In Table 4, it is shown that the multiple regression correlation with only RBRs correlated very well with the mod AASHTO density. This is in line with the original Semmelink (1991) data set with the larger sample set. It has a high coefficient of determination (R^2) value of 0.85 indicating the value of the inclusion of the RBRs. This regression analysis allows the ‘unlocking the embedded knowledge in the grading curve as a whole’ in correlation with density achievable.

Table 3: Density, CBR, calculated RBRs and Atterberg indicators from Semmelink (1991) data set

	Material parameters from semelink data set													
Sample	**CBR**	**Mod AASHTO**	**MDD (Vib) (%SD)**	**CA**	**PN/PO**	**Cf/Fc**	**F/C**	**I/PN**	**FAcm**	**FAmf**	**PI**	**OMC**	**LS**	**LL**
NPAB	69	76,05	77,44	0,78	0,29	1,29	1,93	3,50	2,67	0,63	13,00	10,31	8,50	44,00
LABD1	77,7	74,89	79,59	0,46	4,46	0,34	1,73	2,70	1,47	1,00	15,00	7,82	5,00	25,50
TPA3	204,2	74,47	77,47	0,61	0,87	0,76	1,83	6,14	0,92	0,92	12,00	9,40	6,50	30,00
TPA1	88,7	75,45	79,11	0,41	0,47	1,44	4,31	0,46	2,69	0,40	10,00	8,06	4,50	27,00
CPA1	336,2	86,03	90,24	0,64	3,71	0,76	0,98	0,08	0,94	0,47	3,00	3,92	2,00	17,00
DENS7	105,9	79,81	84,28	1,43	17,50	1,66	0,55	1,51	0,92	0,65	5,20	6,58	3,70	25,00
TPA2	126,2	77,20	82,14	1,38	0,33	1,18	2,38	5,50	2,69	0,38	6,00	7,22	2,50	29,00
NPAE	257,1	85,52	88,33	0,43	2,93	3,47	0,51	0,58	0,68	1,00	4,00	5,01	2,00	18,00
FERR1	629	81,12	86,79	1,05	0,97	0,43	0,43	2,13	0,82	0,82	4,00	4,82	2,00	20,00
OFS2	526,6	79,44	83,96	0,59	4,42	3,02	0,43	0,73	0,39	1,00	0,00	5,61	0,00	0,00
NPAA	505,1	82,23	88,04	0,73	1,75	1,38	0,96	1,14	1,89	0,59	0,00	4,55	0,00	0,00
POSS1	822	82,77	86,74	0,30	26,00	3,88	1,91	0,31	0,61	0,47	0,50	4,09	0,50	19,00
DENS8	31,5	78,37	77,81	0,24	2,05	1,07	1,05	0,36	0,37	1,00	14,00	10,74	7,60	33,40
OFS3	809	74,07	89,52	2,76	4,67	0,45	0,59	3,36	0,48	0,30	0,50	2,85	1,00	0,00

Table 4: Combined summary table of multiple regression of density (MAD) versus all RBRs

Regression Statistics			ANOVA					
Multiple R	0,92			*df*	*SS*	*MS*	*F*	*Significance F*
R Square	0,85		Regressio	7	177,34	25,33	4,89	0,04
Adjusted R Square	0,68		Residual	6	31,10	5,18		
Standard Error	2,28		Total	13	208,44			
Observations	14							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	98,60	6,27	15,73	0,00	83,26	113,93	83,26	113,93
CA	-5,85	1,98	-2,95	0,03	-10,70	-1,00	-10,70	-1,00
PN/PO	-0,09	0,12	-0,76	0,48	-0,40	0,21	-0,40	0,21
Cf/Fc	0,81	0,76	1,06	0,33	-1,05	2,66	-1,05	2,66
F/C	-4,03	1,09	-3,71	0,01	-6,68	-1,37	-6,68	-1,37
I/PN	-0,22	0,46	-0,48	0,65	-1,36	0,91	-1,36	0,91
FAcm	0,19	1,31	0,14	0,89	-3,01	3,39	-3,01	3,39
FAmf	-13,75	4,94	-2,78	0,03	-25,83	-1,66	-25,83	-1,66

If the Atterberg indicators and OMC of the materials are included the result from the multiple regression is as shown in Table 5. In this case, the R^2 value has now increased to a very significant value of 0.99. This is a high correlation value and even the adjusted R^2 value is still 0.92. It clearly illustrates that it is possible to get very good correlation with density achievable using RBRs and standard Atterberg and OMC values.

