Characterization and Improvement of Natural and Blended un-bound Gravels From Khartoum State for Use as Base Course Material

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Abstract

This paper presents the outcome of a comprehensive testing program aimed at studying the strength, stiffness and deformation characteristics of three selected natural unbound materials in their natural state and when blended with Wadi sand or crushed stone with different size grades to satisfy base course specifications. A graded crushed stone sample was prepared as reference material. The natural materials C1, M2 and F3 were obtained from open quarries to represent coarse, medium and fine gradations, respectively. The materials were also stabilized with cement. Only 1% cement by weight of dry material rendered the three unbound gravels to behave as rigid materials. The California Bearing Ratio (CBR), resilient modulus (M_R) and permanent deformation (PD) tests were performed on the natural, blended and stabilized samples for determination of their strength, stiffness and deformation characteristics.

Initial assessment of the improvement methods has shown that the strength (CBR) of the three materials, blended with Wadi sand, significantly improved to satisfy or nearly satisfy the GB3 requirement. Blending with crushed stone improved the gradation and caused large increase in strength (CBR) of the three materials. Cement stabilization of the three materials using 1% cement by weight of dry material rendered them to become hard material with CBR exceeding 100%. Further study of the stiffness and deformation characteristics of the studied materials has shown that blending with crushed rock gave better results in terms of increase in stiffness compared to Wadi sand when coarse gravel size material was added. It was enhanced by the improvement of gradation and interlocking caused by the shape of the coarse crushed stone particles. The crushed stone mix measured M_R values exceeding 250 kPa indicating very stiff mix of superior quality when compared to the naturally occurring unbound materials and their corresponding blended products. Cement stabilization resulted in a very rigid material with M_R values twice those for the pure crushed stone sample. The graded pure crushed stone sample showed very high resistance to permanent deformation when compared to the natural or blended materials. Blending a material with graded crushed

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stone gave lower PD values compared to blending the same material with Wadi sand. This investigation has also shown that blending with sand and crushed rock could result in high increase in the strength of unbound material as demonstrated by CBR values, but would not necessarily result in comparable increase in rigidity or in resistance to permanent deformation.

Key words: Unbound gravel, gradation, stabilization, resilient modulus, permanent deformation

مستخلص

هذه الورقة تقدم مخرجات برنامج مكثف للتجارب ويهدف إلى دراسة القوة والمتانة وخصائص التشكل لثلاثة عينات مختارة من مواد الخرسانة الترابية في حالتها الطبيعية وعندما خُلطت برمل الوادي أو الحجر المكسور من أحجام مختلفة التدرجات لتطابق مواصفات طبقة الأساس. عينة من الحجر المكسور المدرج قد جُهز كمادة مرجعية . المواد الطبيعية F3، M2 ، C1 قد تم أخذها من مقالع مفتوحة لتمثل التدرجات الخشنة والمتوسطة والناعمة بالتوالي . هذه المواد ايضاً قد خُلطت بالأسمنت بنسبة 1% بالوزن من المادة الجافة لتثبيتها وجعلها مواد شبه صلدة. أجريت تجارب نسبة التحمل الكلفورني ومعامل الرجوعية والهبوط الدائم على عينات الخرصانات الترابية في حالتها الطبيعية والمعالجة (المخلوطه) لتحديد خصائصها للقوة والمتانة والتشكل .
التقييم المبدئي للطِرق المحسنة أظهرت بأن القوة للعينات الطبيعية الثلاث والمخلوطه بالرمل قد تحسنت وإستوفت تقريباً مواصفات (GB3) . عملية الخلط بالحجر المكسور أدت إلى تحسن التدرج وتسببت في زيادة كبير في القوة (CBR) للعينات الثلاثة . خلطالمواد الثلاثة بالاسمنت بنسبة 1 % بالوزن من المادة الجافة ادى الى تحولها كمادة متصلدة مع زيادة قوة تحمل كلفورنيا إلى 100 %. دراسة لاحقة لخصائص المتانة والتشكل للمواد المدروسة اظهرت بان الخلط بالحجر المكسور اعطت نتائج أحسن بالنسبة لزيادة المتانة مقارنة برمل الوادي عند أضافة المادة الخرسانية الخشنة هذا ناتج من تحسين التدرج والتداخل الناتج من شكل جزئيات الحجر المكسور. عينة خلطة الحجر المكسور أعطت قيم لمعامل الرجوعية أعلى من250 كيلو باسكال وهو مؤشر لخلطة ذات متانة عالية وجودة مميزة عند مقارنتها بالمواد الخرسانية الطبيعية ونظيراتها المنتجة بالخلط. عملية التثبيت بالاسمنت أدت الى مادة عالية التصلد ذات قيم معامل رجوعية ضعف تلك التى من عينة الحجر المكسور الخالص. عينة الحجر المكسور الخالص والمدرج اظهرت مقاومة عالية للهبوط الدائم بالمقارنة مع عينة الخرسانة الطبيعية وعينات الخرصانة المعالجة. معالجة الخرسانة الطبيعية بالحجر المكسور المدرج اعطت اقل قيم للهبوط الدائم مقا رنة بنتائج نفس الخرسانة الطبيعية المعالجة بالرمل الطبيعى الخشن. هذه الدراسة اظهرت ايضا أن المعالجة بالرمل الخشن والحجر المكسور قد تؤدي الى زِيادة عالية فى القوة للمادة الخرسانية كما هو واضح من قيم التحمل الكلفورنى . ولكن ليس مهماً ان يسجل أى زيادة فى التصلد او أى زيادة فى مقاومة الهبوط الدائــم .

1. Introduction

The pavement materials commonly used for road construction in Sudan are natural unbound gravelly materials that can be easily mined, collected and batched from open quarries situated within relatively short distances from the construction sites.

They are used as pavement materials of natural gravels.Many pavements had experienceddistresses, consequently expensive maintenance were needed. These natural gravels often satisfy the technical requirements of sub-base materials specifications,but seldom satisfy those of base course.

