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Particle crushing during compaction of laterite and lateritic soils

Concassage de particules lors du compactage des sols latéritiques et latéritiques

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ABSTRACT: The engineering properties of laterites and lateritic soils can be greatly improved by compaction and generally the higher the level of compactive effort the better the level of compaction achieved. There is therefore a tendency towards selecting bigger capacity compaction plant for road construction. Lateritic soils abound in the tropics and are used extensively in the construction of various pavement layers. The mode of formation of laterites and lateritic soils creates a structure that is vulnerable to particle crushing under high compactive stresses. The study seeks to investigate the level of particle crushing that occurs in the field and how these levels are related to the compactive efforts used in standard laboratory compaction. Compaction of the subbase on three on-going road construction projects in different climatic zones of the country was undertaken. The levels of compaction achieved in the field, and the grading before and after field compaction were determined. Samples of the lateritic subbase material were sent to the laboratory and subjected to compactive efforts ranging from 10 blows of a 4.54kg rammer to 55 blows in the CBR mould. The grading as well as the levels of compaction and the CBR strength under soaked conditions were measured after each round of compaction. The effects of the different compaction energy levels on particle crushing are analysed in terms of the grading and the subsequent levels of compaction.

RÉSUMÉ : Les propriétés d'ingénierie des latérites et des sols latéritiques peuvent être grandement améliorées par le compactage et généralement plus le niveau d'effort de compactage est élevé, meilleur est le niveau de compactage atteint. Il y a donc une tendance à choisir des installations de compactage de plus grande capacité pour la construction de routes. Les sols latéritiques abondent sous les tropiques et sont largement utilisés dans la construction de diverses couches de chaussées. Le mode de formation des latérites et des sols latéritiques crée une structure vulnérable à l'écrasement des particules sous des contraintes de compactage élevées. L'étude vise à étudier le niveau de broyage des particules qui se produit sur le terrain et comment ces niveaux sont liés aux efforts de compactage utilisés dans le compactage standard en laboratoire. Le compactage de la sous-base sur trois projets de construction de routes en cours dans différentes zones climatiques du pays a été entrepris. Les niveaux de compactage atteints sur le terrain et le nivellement avant et après le compactage sur le terrain ont été déterminés. Des échantillons du matériau de fondation latéritique ont été envoyés au laboratoire et soumis à des efforts de compactage allant de 10 coups de pilonneuse de 4,54 kg à 55 coups dans le moule CBR. La granulométrie ainsi que les niveaux de compactage et la résistance du CBR en conditions trempées ont été mesurés après chaque cycle de compactage. Les effets des différents niveaux d'énergie de compactage sur le broyage des particules sont analysés en termes de granulométrie et des niveaux de compactage ultérieurs

KEYWORDS: laterite and lateritic soil, compaction, compaction energy level, grading, particle crushing

1 INTRODUCTION

In tropical climatic zones, laterites and lateritic soils characterized by high concentrations of the oxides of iron and aluminium, provide a ready source of road construction material. The oxides of iron and aluminium in these soils assist in binding primary particles together to produce secondary particles of varying sizes and strengths. The coarse fraction of most lateritic soils therefore consists of both quartz and concretionary gravels. Even though they are generally deemed not durable enough to be used as an upper pavement layer in high traffic pavements, they have been extensively used successfully in the lower layers of pavements carrying normal traffic levels and for the construction of pavements for low volume roads (Nanda and Krishnamachari 1958 and Arulandann 1969, Lyon and BRRI 1972).

The engineering properties of most soils are improved by compaction and because higher compactive effort generally gives higher levels of compaction, there is a tendency in many developing countries towards selecting higher capacity plant for compaction on road construction projects. Under these high compaction forces there is a tendency towards particle crushing. Particle crushing in aggregates have been shown to affect the engineering properties including the resilient modulus which can lead to stress concentrations and bring about failure (Esfahani and Goli 2017). Several factors including the particle size distribution, the particle shape, particle hardness, the state of stresses, the effective stress path as well as the water content and the void ratio affect particle crushing under stress (Hardin, 1985). Despite the substantial differences between laboratory and field compaction processes, the standard laboratory compaction (ASTM D1557-91) is used not only for quality control but also for the planning of field compaction.