Table 5: Combined Summary output of Mod AASHTO density correlated with all RBRs, Atterberg Indicators and OMC

Regression Statistics			ANOVA					
Multiple R	0,99			*df*	*SS*	*MS*	*F*	*Significance F*
R Square	0,99		Regressio	11	285,64	25,97	14,64	0,07
Adjusted R Square	0,92		Residual	2	3,55	1,77		
Standard Error	1,33		Total	13	289,19			
Observations	14							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	102,01	4,85	21,03	0,00	81,14	122,88	81,14	122,88
CA	-1,10	1,29	-0,86	0,48	-6,65	4,44	-6,65	4,44
PN/PO	-0,12	0,09	-1,42	0,29	-0,50	0,25	-0,50	0,25
Cf/Fc	0,50	0,75	0,67	0,57	-2,73	3,74	-2,73	3,74
F/C	-2,07	1,14	-1,82	0,21	-6,98	2,84	-6,98	2,84
I/PN	-0,18	0,30	-0,61	0,61	-1,47	1,11	-1,47	1,11
FAcm	-0,14	0,90	-0,16	0,89	-4,00	3,72	-4,00	3,72
FAmf	-6,89	5,88	-1,17	0,36	-32,20	18,43	-32,20	18,43
PI	0,18	0,43	0,43	0,71	-1,65	2,01	-1,65	2,01
OMC	-1,70	0,56	-3,05	0,09	-4,10	0,70	-4,10	0,70
LS	-0,18	0,79	-0,22	0,84	-3,56	3,20	-3,56	3,20
LL	0,06	0,08	0,67	0,57	-0,30	0,41	-0,30	0,41

The majority of tests methods (CBR and Atterberg types) were developed in the northern hemisphere, specific for materials in that region, more than 50 years ago (Jordaan et al., 2017). The development of alternative tests and limits for the improved performance characterisation and classification of UGMs and their stabilised derivatives in the latest SANRAL research project, is aimed at providing material properties derived from testing conditions that simulate typical conditions that the materials will be exposed to in service. Such data sets focussing on triaxial and repeated triaxial loading tests are still under development and will certainly add to the knowledge and correlations possible.

Semmelink previously showed that density increase leads to significant , even exponential, increase in CBR at higher density values as illustrate din Figure 2. As illustrated for the highest quality UGM, a G1, CBR values well beyon the original reference of 100% is achieved, making the use of CBR as strength indicator for such better quality UGMs more than merely dubious. In spite of doubt regarding the empirical nature of the CBR as a strength indicator, the Semmelink data set was used to do a multiple regression analysis of CBR versus the calculated RBRs. In Table 6, it shows a reasonable R^2 value of 0.60. At first glance it may appear to be a reasonable value for a good correlation, but the adjusted R square value is a low 0.12 value. That clearly diminishes the accuracy or reliability of the correlation. That confirms the original analysis done by Semmelink who also found that CBR is not a reliable strength value, being largely empirical and even with a better description of the CAP derived RBRs still don’t overcome the variability that CBR inherently has.

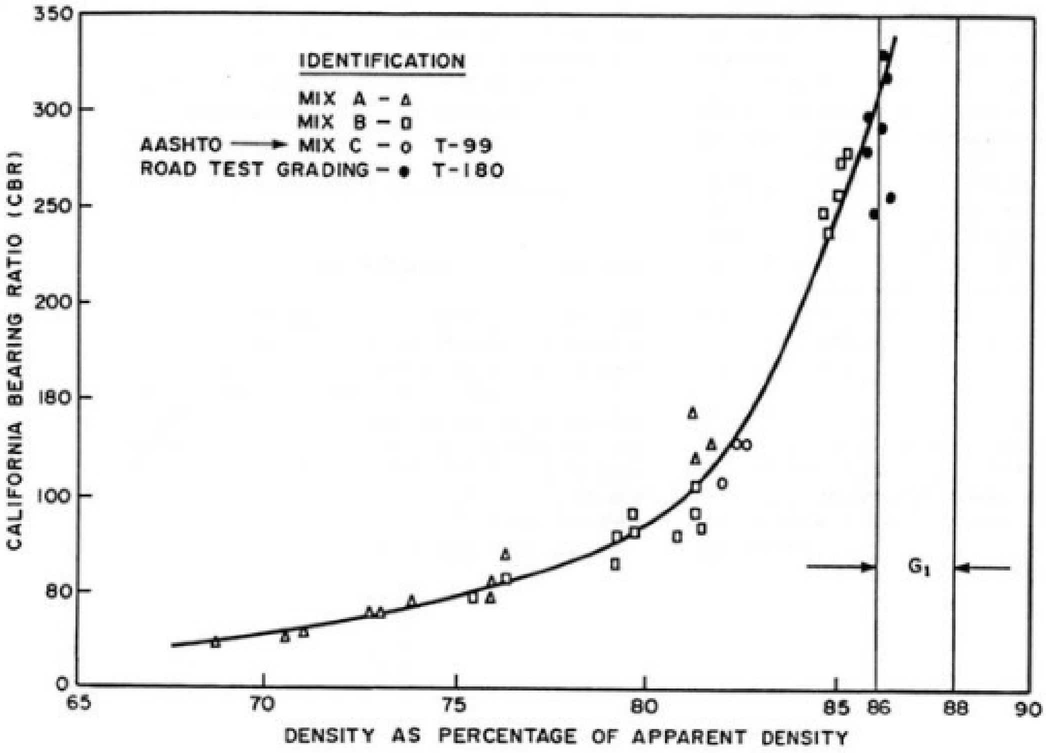

Figure 2: Impact of density of UGMs on CBR (Semmelink, 1991)