As known, the base course plays a vital role in supporting traffic loading and therefore, it should be stiff enough to attenuate the stress level on the subgrade soil without causing excessive settlement.Due to limited available sources of good quality road construction materials from these open quarries,local construction companies blend them either with natural coarse Wadi sand or crusher rock dust.

Due to the lack of Sudanese code and specifications for the design and construction of pavements, AASHTO, Transport Research Laboratory of United Kingdom (TRL)standards and other codes of practices are adopted. The selection of subbase and base materials according to the mentioned design standards is based on specified gradation jackets and strength requirements. In some cases the available materials may not satisfy the mentioned standards and therefore have to be mechanically blended with crushed stone and/or Wadi sand.Worldwide, chemical stabilization using lime or cement has been widely practiced in road construction to upgrade and improve subbase quality materials to the level of road base materials [1].

This paper focuses on assessing different blending and stabilization exercises for three natural unbound aggregates, of sub-base quality, obtained from open quarries in Khartoum state,in an attempt to upgrade them to be used as road base materials. Comprehensive testing program was executed forstudying the effects of mechanical blending with crushed stoneand chemical stabilization using cement on strength, stiffness and deformation resistance (CBR, resilient modulus M_R and permanent deformation PD). The effort exerted in this investigation mainly aims at enhancing the understanding of the relevant industries and practitioners for recognizing the causes that lead pavements to rut.

2. Literature Review

The term bound materials is used for materials with linear or about linear stress-strain relationship whereas the term unbound is used for those with stress-dependent trend or non-linear stress-strain behavior [2]. Transport Research Laboratory (TRL) associated the code GB3 with limited specifications for naturally occurring gravels or blends satisfying road- base requirements [3].

The base layer is the first pavement structural layer that confronts the repeated traffic load impacts and should be stiff enough to attenuate the stress level on the subgrade soil to a level which can withstand significant deformation and to provide adequate support for the surfacing as construction platform[4]. Frank et al. [5] reported that it is practical to produce base course with a dense grading by blending normal quarry product with crusher dust or sand. Dawson et al. [4] expressed that the necessity of using a minimally treated materials means that it is impossible to engineer it to meet all requirements equally well.Soil-cement mixturebase is not acceptable for use as stabilized base course for flexible pavements in airfields in particular [6].

Bennert et al. [7] and Omer et al. [8] reported that the aggregate gradation has great influence on the measured CBR values.They pointed out that as the gradation of unbound material moves from fine side (low end- New Jersey {Base limits}) to the coarse side (high end), the strength increases.

The resilient modulus (M_R) is the elastic modulus under dynamic loading.It can be numerically quantified as the ratio of the applied deviator stress $\sigma_d$to the recoverable vertical strain “resilient strain”(ϵ_r).

Resilient Modulus $(M_R) = \frac{\sigma_d}{\epsilon_r}$ (1)

The resilient modulus has been extensively researched worldwide for over 30 years.The measured laboratory MR under the optimum compaction condition could reflect the actual resilient behavior of granular material in flexible pavements[9]. Stolle et al. [10] demonstrated that M_R testing provides a mean of characterizing pavement construction materials, including subgrade under variety of conditions, i.e. moisture, density, stress levels;these conditions are important for higher strength unbound aggregates whereas liquid limit, plasticity index, and amount of fines are important parameters with respect to M_R of lower strength unbound aggregates. According to Lekarp et al. [11] stress has the most significant impact on resilient properties of granular materials; the M_R increases considerably with the increase of confining pressure and bulk stress. Italso increases with the increase of density but decreases with the increase of fines content. Stolle et al [10] noted that the resilient modulus increases as bulk stress increases while it decreases with shear stress. Lekarp et al. [11] pointed out that well graded material can achieve higher density, lead to higher stiffness and the resilient modulus increases as maximum particle size increases. According toTheyse et al.

[12] an increase in the level of confinement of unbound aggregate causes the material to respond in stiffer manner with associated higher value for resilient modulus of the material. Bahia et al. [13], Stolle et al. [10] Cheung et al. [14] reported that as aggregate angularity and surface roughness increased, the resilient modulus considerably improved, which was primarily due to the increase of shear strength with better aggregate interlocking and frictional properties and the increased confinement levels expressed by higher bulk stresses. Crushed stone was reported to yield slightly higher M_R values than that measured by rounded stones [10].

Numerous researchers developed different regression equations for predicting resilient modulus values. The recent and the most validated one is the generalized constitutive model developed under NCHRP 1-28 and was used within the context of the 2002 Mechanistic-Empirical Pavement Design Guide is:

$$M_R = k_1 p_a \left[\frac{\theta}{p_a}\right]^{k_2} \left[\frac{\tau_{oct}}{p_a} + 1\right]^{k_3} \quad (2)$$

Where,

M_R = resilient modulus

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$ (major & minor principal stresses)

τ_{oct} = octahedral shear stress

p_a = normalizing stress (atmospheric pressure) =14.67 psi (101.22 MPa)

k_1, k_2, k_3 = material dependent regression constants

Rutting is the main cause of damage in low to medium trafficked flexible pavements. Its cause can be attributed to accumulation of permanent deformations [5]. Magnusdottir et al. [15] noted that in the road pavement structure the largest part of the strain is caused by the elastic response with only a small part due to plastic behavior.The elastic response reflects the stiffness characteristics of the specimen and the plastic strain leads to permanent deformation. Arnold et al. [16] commented that 30% to 70% of the surface rutting is attributed to the unbound granular materials layers. Granular materials exhibit two types of deformation when subjected to repeated loading: resilient deformation which could lead to fatigue cracking of the overlay bound surface and permanent (plastic) deformation. According to Lekarp et al. [17] the stress level is one of the most important factors affecting the development of permanent deformation in granular materials. Cheung et al. [14] and Barksdale and Itani[18] studied the influence of aggregate shape and surface characteristics on aggregate rutting. It has been found that cube-shaped rounded river gravel with smooth surface is much susceptible to rutting than crushed aggregate. Lekarp et al. [17] summarized the findings investigated earlier by Barksdale (1972, 1991) and Thom and Brown (1988), and reported that permanent deformation resistance in granular material is reduced as the amount of fines increases. Dawson et al. [4] pointed out that the material grading is more significant to permanent deformation than the degree of compaction (density) with the highest plastic strain resistance reflected to the densest mix. Arnold et al. [16] pointed out that the available natural materials canbe assessed for their suitability for use in a pavement by considering performance criteria such as resistance to permanent deformation and degradation rather than relying on compliance with inflexible specification.