In 2002 a study of compaction of laterite and lateritic gravel on several on-going road projects in different parts of the country was undertaken to provide a better understanding of the behaviour of laterite and lateritic sub-base and base material during compaction. This paper reports on part of the results from that study and focuses on comparing the particle crushing that occurred in the field with that occurring in the laboratory. Field compaction using heavy compaction plant on three road construction sites in different climatic zones of the county are reported in terms of the levels of compaction achieved and the particle size distribution before and after field compaction. The laboratory component of the study subjected samples to laboratory compaction under different compactive efforts and to the soaked CBR test. The levels of compaction as well as the soaked CBR achieved and the corresponding particle crushing defined as change in grading before and after compaction that occurred under field and under laboratory compaction are computed and discussed.

2 MATERIALS AND METHOD

2.1 *Study Sites*

Three road construction sites designated T-K, JZ-Y and A-N located in the low, medium and high rainfall zones of the country with mean annual rainfall of 1100mm, 1250mm and 1430mm respectively were selected for the study. Figure 1 shows the location of the study sites superimposed on the rainfall map of Ghana.

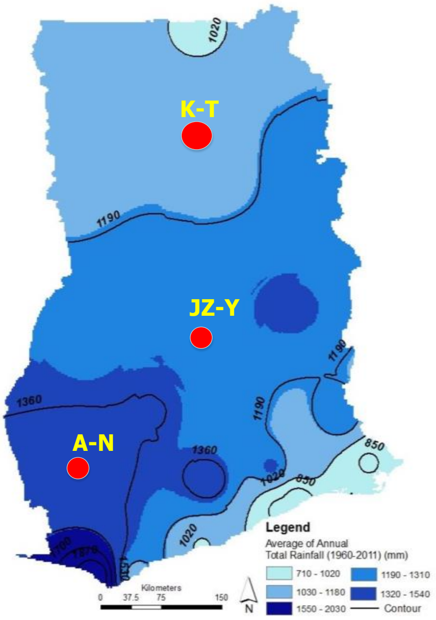

Figure 1. Location of Study Sites

2.2 *Field Studies*

2.2.1 *Study Sections*

For the field studies for each project site a 100m length study section stretching from the road centerline to the edge of the drain was demarcated on one half of the road section. For each site at the time of the study, the sub-base layer was being constructed on the prepared subgrade following the Contractors field procedures. The measurements, however were done according to standard procedures.

2.2.1 *Field Compaction*

On each construction site, the lateritic gravel material from the borrow pit was dumped from trucks in heaps along the road. Before spreading, some of the soil samples was scooped into sample sacks using shovels and designated "raw field samples". A motor grader was used to spread the natural soil material to form a loose bed 180mm thick on T-K and JZ-Y and 200mm thick on A-N. Then a water bowser was used to sprinkle water on the constructed loose layer bed. A period of about three hours was allowed to elapse in order to allow the water to penetrate the soil and for the surface to dry out sufficiently. The compaction equipment was then used to roll the loose layer bed the designated number of passes. Table 1 lists the compaction plant used at the various sites. The service weights which is the ballasted weights on site range from 11.4 to 17.2 tons. For site A-N(SB) a pneumatic tyre roller (PTR) was used to apply 30 passes of static rolling before being subjected to the 30 passes of the vibratory roller. After compaction, the levels of compaction achieved were measured by the in-situ density tests conducted using the sand replacement method (BS1377-90 or ASTM D 1556) and the Speedy Moisture Tester (ASTM D 4944-89). Then a 1.0m x1.0m area was demarcated near the in-situ density test location and the compacted material was excavated using a pickaxe and placed in a container and designated "field compacted sample"

Table 1. Field Compaction Plant and output

Site Code	*Compaction Plant*	*No of Passes*	*Service Weight (kg)*	*Field Effort (tons/mm)*
T-K	IR-SD100	40	17,200	3.82
JZ-Y	Ham Roller,	35	11,400	2.22
A-N	CAT-CS583C	30	15,250	4.46
	PTR	30	14,515	

IR: Ingersoll Rand, PTR Pneumatic Tyre Roller

2.3 *Laboratory Studies*

2.3.1 *Sample Preparation*

Both the "field raw samples" and the "field compacted samples" were taken to the laboratory for further analysis. In the laboratory, the samples were emptied into sample trays and air dried. The lumps in the compacted samples were broken with a rubber mallet and stored for subsequent testing. The bulk airdried "field raw samples" were then mixed together using a shovel and sampled into smaller quantities using a riffle box and stored for the individual laboratory tests.