Table 6: Summary table of multiple regression analysis of CBR versus RBRs

Regression Statistics	
Multiple R	0,77
R Square	0,60
Adjusted R Square	0,12
Standard Error	262,37
Observations	14

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	7	609163,37	87023,34	1,26	0,40
Residual	6	413019,94	68836,66		
Total	13	1022183,31			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	1176,76	722,31	1,63	0,15	-590,68	2944,20	-590,68	2944,20
CA	-45,86	228,46	-0,20	0,85	-604,88	513,15	-604,88	513,15
PN/PO	-5,43	14,27	-0,38	0,72	-40,36	29,50	-40,36	29,50
Cf/Fc	71,55	87,58	0,82	0,45	-142,76	285,86	-142,76	285,86
F/C	-72,38	125,10	-0,58	0,58	-378,49	233,74	-378,49	233,74
I/PN	20,70	53,35	0,39	0,71	-109,83	151,24	-109,83	151,24
FAcm	-207,18	150,80	-1,37	0,22	-576,17	161,80	-576,17	161,80
FAmf	-832,04	569,11	-1,46	0,19	-2224,60	560,51	-2224,60	560,51

In an effort to see if the addition of the Atterberg indicators and OMC values are significant the RBRs versus CBR the multiple regression results are shown in Table 7. The R^2 value now increased to a good value of 0.8. However, the adjusted R square value literally changed to a negative value. This further emphasizes the point made above. The inherent variability related to CBR trends to negate any good correlation with either RBRS, Atterberg Indicators and OMC.

Table 7: Summary table of multiple regression analysis of CBR versus RBRs and Atterberg indicators and OMC

Regression Statistics	
Multiple R	0,90
R Square	0,80
Adjusted R Square	-0,29
Standard Error	317,93
Observations	14,00

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regressio	11	820022,66	74547,51	0,74	0,70
Residual	2	202160,65	101080,32		
Total	13	1022183,31			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	816,95	1158,01	0,71	0,55	-4165,57	5799,47	-4165,57	5799,47
CA	-55,92	307,80	-0,18	0,87	-1380,30	1268,46	-1380,30	1268,46
PN/PO	6,59	20,93	0,32	0,78	-83,45	96,63	-83,45	96,63
Cf/Fc	-42,44	179,62	-0,24	0,84	-815,28	730,39	-815,28	730,39
F/C	112,29	272,21	0,41	0,72	-1058,95	1283,53	-1058,95	1283,53
I/PN	38,18	71,43	0,53	0,65	-269,17	345,53	-269,17	345,53
FAcm	-92,83	214,20	-0,43	0,71	-1014,47	828,82	-1014,47	828,82
FAmf	214,80	1404,76	0,15	0,89	-5829,38	6258,98	-5829,38	6258,98
PI	-54,02	101,60	-0,53	0,65	-491,17	383,13	-491,17	383,13
OMC	-75,73	133,34	-0,57	0,63	-649,46	498,00	-649,46	498,00
LS	86,63	187,51	0,46	0,69	-720,17	893,44	-720,17	893,44
LL	-6,43	19,61	-0,33	0,77	-90,82	77,95	-90,82	77,95

4.3 Correltion of RBRs With Resilient Modulus (M_R)

4.3.1 Van Aswegen Data Set

Van Aswegen (2013) studied the effect of moisture and density on the resilient response of UGMs. The data set from this PhD thesis provided a spread of materials varying from G1 material quality to G8 material quality. In Table 8 the grading data sets and sample identification are shown with the NMPS sieve highlighted.