3. Materials and Testing

The materials used in this investigation were obtained from open quarries in Khartoum state and are colluvial deposits originally conglomerates belonging to Nubian Sandstone Formation [19]. The formationswere deposited by braided streams under semi-dry tropical climate.These natural gravels satisfysubbase requirements but seldom satisfy base ones.For this investigation, three natural unbound gravels were used from known quarries, namely Umm Ketti (C1), Al-Silait(M2) and Huttab(F3).They are currently used in the state pavement construction and represent the three levels of gradation, coarse (C1), medium (M2) and fine (F3),respectively. Fig.1 shows the three gradations plotted with the Transport Research Laboratory (TRL) standard envelope for GB3 base material. The coarse aggregates (gravels) are about rounded or elongated for F3 and M2 materials whereas they are rounded to angular for C1 material.

Representative samples were batched from each quarry in plastic bags and transported to the laboratory. Proper manual mixing was done and the samples were then bagged and stored in plastic barrels. Natural sand from the seasonal water sources locally known as Wadis was obtained for use as blending agent (Fig.1). Fresh crushed basaltic stone with three different sizes (19-12 mm, 12-5 mm, and 5-0 mm) was also provided from a crushing plant in south-wast Khartoumfor the blending process.

The objective of this research is to evaluate the different blending agents often used to upgrade unbound gravelly materials in Khartoum state for adoption as base materials using the resilient modulus (M_R) and permanent deformation(PD) tests as evaluation measures. The preceding literature review has shown that the stiffness and PD are good indicators for good performance of a pavement structure. The alternative chemical stabilization method was also assessed and evaluated for the same unbound materials.

To attain the above-mentioned objectives, three unbound materials which represent coarse, medium and fine gradations were first evaluated in their natural state “as materials that are not satisfying the base materials specifications”. Pure crushed stone mixture satisfying standard requirements (GB1,

Fig. 1) for base materials was prepared and adopted as reference material. The three unbound materials were then subjected to the following processes:

- Blendingwith Wadi sand (WS)
- Blending with graded crushed stone (CS)
- Chemical stabilization with Ordinary Portland cement (OPC)

The activities exerted in each of the mentioned processes involved:

- Mixing with the blending or stabilizing agent to attain the required mix standards. and
- Performing the required tests on the selected mix or the mix satisfying the required specifications. This will necessarily include gradation, CBR, M_R and PD tests.

The three unbound gravel samples were initially subjected to the following laboratory tests: sieve analysis, Atterberg Limits and Linear Shrinkage of the fines particles, Modified Proctor, California Bearing Ratio (CBR) and Los Angeles Abrasion. The results of the sieve analysis are given in Fig.1 whereas the results of the other tests are summarized in Table 1.

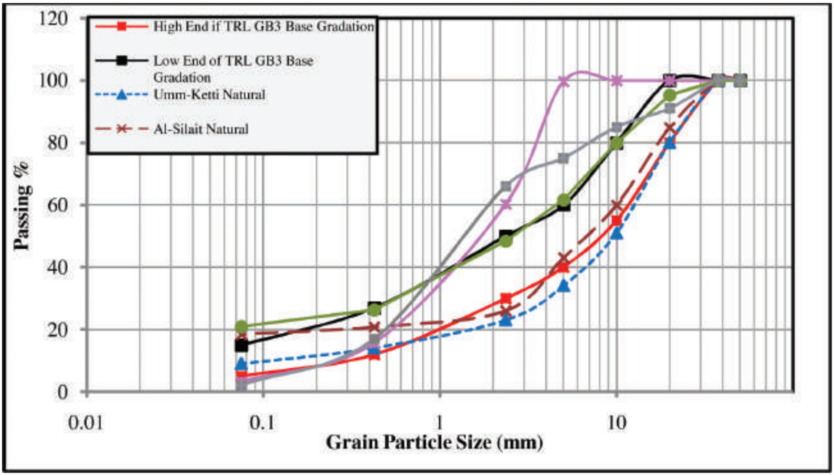

Fig.1 Grain Size Distribution for the Three Samples of Natural Unbound Gravels, WadiSand and Crushed stone Compared with TRL GB3

Table 1: Measured Engineering Properties for the Selected Natural Materials

Source	%OMC	MDD (kN/(m^3	%CBR	%LL	%PI	%LS	%FC	%LA
Umm-Ketti	6.4	22.07	68	27	11	12.5	9	32
Al-Silait	7.2	21.0	56	36	15	6.4	18.5	37.24
Huttab	5.88	21.68	32	36	19	7.9	21	29.16

*Note: LL is Liquid Limit, PI is Plasticity Index, LS is Linear Shrinkage, FC is Fines Content and LA Los Angeles.

The mechanical blendingof the three materials with Wadi sand was executed by adding 15%, 25%, and 35% of Wadi sand to the three unbound natural gravels aiming at studying the effects on their engineering properties.The blends with 25% of each sandy agent were found to closely satisfy TRL-GB3 base requirements in terms of gradation, fines content, plasticity and strength (Fig.2, and Table 2).