2.3.2 *Sample Characterization*

For the Atterberg limit tests, part of the air-dried bulk samples of the "field raw samples" was sieved through the 0.425mm sieve to obtain the test samples. The Cassagrande Apparatus was used for the liquid limit tests, while the grading analysis used wet sieving and the hydrometer method in accordance with BS1377: Part 1 and Part 2:1990. The grading analysis was also performed on the 'field compacted' samples to obtain the particle size distribution after field compaction.

2.3.3 *Studies on Compacted Samples*

For the compaction studies, the airdried "field raw samples" were sieved through the 20mm sieve and the material retained was replaced. The compaction characteristics for each sample using the Modified Proctor compaction standard with sample re-use was performed in accordance with BS 1377 Part 4 (ASTM D1557-91).

For each source material, six-8kg bulk samples were prepared two for each test using 10 blows, 25 blows and 55 blows of the 4.54kg rammer. For each bulk sample, the amount of water equivalent to the optimum water content (w_{opt}) was added, thoroughly mixed and stored in a polythene bag to prevent moisture loss and left to equilibriate. After that the sample was compacted in the CBR mould in five layers using 10 blows of the 4.54kg rammer per layer. After determining the water content from the trimmings, the sample was weighed and subjected to the unsoaked CBR test. After the CBR test, the sample was extruded from the mould, lumps broken down with a rubber mallet and subjected to grading analysis test to obtain the particle size distribution after laboratory compaction. Duplicate samples were subjected to the 4-day soaked CBR test. The procedure was repeated for samples prepared using 25 blows and 55 blows respectively.

3 DISCUSSION OF RESULTS

3.1 *Characteristics of Soils Studied*

The index properties of the raw field samples are summarized in Table 1, while Figure 2 shows the grading curves of the samples taken from the field before and after field compaction. The figu re shows among other things that before compaction A-N(SB) fell outside the grading bands specified in the standar d specification of a G60 subbase natural gravel material (MoT 2007). Both the liquid limits (LL) and the Plasticity Index (PI) of A-N(SB) also fell outside the specified limit s of 35 and 15 respectively. The high values illustrate the difficulty of obtaining natural gravel material that meets th e standard specifications in high rainfall tropical zones. It has been suggested that these specifications may be inappr opriate especially for low volume roads and Pinard et al. (2020) have proposed an alternative approach for material e valuation for low volume roads.

Table 2. Index Properties of raw field samples

Site and Material Code	*GRADING (%)*				*LL*	*PI*
	Gravel	*Sand*	*Silt*	*Clay*		
T-K (SB)	79	14	4	4	35	12
JZ-Y (SB)	70	14	10	7	31	15
A-N (SB)	85	8	4	3	40	19

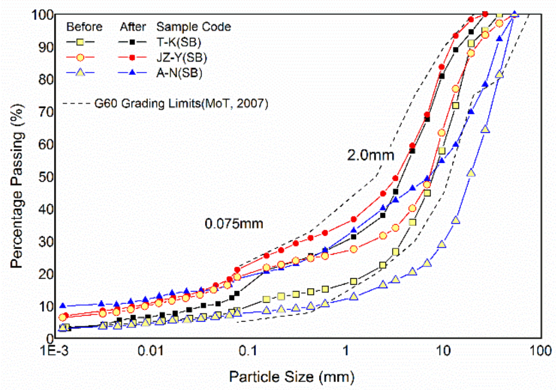

Figure 2. Grading curves before and after field compaction

3.3 *Effect of Compactive Effort on Level of Compaction*

The laboratory compaction curves for the three soils are shown in Figure 3. The compaction states that were achieved in the field are also superimposed. Table 3 summarizes the results of the laboratory and field compaction including the optimum water contents (w_{opt}) and the maximum dry density (MDD, $(r_d)_{max}$) after the Modified Proctor tests. It also shows the levels of compaction (LC= $(r_d/(r_d)_{max})$ achieved after field compaction as well as the water content ratio (w/w_{opt}) under which the field compaction was effected. The water content ratio quantifies the deviation of the water content from the optimum. It can be seen that the field compaction water content ratio for T-K and JZ-Y were just below 0.9 indicating compaction on the dry side of w_{opt}, but for A-N(SB) the ratio was 1.26 which shows compaction on the wet side of w_{opt}. Tatsuoka et al (2015) have discussed the challenges involved in using laboratory determined optimum water content to predict field dry densities under high field compaction efforts. Nonetheless, the high water content on A-N(SB) illustrates the difficulty of field water content control in the very wet environments.