Table 8: Grading information of data set of samples from van Aswegen (2013)

TRH 14 class	Material	Sample	Sieve sizes (mm)									
			75	53	37,5	26,5	19	13,2	4,75	2	0,425	0,075
G1(01)	Cr Nor	11306a	100,0	100,0	100,0	95,1	73,7	55,3	34,5	25,4	14,3	5,3
G1(13)	Cr Nor	11306b	100,0	100,0	100,0	85,0	67,5	54,8	35,9	26,5	14,5	5,3
G1(23)	Cr Nor	11306c	100,0	100,0	100,0	92,2	72,7	56,4	32,4	23,7	13,3	5,0
G5(3)	W Chert	11307(a)		100	82,67	71,28	69,13	66,11	56,04	46,35	37,1	28,34
G5(15)	W Chert	11307(b)	100	73,44	66,92	64,28	63,36	60,78	51,21	42,06	33,82	25,2
G5(24)	W Chert	1130(c)		100	90,17	86,77	81,18	78,32	66,58	54,24	41,48	31,32
G4/G6	W Dol	11726(a)	100	100	90,81	76,2	63,95	51,11	34,29	26,09	17,01	10,91
G4/G6	W Dol	11726(b)	100	100	94,29	69,66	56,22	47,93	32,39	24,47	15,96	10,15
G4/G6	W Dol	1172(c)	100	100	94,02	87,91	72,97	59,82	37,45	27,74	18,16	11,43
G6	W Dol?	11357(1)	100	100	97,63	88,48	79,98	71,66	54,48	41,14	24,91	15,05
G6	W Dol?	11357(2)	100	100	92,4	83,8	73,17	63,8	48,14	36,67	22,13	12,29
G6	W Dol?	11357(3)	100	100	96,55	88,53	79,23	71,55	52,98	39,42	23,71	13,6
G8	Bergville	11721(1)	100	100	95,73	89,36	82,3	74,19	57,6	44,96	31,11	23,66
G8	Bergville	11721(2)	100	100	97,15	93,81	85,9	77,12	58,87	46,68	32,97	25,94
G8	Bergville	11721(3)	100	100	97,32	91,87	86,37	78,77	60,83	47,67	33,38	25,8
G7/8	D804	11728(1)	100	100	96,28	90,07	86,48	81,4	67,2	56,63	46,43	33,34
G7/8	D804	11728(2)	100	100	94,03	92,5	85,67	80,08	65,1	53,89	42,73	26,67
G7/8	D804	11728(3)	100	100	100	93,03	84,63	79,77	65,83	55,17	44,08	27,71
Key		NMPS										

The calculated RBRs are shown in Table 9 with the CBR, Densities and M_R values. The M_R values are from a larger data set of M_R values. A saturation level of 20%, a 50% failure with 100kPa confining stress had been selected to correlate with the densities of basic Atterberg indicators prepared in a group.

In Table 10 the CBR values are showing a very good R^2 value of 0.81 for the RBRS, Atterberg indicators and OMC. In Table 10 the M_R values correlated well with the same RBRs, Atterberg indicators and OMC of the material samples. In this case an R^2 value of 0.8 is achieved.

Table 9: Density, CBR, M_R and calculated RBRs and Atterberg indicators from van Aswegen (2013) data set

TRH 14 class	Sample	LL	PL	PI	LS (%)	OMC (%)	CA	PN/PO	Cf/Fc	F/C	I/PN	FAcm	FAfm	Mod AASHTO	CBR (%)	M_R (kPa)
G1(01)	11306a	0	0	0	0	5,4	0,66868	8,122449	0,372031	0,364615	0,751005	0,808453	0,026978	99	260	934
G1(13)	11306b	0	0	0	0	6,5	0,626383	2,014009	0,423675	0,453411	1,275532	0,769808	0,025021	100	275	1011
G1(23)	11306c	0	0	0	0	6	0,750803	4,57289	0,318154	0,346086	1,19244	0,79635	0,009606	100	262	1088
G5(3)	11307(a)	31,34	19,25	12,09	5,83	10,7	0,424036	0,781304	0,74026	2,104394	0,966765	0,468117	0,947027	99	61	1137
G5(15)	11307(b)	32,7	19,77	12,93	5,83	10,3	0,331605	0,107618	0,753086	3,259707	3,412921	0,440171	1,046117	100	55	421
G5(24)	1130(c)	31,46	19,67	11,79	5,18	10,5	1,110701	0,6387	0,5299	1,667384	2,849704	0,796238	0,103448	100	47	803
G4/G6	11726(a)	30,21	22,36	7,86	4,85	6,89	0,822746	2,922742	0,276467	0,606688	1,104244	0,36291	0,671806	98	43,3	735
G4/G6	11726(b)	30,27	22,62	7,65	5,18	7,59	0,544312	6,66725	0,332354	0,523263	0,625952	0,362745	0,682726	98	27,5	938
G4/G6	1172(c)	31,2	22,37	8,83	5,18	6,89	0,798407	2,323408	0,298628	0,461027	1,142043	0,702505	0,044885	98	35,4	1141
G6	11357(1)	29,75	20,92	8,83	5,83	7,6	1,076923	1,460069	0,531782	0,869033	1,814507	0,607517	0,033888	100	19	1249
G6	11357(2)	30,64	22,22	8,42	5,83	7,6	0,932911	2,530263	0,45825	1,087664	1,301612	0,535938	0,676754	100	27,5	1046
G6	11357(3)	30,09	22,03	8,06	5,5	7,6	1,12935	1,480384	0,488951	0,802688	1,892226	0,643539	0,038192	100	23,25	843
G8	11721(1)	24,81	19	5,81	5,18	8,3	1,132507	1,425752	0,473828	1,012613	1,926829	0,537906	0,047653	98	17	1227
G8	11721(2)	29,15	19,44	9,71	5,18	8,3	1,33042	2,696284	0,450394	0,990452	1,823847	0,512764	0,068563	98	17	998
G8	11721(3)	25,57	17,87	7,71	5,18	8,3	1,464908	1,611316	0,459486	1,078507	2,374046	0,530441	0,055983	98	17	769
G7/8	11728(1)	28,76	18,12	10,63	6,47	9,4	1,33172	0,873112	0,411788	1,693481	2,856978	1,283333	0,131373	100	55	1833
G7/8	11728(2)	26,84	18,65	8,19	6,47	9,4	1,314759	1,656	0,426117	1,395752	2,108696	1,439068	0,060036	100	55	1333
G7/8	11728(3)	28,56	18,51	10,05	6,8	9,4	1,216016	1,902439	0,450813	1,457211	1,855204	1,476105	0,064022	100	55	833