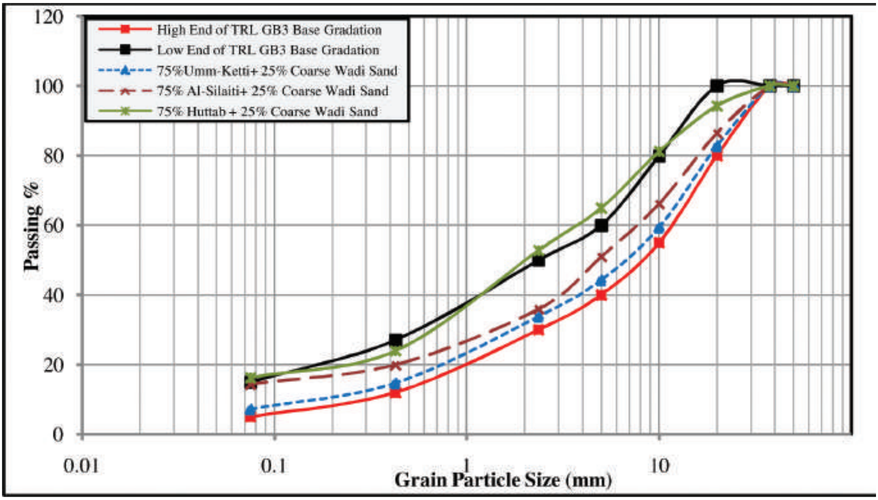

Fig. 2 Grain Size Distribution for the Three Natural Gravel Blended with 25% CoarseWadi Sand

Table 2: Measured Engineering Properties of the Selected Unbound Materials after Blending with WS

Source	85% Natural+15% Coarse Wadi Sand			75% Natural+25% Coarse Wadi Sand			65% Natural+35% Coarse Wadi Sand		
	%CBR	%PI	%FC	%CBR	%PI	%FC	%CBR	%PI	%FC
Umm-Ketti	126	10	10	79	7	7.25	189	7	6.7
Al-Silait	65	16	16	98	14	14.4	150	11	12.7
Huttab	100	17	18.2	74	15	16.3	60	10	14.25

The blend with graded crushed stone CS was attained by mixing the three natural gravels with different percentages fromthe three sizes of crushed basaltic stone through several trials. These trials led to blends that fitted well the TRL-GB3 gradation and satisfied to large degree the engineering properties of GB3 material (Fig. 3and Table3). The blending resulted in that C1 blend is a mix of 61% C1 and 39% CS (5-0 mm); M2 blend is formed from 50% M2, 7% CS(19-12 mm), 8% CS(12-5 mm) and 35% CS(5-0 mm) and F3blend is a mix of 65% F3, 20% CS(19-12 mm) and15% CS (12-5 mm). The attained gradations are given in Fig. 3.

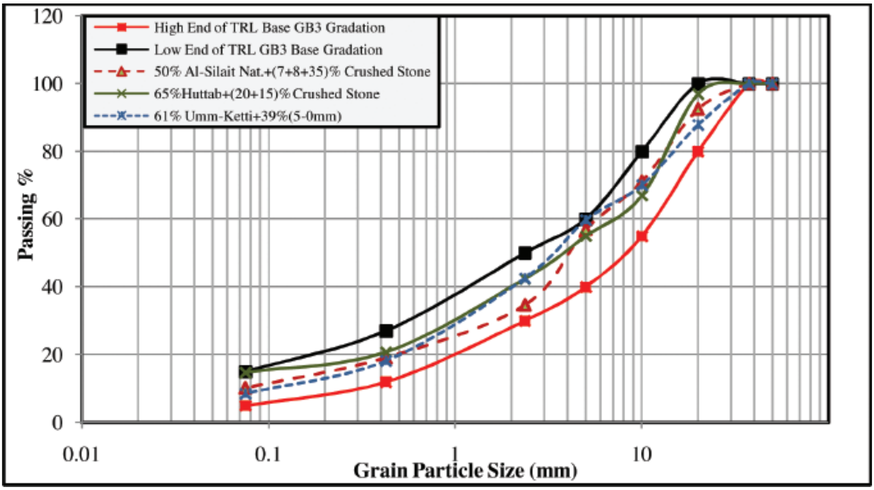

Fig. 3: Grain Size Distribution for the Three Natural Blends with Crushed Stone (TRL GB3)

Table 3: The Engineering Properties of the Unbound Materials Blended with CSand Reference CS Sample.

Source	%CBR	%PI	%FC	%LA
Umm-Ketti	> 100	9	7	32
Al-Silait	> 100	10	10.3	35.5
Huttab	> 100	13	14.1	20.0
Crushed Stone	>>100	0	5.17	7.66

*Note: PI is plasticity Index, FC is Fines Content and LALos Angeles

The reference pure crushed stone sample constitutes50.3 % CS(19-12 mm), 22.4% CS(12-5 mm) and 27.3% CS(5-0 mm) (Fig. 4). The engineering properties of the reference sample are given in Table 3.

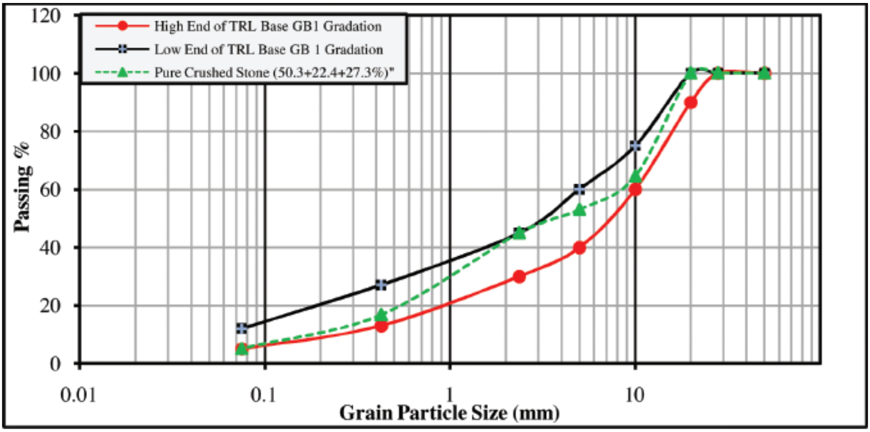

Fig. 4: Grain Size Distribution for Pure Crushed Basaltic Stone Blend that Satisfied GB1 Base

The original and blended materials were prepared at their optimum moisture contents (OMC), compacted in the resilient modulus mold to their corresponding maximum dry densities (MDD) using standard vibratory compactor; afterwards the resilient modulus (M_R) and permanent deformation (PD) tests were performed on each of the samples in accordance to AASHTO T-307 TP 46 – 99 and AASHTO- NON STANDARD TEST, respectively.

The M_R test results are given in terms of M_R versus test sequence.The test results are displayed in Figure 5 for the untreated samples and in Figure 6 for the samples blended with 25 % WS sand and in Figure 7 for the samples blended with CS. The Mr test result for the pure crushed reference sample is given also in Figure 7. The Mr values which are the values corresponding to the 6th sequence are given in Table 4.

The permanent deformation test results are given in Table 5for all the aforementioned blends. The accumulated deformations following the application of 10000 load repetitions at sample confinement stress of 21kN/m2 are summarized in Table 5.

Locally manufactured Ordinary Portland Cement (OPC) was used for chemical stabilization of the natural unbound materials. The percentage attempted were 2 , 4 , 6 and 8% by weight of the dry material. The stabilization was carried out on the three samples in question in accordance to B.S. 1924 [3]. The given cement contents resulted in very hard product (CBR >>100), therefore it was decided to use 1% cement content for the chemical stabilization of the three natural materials. The samples were then properly mixed with 1% by weight Ordinary Portland Cement, compacted in the Mr mould and then tested for M_R. The results from the M_R test are presented in Figure 8.

Table 4: The Resilient Modulus Values (MPa) for the Natural Materials, their Corresponding Blends and Reference Crushed Stone Sample

Material Source	Natural	75% Natural+25% Coarse Wadi Sand	Natural+ Crushed Stone (Blends (TRL/GB3 Base
Umm-Ketti	86	116	86
Al-Silait	80	86	90
Huttab	88	92	110
Pure Crushed Stone	250<	-	-
(Cement Stabilized C1 (1% cement	573	-	-

Table 5: Summary of Permanent deformation Test Results(mm) for the Natural Materials, their Blends and for the Reference Crushed Stone Sample

Material Source	Natural % 100	75% Natural+25% Coarse Wadi Sand	Natural+ Crushed Stone (Blends (TRL/GB3 Base
C1	0.09	0.12	0.01
M2	0.1	0.18	0.295
F3	0.141	0.12	0.13
Pure Crushed Stone	0.0037	---	----

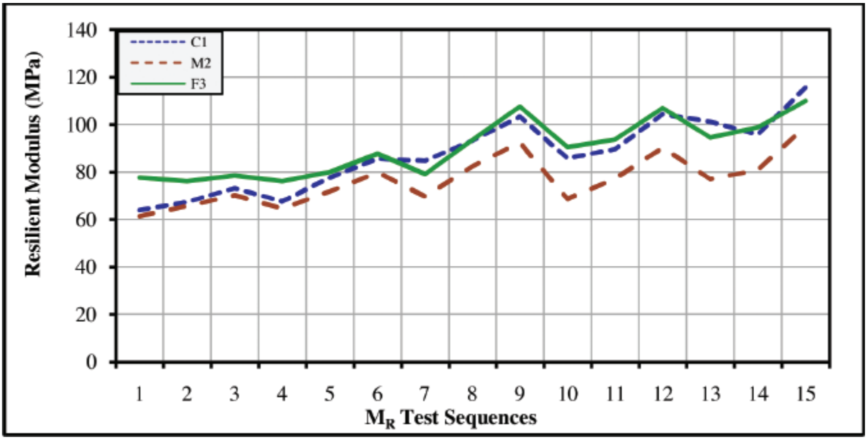

Fig. 5: Resilient Modulus Results for the three Natural Gravels versus Test Sequences

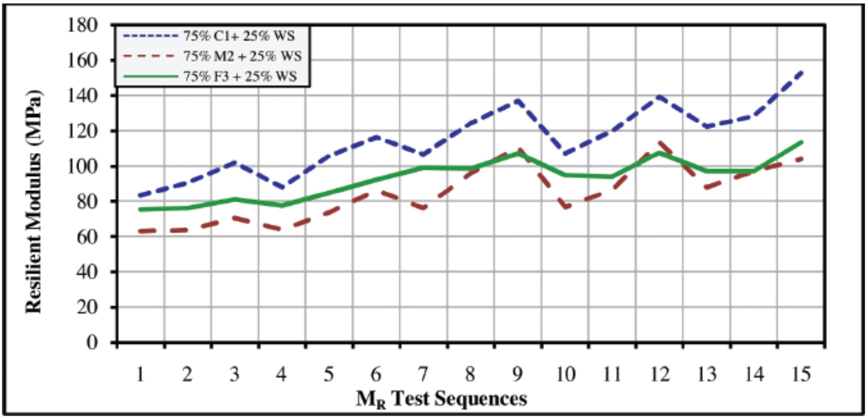

Fig. 6: M_R Results for the Three Natural Gravels Blended with 25 % WS (TRL GB3)

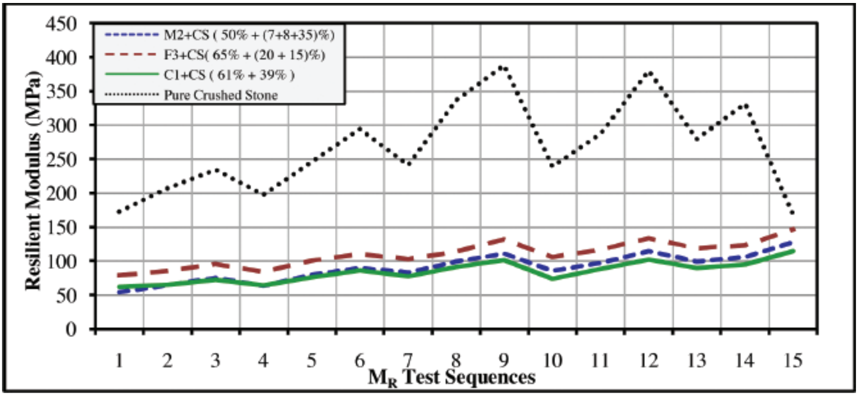

Fig. 7: MR Resultsfor the Three Natural Gravels Blended with CS (TRL GB3) and the Pure CS (TRL GB1)