Table 10: Summary output of RBR and Atterberg Indicators correlation with M_R

Regression Statistics	
Multiple R	0,900446551
R Square	0,810803991
Adjusted R Square	0,356733569
Standard Error	239,7398454
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	1231556,533	102629,7	1,785635	0,271089539
Residual	5	287375,9673	57475,19		
Total	17	1518932,5			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	2262,261162	1318,266859	1,716087	0,146801	-1126,451679	5650,974	-1126,4517	5650,974003
LL	55767,58993	18429,48214	3,025999	0,029215	8393,097884	103142,082	8393,09788	103142,082
PL	-55845,1985	18409,51535	-3,0335	0,028965	-103168,3643	-8522,03276	-103168,36	-8522,032761
PI	-55786,2226	18443,16227	-3,02476	0,029256	-103195,8805	-8376,56469	-103195,88	-8376,56469
LS (%)	303,4200543	295,9745049	1,025156	0,352304	-457,4066319	1064,24674	-457,40663	1064,24674
OMC (%)	45,75458669	120,6534875	0,379223	0,720093	-264,3950767	355,90425	-264,39508	355,9042501
CA	181,7725751	597,9279424	0,304004	0,77337	-1355,250133	1718,79528	-1355,2501	1718,795283
PN/PO	-69,3049348	50,49618187	-1,37248	0,22828	-199,1095027	60,4996331	-199,1095	60,49963311
Cf/Fc	-1606,91763	1573,480495	-1,02125	0,35398	-5651,678005	2437,84276	-5651,678	2437,842755
F/C	-74,9322744	725,8825085	-0,10323	0,921794	-1940,872666	1791,00812	-1940,8727	1791,008117
I/PN	-167,089946	335,2423304	-0,49842	0,639339	-1028,857791	694,677899	-1028,8578	694,6778988
FAcm	-631,595516	583,8559426	-1,08177	0,328747	-2132,444997	869,253964	-2132,445	869,2539642
FAfm	4,00646677	640,7427175	0,006253	0,995253	-1643,075124	1651,08806	-1643,0751	1651,088058

4.3.2 Theyse& Kannemeyer Data Set

Theyse and Kannemeyer (2019) used a data set collected over a period from 1995 to

2015. The Atterberg indicators and the OMC of the various material samples were provided in a table in the paper. The grading information was presented in graph form as published in Theyse & Kannemeyer (2019). The NMPS, as defined before, are indicated in Table 12. Samples where not enough sieve sizes up to the 0.075 filler sieve size are identified. These samples had to be discarded in the further RBR calculations and analysis as the micro range RBRs cannot be calculated.

Table 12: Grading information set from Theyse & Kannemeyer (2019)