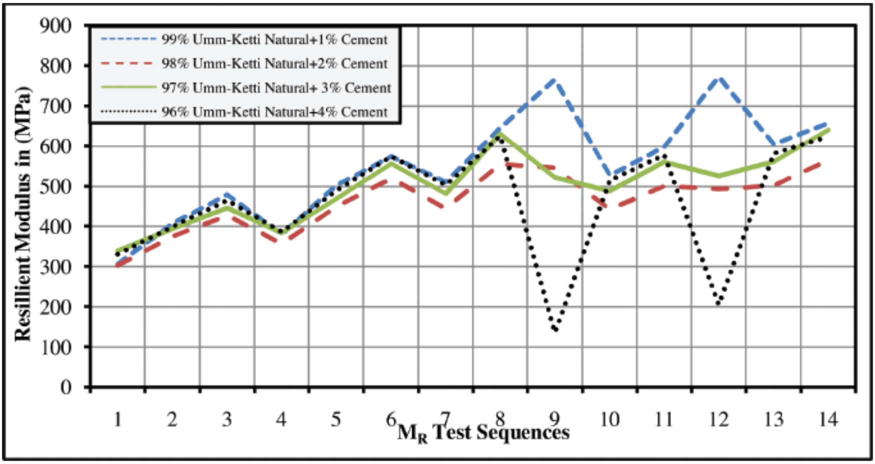

Fig.8: The Measured MR Values for the Four Umm-Ketti Cemented Samples

4. Analysis and Discussions

The exercise carried out in this study aimed at evaluating the improvement techniques carried out by contractors in an attempt to up-grade the engineering properties of natural unbound gravelly subbase materials for use as road base material in Khartoum state. The presented test data will be analysed to assess the improvement attained when Wadi sand, crushed stone and cement are utilized. Usually the blending exercise is performed to fit the gradation curve of the blended material inside the required grading envelope and to reduce its plasticity to acceptable limits (PI <= 6) and increase its strength (CBR) to reach or exceed 80. The targeted improvements should reflect in higher resilient modulus (M_R) and lower permanent deformation PD.

4.1 Compliance with GB3 Requirements

4.1.1 Natural Materials

Figure 1 plots the gradation curves for the three natural gravelly unbound materials compared to TRL GB3 base gradation bands. The gradation curve C1 lies within the coarse zone and plotted below the lower envelope of the GB3 gradation, M2 curve within the middle range whereas F3 curve coincides with the fine zone of TRL GB3 base gradation envelope; therefore the three natural materials represent the three gradation zones for (coarse, middle and fine). It can be observed that the three natural unbound materials do not satisfy GB3 base requirements in terms of gradation, plasticity and strength. Material C1 is gap graded with deficiency in sand size; the fines content for M2 and F3 exceed 12% whereas the plasticity index of C1 material exceeds 6. The CBR value is less than 80 for the three materials. However, C1 is the closest to satisfying the requirements. The Los Angeles Abrasion value is higher for M2 material (37%) compared to C1 (32%) and F3 (29%).

In this discussion, initial assessment will be made first for the effect of the improvement agents, i.e. Wadi sand, crushed stone and cement on the gradation, plasticity, abrasion and CBR of the three materials targeting compliance with GB3 base coarse specification. Afterwards the effect of the improvement agents on the resilient modulus M_R and permanent deformation PD of each material will be discussed.

4.1.2 Blending with Wadi Sand

Wadi sand is a natural material which is available in most of the regions of Sudan. It generally does not need processing and is mixed with the natural unbound materials to improve its gradation and reduce its plasticity. The natural Wadi sand reported 25% retained on 5.0 mm sieve, i.e gravel size particles. The sand is medium size to coarse. That means Wadi sand would contribute to enhance the gradation zones (fine and coarse) of the three natural gravels.

During the initial stages of this experimental study, trials were made to mix the three materials with amounts less than 10% but no significant improvement in gradation, plasticity and strength was realized. It was then decided to add 15%, 25% and 35% of Wadi sand to the three materials and it was found that the mixes with 25% Wadi sand are closer to satisfy GB3 requirements (Table 2). Blended Material C1 almost satisfied the gradation requirements (Figure 2). As for other requirements a slight increase in plasticity index (PI is 7 instead of 6) is noticed. Blended Material M2 satisfied the strength requirements but plasticity index is still high and the fines content slightly higher than required. Blended Material F3 has high plasticity and fines and the measured CBR is slightly lower than required. Therefore, the coarse Wadi sand could be used to improve the gradation of relatively coarse unbound materials in order to satisfy the GB3 requirements. It is not effective in reducing gradation and plasticity of unbound aggregates with high fines content.

The CBR value significantly improved when Wadi sand was added to the three materials. This is attributed to the resulted improvement in gradation and reduction in plasticity of the three materials. It is concluded that blending with Wadi sand will not always fully satisfy GB3 requirements. Significant improvement in strength can be attained. Effects on gradation could be positive when the initial gradation of the unbound material is towards the coarse range.

4.1.3 Blending with Crushed Stone

The crushed stones used in this blending exercise constituted three gradation sizes of crushed stone(coarse CS19-12 mm, medium CS12-5mm and fine CS< 5 mm). Material C1 was blended with 39% fine crushed stone which is within the gradation range of sands. Material M2 was blended with the three gradation sizes of CS but still the quantity of added fine crushed stone was higher (35%) whereas Material F3 was blended with the coarse and medium sizes only. The gradation curves for the three blended materials are generally within the gradation jacket of GB3 (Fig. 3). The fine content of F3 is above the specified limits of GB3 and the plasticity index of the three blended materials is still higher than the specified limits (Table3). The measured CBR of the blended materials was very high (more than two folds) for the three blended materials compared to those of the naturally occurring materials. This indicates significant improvement in strength for the blended materials. It is concluded that though significant improvement in strength has been measured for the blended materials, the three blended materials do not fully satisfy GB3 requirements for base course material. Surprisingly, the relatively high plasticity compared to the specified GB3 limit (PI<6) did not adversely affect the strength of the blended materials.

The CBR of the pure crushed stone mix was very high and exceeded 100%.

4.2 Chemical Stabilization

This part of the investigation was performed basically to study the effect of chemical stabilization process on strength for the three natural gravels in question. Referred to TRL Road Note 31; there are three types of chemical stabilisers, cement, lime, lime-pozzolan. From the fines content and plasticity indices (Table 1), only cement is deemed suitable for the stabilization of the three materials. The stabilization process with cement was carried out in accordance to B.S. 1924 [2]. The added cement quantity started with 1 ,2 , 4 and 6%. It was observed that with a minimum percentage of cement (1% only) the measured CBR was very high (>100%) for the three samples. Therefore, very small quantities of OPC if mixed properly with the quarry materials will remarkably improve their strength. Hence, cement proved to be very efficient in increasing the strengthof the unbound aggregates of Khartoum state.

4.3 Effect of the Improvement Agents on Resilient Modulus and Permanent Deformation

4.3.1 Effects on Resilient Modulus

The resilient modulus M_R results were plotted versus bulk stress (Θ) for each material blended with Wadi sand and crushed stone. Figure 9 displays the test results for C1 material, Figure 10 for M2 material and Figure 11 for F3 material. The figures show the increase of M_R with bulk stress (Θ) which is the summation of major and minor principal stresses (equation 2).

The natural Materials C1and M2 are gap graded and lack sand size particles. The addition of Wadi sand and sand size crushed stone improved the gradationof C1 (Figure 2 and Figure 3). The uniformity coefficient is higher for C1 Wadi sand blend compared to C1 crushed stone (CS< 5mm) blend. The resilient modulus of the untreated C1 material is 85.5 MPa and increased to 116.3 MPa on addition of Wadi sand but did not show any remarkable increase (85.8MPa) on addition of CS.The sand blend plotted above the natural material and the CR blend showing remarkably higher stiffness (Figure 9).

The M_R test results for M2 material in terms of bulk stress are shown in Figure 10. The crushed rock blend plotted above the Wadi sand blend and M2 blend especially for bulk stress values exceeding 30kPa. The resilient modulus is higher for the crushed stone blend (90.1 kPa) and is 86.2 kPa for the Wadi sand blend and about 80 kPa for the M2 material.

The fine unbound material F3 measured high resilient modulus compared to C1 and M2 materials (Figures 9, 10 and 11). This is contrary to the CBR test results which showed low CBR for this material compared to the other two materials. This might be due to the noticeable difference in their gradation, plasticity and in the test conditions. Materials C1 and M2 are gap graded and could be affected by dynamic loading whereas the natural material F3 has uniform gradation for the sand and gravel sizes and could give better interlocking compared to C1 and M2. The CBR test is carried under wetted conditions and is therefore sensitive to plasticity of the fine fraction. F3 and M2 materials measured higher plasticity compared to C1; this could affect their CBR values. The blended F3 materials measured higher M_R values compared to the untreated F3. The crushed stone blend plotted well above the Wadi sand blend which plotted above the natural F3 material. This could be attributed to the improvement in the coarse fraction of F3 blended with crushed stone.

The blending exercise have shown that blending with crushed stone gives better results in terms of increase in stiffness compared to Wadi sand when coarse gravel size material is added. This is noticed in the results of the blended F3 and M2 materials. It is enhanced by the improvement of gradation and interlocking caused by the shape of the coarse crushed stone particles. The crushed stone mix measured M_R values exceeding 250 kPa (Figure 7) indicating very stiff mix of superior quality when compared to the naturally occurring unbound materials (Table4) and their corresponding blended products. On the other hand, the cement stabilization resulted in a very rigid material with M_R values 572 kPa for the 1% cement mixture which almost twice of the measured value for the pure crushed stone sample.

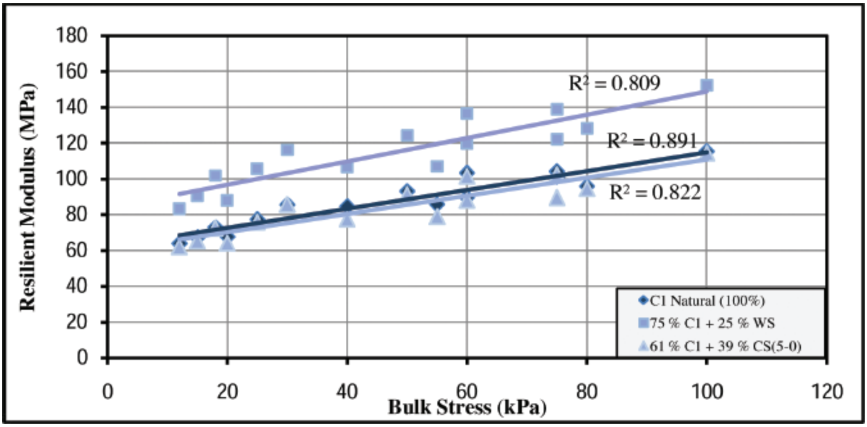

Fig. 9: M_R Results for C1 Natural Gravel & its Two blends (satisfied GB3 Base)