	% Passing by mass										
	Sieve size (mm)										
sample	75	63	53	37,5	26,5	19	13,2	4,75	2	0,425	0,075
KZN Aeolian sand	100	100	100	100	100	100	100	99	97	87	9
D514 Gran (B)	100	100	100	100	100	100	100	97	86	46	14
D514 Gran (SB)	100	100	100	100	100	100	100	95	80	40	21
D804 Calc (B)	100	100	100	100	87	83	78	65	54	44	28
S191 Dol (B)	100	100	100	99	78	72	63	44	34	22	17
S191 Dol (SB)	100	100	100	100	94	72	60	44	34	21	14
P10-2 Shale (B)	100	100	100	100	95	88	78	55	42	31	25
R538 SandS	100	100	100	100	93	83	74	55	46	40	18
Prima river gravel	100	100	100	100	99	96	68	46	39	27	4
Donkerhoek Sands	100	100	100	100	96	89	65	46	32	25	10
Quicksand burnt shale	100	100	100	99	74	70	52	36	27	16	10
R35 dolerite base	100	100	100	92	89	80	75	64	39	14	5
N7 hornfels base	100	100	100	99	87	71	58	32	20	11	7
Brewerskloof eucrite	100	100	100	99	96	85	68	48	30	18	6
Peninsula hornfels	100	100	100	99	95	85	75	47	29	14	7
Ferro quartzite	100	100	100	99	78	56	43	27	17	9	5
Coedmore tillite	100	100	100	100	89	80	65	45	30	14	7
Sterkspruit sandstone	100	100	100	100	100	86	70	46	30	17	7
N4 ext. norite base	100	100	100	100	95	74	55	35	26	14	7
Laezonia amphibolite	100	100	100	95	85	75	67	50	37	19	8
Key		NMPS									
		Samples where not enough sieves remain to calculate RBRs									

Theyse and Kannemeyer (2019) in effect adhered to contiguous aggregate fractions or packing to calculate the gravel/sand ratio described in Equation 12. The gravel/sand ratios were plot versus the clay or silt fraction for each material sample subsequently tested. This is already an improvement in "unlocking the inherent knowledge of the grading curve", but can obviously be improved on. Each sample had their resilient modulus (M_R) value determined and could be deduced or extracted from the combined Figure 3 published in Theyse & Kannemeyer (2019).

$$\frac{\text{Gravel}}{\text{Sand}} = \frac{100-\text{pp4.75Gravel}}{\text{pp4.75}-\text{pp0.075}} \tag{12}$$

- Where pp4.75= percentage passing the 4.75mm sieve by mass
- Pp0.075= percentage passing the 0.075mm sieve by mass and also classed as silt and clay fraction

In Table 13 the sample values for the Atterberg and OMC are shown. As indicated before three samples had to be discarded due to the low NMPS preventing the whole range of RBRs to be calculated. These are mostly sand or clayey materials. In Table 14 the multiple regression results from M_R versus all the calculated RBRs**,** Atterberg indicators and OMC show a good R^2 value of 0.86. This implies, as for the van Aswegen data set, that RBRs can effectively be used to correlate with the MR value with normal Atterberg indicatorsand their OMC values. It clearly can be sued to enhance the suggested UGM grading system described by Theyse and Kannemeyer (2019) and provide additional objective criteria.

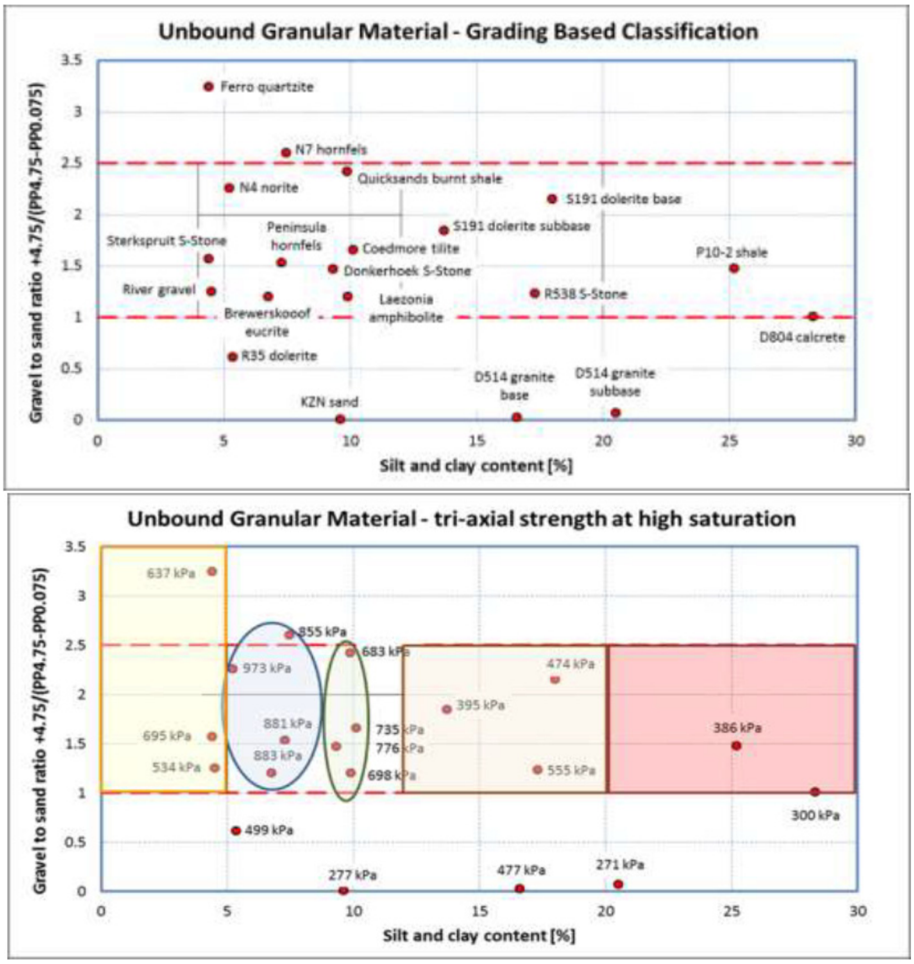

Figure 3: Combination of material sample identification and M_R values (Theyse & Kannemeyer, 2019)

Table 13: M_R calculated RBRs and Atterberg indicators and OMC from Theyse & Kannemeyer (2019) data set

sample	CA	PN/PO	Cf/Fc	F/C	I/PN	FAcm	FAmf	GM	LL	PI	LS	OMC	M_R (kPa)
D804 Calc (B)	0,59	0,69	0,85	2,95	1,44	0,91	1,60	2,25	35	14	7,7	10,2	300
S191 Dol (B)	0,32	27,00	0,85	1,75	0,33	1,20	0,42	2,3	30	11	5,4	8,2	474
S191 Dol (SB)	0,40	6,67	0,63	1,50	0,47	0,41	0,54	2	29	11	6,6	7,9	395
P10-2 Shale (B)	1,05	0,83	0,57	2,39	2,30	0,85	0,55	1,74	28	10	6	9,2	386
R538 SandS	0,73	2,71	0,47	1,45	1,00	0,67	3,67	1,97	17	3	2	5,7	555
Prima river gravel	0,69	7,00	0,32	1,45	0,79	1,71	1,92	2,32	0	0	0	5,8	534
Donkerhoek Sands	0,54	2,18	0,74	1,07	0,79	0,50	2,14	2,35	18	1	1	6,7	776
Quicksand burnt shale	0,60	29,00	1,39	1,11	0,62	0,44	0,55	2,46	25	9	6,5	11,2	683
R35 dolerite base	0,44	1,27	2,27	0,95	0,79	1,00	0,36	2,41	33	4	2	5,8	499
N7 hornfels base	0,62	2,23	0,46	2,56	0,90	0,75	0,44	2,6	23	8	1	5,5	855
Brewerskloof eucrite	0,63	1,13	0,90	1,30	1,18	0,67	1,00	2,46	17	1	1	5,5	883
Peninsula hornfels	1,12	0,67	0,64	1,24	2,80	0,83	0,47	2,53	17	3	1	6,3	881
Ferro quartzite	0,28	43,00	2,00	0,77	0,30	0,80	0,50	2,7	16	4	0	5,7	637
Coedmore tillite	0,57	2,18	0,75	1,02	0,83	1,07	0,44	2,39	20	5	1	6,3	735
Sterkspruit sandstone	0,80	1,14	0,67	1,15	1,50	0,81	0,77	2,52	14	1	0	5,3	695
N4 ext. norite base	0,44	8,00	0,45	0,58	0,50	1,33	0,58	2,58	0	0	0	6	973
Laezonia amphibolite	0,52	1,20	0,76	1,43	0,94	1,38	0,61	2,34	21	4	2,3	5,4	698

Table 14: Summary Output of resilient modulus verss RBRS Atererg indicators nd OMC for Theyse & Kanemeyer data, 2019

Regression Statistics	
Multiple R	0,92453591
R Square	0,85476664
Adjusted R Square	0,41906657
Standard Error	149,514077
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	526266,0453	43855,5	1,96182351	0,270119011
Residual	4	89417,83709	22354,46		
Total	16	615683,8824			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-40,7502822	878,5079185	-0,04639	0,96522624	-2479,879292	2398,37873	-2479,87929	2398,378728
CA	25,2425452	697,9187174	0,036168	0,97288115	-1912,490462	1962,97555	-1912,49046	1962,975552
PN/PO	0,34779269	6,18082737	0,05627	0,95782561	-16,81293521	17,5085206	-16,8129352	17,50852058
Cf/Fc	-218,631561	164,5880498	-1,32836	0,2547811	-675,6012465	238,338124	-675,601246	238,3381239
F/C	-27,4438058	149,432066	-0,18365	0,86321884	-442,333734	387,446122	-442,333734	387,4461223
I/PN	-14,9071688	207,6316749	-0,0718	0,94621059	-591,3851162	561,570779	-591,385116	561,5707786
FAcm	-140,955759	145,1513146	-0,9711	0,3864905	-543,9604156	262,048898	-543,960416	262,0488981
FAmf	-57,7885008	67,83489139	-0,8519	0,44226978	-246,128353	130,551351	-246,128353	130,5513513
GM	425,350933	320,0083031	1,329187	0,25453126	-463,1345532	1313,83642	-463,134553	1313,83642
LL	6,72171285	14,64226706	0,459062	0,67002769	-33,93173787	47,3751636	-33,9317379	47,37516357
PI	-30,2289156	45,38748739	-0,66602	0,54184327	-156,2447828	95,7869516	-156,244783	95,78695158
LS	-18,8517835	75,47294078	-0,24978	0,81505929	-228,3982605	190,694693	-228,398261	190,6946935
OMC	24,3296999	74,02808375	0,328655	0,75890268	-181,2052109	229,864611	-181,205211	229,8646107