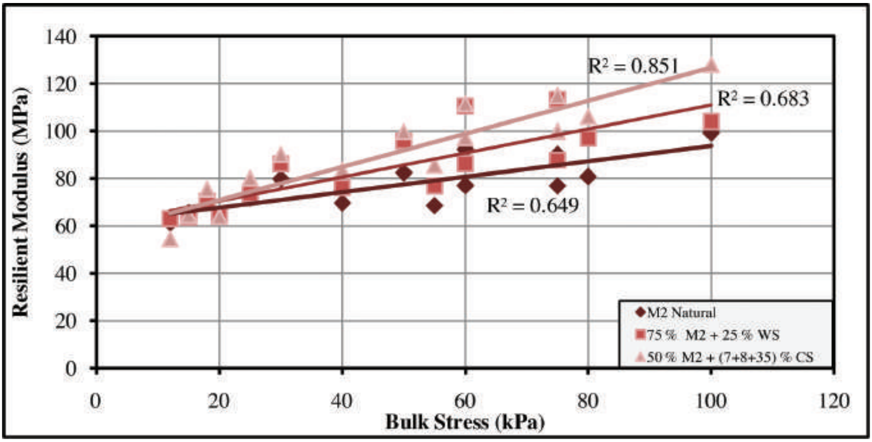

Fig. 10: MR Results for M2 Natural Gravel & its Two blends (satisfied GB3 Base)

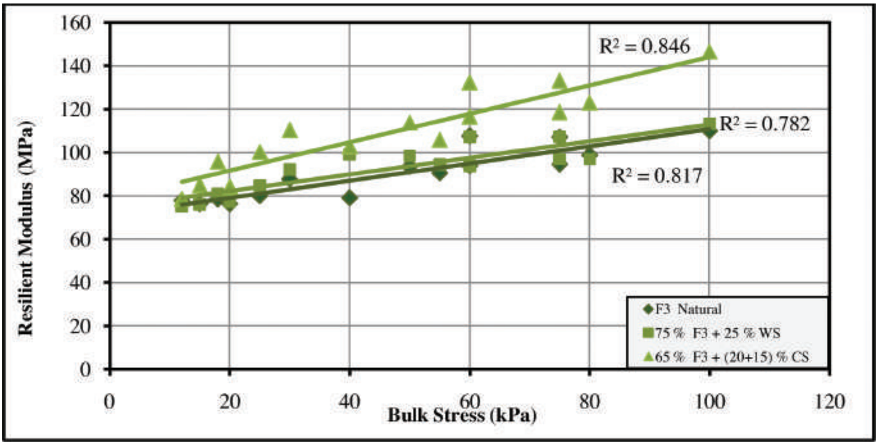

Fig. 11: MR Results for F3 Gravel & its Two blends (nearly or satisfied GB3 Base)

4.3.2 Effects on Permanent Deformation

Permanent deformationtest is well known as a governing test that predicts the rutting level of pavements under repeated traffic loading. The three natural gravels, their blends and the pure crushed stone sample were subjected to

this test according to AASHTO99 -307/Non Standard Test. The permanent deformation results were summarized in Table 5.The accumulated plastic deformation in millimetres measured after 10000 load applications and 21 kPa confinement are presented in Table 5 for C1, M2, F3 and their corresponding blends and the crushed stone samples. Material F3 measured the highest PD compared to M2 and C1 which measured about the same value. The M2 blends measured the highest permanent deformation whereas C1 blends measured the lowest deformations. Rutting and PD are found to be sensitive to fines content [17 - 22]. Here, M2 and F3 blends contain high amounts of sand size particles (passing 4.75 mm sieve); this could justify the relatively high "measured" PD values.
The crushed stone sample measured the lowest PD values and demonstrated the highest resistance to plastic deformations. The tests have shown that adding crushed stone to natural unbound materials will not necessarily improve their resistance to permanent deformation, especially if the materials contain substantial quantities of sand size materials. Well graded crushed stone material satisfying GB1 requirement offer high resistance to rutting and would not compare with natural materials blended with crush stone. The addition of small quantity of cement (1%) changed the unbound material to hard material with very high resilient modulus.

This investigation has also shown that blending with sand and crushed stone could result in high increase in strength as demonstrated by CBR values, but would not necessarily result in comparable increase in rigidity or in resistance to permanent deformation.

5. Conclusions

* Initial assessment of blending the three materials with Wadi sand has shown that the sand was effective in improving the gradation of the coarser C1 material. The strength (CBR) of the three materials, blended with Wadi sand, significantly improved to satisfy or nearly satisfy the GB3 requirement. Blending with crushed stone improved the gradation and caused large increase in strength (CBR) of the three materials. Cement stabilization of the three materials using 1% cement by weight rendered them to become hard material with CBR exceeding 100%.
* The resilient modulus tests on the natural samples showed high M_R values for F3 material compared to C1 and M2 materials. This is contrary to the CBR test results. This indicates poor correlation between CBR and M_R. This might be due to the noticeable difference in their gradation, plasticity and in the test conditions.

* The test results of the three materials blended with Wadi sand and crushed stone have shown that blending with crushed stone gave better results in terms of increase in stiffness compared to Wadi sand when coarse gravel size material is added. This is noticed in the results of the blended F3 and M2 materials. It is enhanced by the improvement of gradation and interlocking caused by the shape of the coarse crushed stone particles. The crushed stone mix measured high M_R values indicating very stiff mix of superior quality when compared to the naturally occurring unbound materials and their corresponding blended products. On the other hand, the cement stabilization resulted in a very rigid material with M_R values almost twice the value measured for the pure crushed stone sample.

* The permanent deformation (PD) results have shown that F3 measured the highest permanent deformation compared to M2 and C1 which measured the lowest. However, M2 measured high permanent deformation when blended with sand and/or crushed stone. The PD values for the blended material could be linked here to the sand content in the sample rather than the fine content of the natural material. The higher the sand size content the higher is PD. The graded pure crushed stone sample showed very high resistance to permanent deformation when compared to the natural or blended materials. This investigation has also shown that blending with sand and crushed stone could result in high increase in strength as demonstrated by CBR values, but would not necessarily result in comparable increase in rigidity or in resistance to permanent deformation. More detailed evaluation and study is needed to better understand the factors contributing to the PD of natural unbound materials.

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