5. CONCLUSION

The development of the grading curve is acknowledged to be a 'blunt instrument' if used alone purely on form and fit within a prescribed grading curve envelope specification in design analyses. It has no reliable or direct correlation to more fundamental material properties like porosity, density and or strength. Traditionally, CBR values are used for strength indication based on historic relations and development in material classifications.

The Bailey Method definition of sieve sizes and known aggregate size on a typical asphalt aggregate grading curve forms the basis of the description of various grading curve parameters. These grading curve descriptors enable a better-focused analysis to derive the 'inherent properties' of the aggregate grading. The basis of the Bailey Method relies on the fundamental ratio of the size of space between aggregates to give further credibility to a universal description of the various aggregate sizes and control sieves on the grading curve.

The CAP principle allows porosity calculation of binary or a range of contiguous aggregates. The grading curve description with various RBRs meets the CAP principle. These RBRs collectively describe the full grading curve. Due to their link to porosity such RBRs reflect more fundamental information about the packing and density arrangement of the aggregate matrix.

The UGMs have gradings even if not specified for lower quality natural gravels. A published data set was explored and reworked to determine the RBRs of the various gradings. The RBRs combined with Atterberg indicators and OMC were correlated via multiple regression analysis. In all cases, high R^2 values could be determined for density (expressed as Mod AASHTO). This implies good correlation is obtained for the density potential of a variety of UGM material qualities.

In the case of correlation with CBR as a strength indicator, the correlations were less successful. Even though the data set can be defined as relatively limited, the issue regarding the lack of correlation of RBRs, Atterberg Indicators and OMC with CBR underlines the problems currently experienced with the CBR still viewed as a universal granular material strength indicator. The CBR is in essence an empirical strength indicator for soils and gravels , combining the cohesion and angle of internal friction, with CBR values normally equal to or below 100%. In the South African material classification methods and specifications typically freshly crushed hard rock UGMs (eg G1 to G4) do not even use or reflect CBR values as they are in essence extrapolated far above the original benchmark of 100%. The current research effort in South Africa indicates that CBR should be “repurposed” and material characterization of strength should rather be based on resilient modulus as determined with the more fundamental test like the triaxial or repeated loads triaxial tests. It is believed in such fundamental material strength characteristics the RBRs will have a better correlation, but data sets are not yet currently available.

Two additional data sets (Van Aswegen, 2013 and Theyse & Kannemeyer, 2019) could be used to show RBRs with normal Atterberg Indicators and the OMC of the UGM correlate well with he more fundamental strength value of M_R. Thus BRs can be used to enhance the material classification based on strength and performance suggested by THeyse & Kannemeyer (2019). It confirms the current research effort in SA on UGMs to focus on the dtermination of basic shear characteristics and M_R via triaxial and repeated load triaxial tests rae a more objective way to describe UGM strength and performance.

This pilot studies indicated that it is possible to untap the “inherent properties” in the grading curves of UGMs to enable a more fundamentally correct evaluation of the grading information. This exploratory work shows grading information via the RBRs, Atterberg indicators and compaction-specific information, like the optimum moisture content (OMC), can provide a very good correlation with UGM density potential. Various ways and means to determine density were available from the data set, but Mod AASHTO was used as a universal method to express the maximum density.

Good quality UGMs like G1 to G4 have good grading specifications and allow easy RBR calculations. Natural gravel UGMs currently do not have grading specifications, relying on GM to combine farious grading knowledge aspects. It is strongly suggested the gradings should be recorded for natural gravels. Lower quality material in the G7 and lower range of sandy gravels, sand or silty/clayey materials need additional sieve sizes to enable RBR calculations as their NMPS may be as low as 5mm or 2mm.

It is clear aggregate fractions between the current sieve sizes in use (0.5 ratios between successive sieve sizes) could be refined by using more sieve sizes in between to enable the evaluation of more single fractions versus a graded contiguous combination of fractions. The whole ASTM sieve size range shows it is possible, particularly the 1mm, 0.5mm 300 microns, and 150 microns. This clearer definition of single-size aggregates in this micro range will enable a better description of the fine aggregate fraction BAP proportions for permeability control purposes. It is also important, specifically for asphalt mixes to have a better definition of grading in the filler range. The Rigden voids already gives such an indication of grading and mastic influence.

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