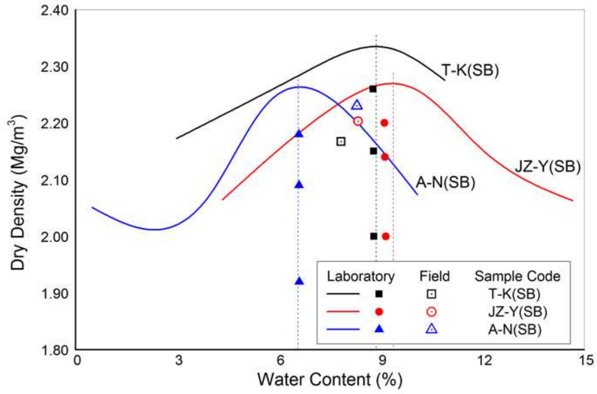

Figure 3. Dry density-water content relationship and compacted states of soil samples investigated

Table 3. Compaction Output

Site and Material Code	*Laboratory Compaction*		*Field Compaction*	
	w_{opt} (%)	*MDD (Mg/m^3)*	*w/w_{opt}*	*LC*
T-K (SB)	8.87	2.334	0.88	0.930
JZ-Y (SB)	9.37	2.270	0.89	0.987
A-N (SB)	6.61	2.264	1.26	0.988

The results of the laboratory investigations are summarized in Table 4. The laboratory compactive effort is defined as the total energy input during compaction per unit volume of s oil also referred to as the specific energy. The Compaction Energy Level (CEL) for any number of blows is thus the ratio of the specific energy to the specific energy for the Standard Proctor (594kNm/m^3, CEL=1.00). The three CEL values investigated are therefore 0.85, 2.13 and 4.69 corres ponding to 10, 25 and 55 blows. The evolution of LC with increasing CEL during laboratory compaction is shown in Figure 4. The general trend is that LC increases quickly as CEL increases from 0.85 but beyond a CEL of about 3.5, there is insignificant change in LC with increasing CEL. For a subbase, the specified minimum LC is 0.95 (MoT, 2007). The LC achieved in the field are also plotted against the equivalent CEL that would give the same LC in the laboratory in Figure 4. It can be seen that the field compaction effect is equivalent to CEL values of 2.37 for T-K(SB), but for A-N(SB) and JZ-Y(SB) they are in excess of 4.69. It must be noted that the field compaction efforts are also not equal on all sites. On A-N(SB) there were 30 passes of a 14.5-ton static roller in addition to the 30 passes of the 15.3-ton vibratory roller. In fact, if the total field compaction effort is divided by the thickness, then the field unit compaction effort in tons/mm are 3.8, 2.2 and 4.4 respectively for T-K(SB), JZ-Y(SB) and A-N(SB). The plot also suggests that in order to attain the specified minimum LC=0.95, minimum CEL values of between 2.37 for JZ-Y(SB) and 3.18 for the remaining samples are required. This suggests that whereas the field compactive effort is inadequate for T-K(SB), it may be excessive for JZ-Y(SB) and A-N(SB) for purposes of achieving the minimum required LC=0.95.

Table 4. Summary of Laboratory Test Results

Parameter	CEL	Site and Material		
		T-K-SB	JZ-Y-SB	AN-SB
Dry Density (Mg/m^3)	0.85	2.00	2.00	1.92
	2.13	2.15	2.14	2.09
	4.69	2.26	2.20	2.18
Level of Compaction	0.85	0.857	0.881	0.848
	2.13	0.921	0.943	0.923
	4.69	0.968	0.969	0.963
Water Content (%)	0.85	8.80	9.15	6.60
	2.13	8.79	9.12	6.59
	4.69	8.78	9.11	6.58
Water Content Ratio	0.85	0.992	0.977	0.998
	2.13	0.991	0.974	0.997
	4.69	0.989	0.973	0.995
Soaked CBR	0.85	36	38	5
	2.13	121	64	40
	4.69	160	77	88
Unsoaked CBR	0.85	62	55	48
	2.13	113	102	109
	4.69	142	82	129
Breakage (B_g)	0.85	0.055	0.120	0.061
	2.13	0.155	0.164	0.150
	4.69	0.194	0.213	0.245
Fines (P_{075})	0.00	14.60	15.06	12.98
	0.85	18.42	16.78	15.31
	2.13	20.93	18.12	20.50
	4.69	21.27	19.13	24.73
Gravel (P_2)	0.00	69.12	68.81	71.24
	0.85	65.51	65.30	70.70
	2.13	59.03	61.41	56.80
	4.69	54.00	58.96	47.87

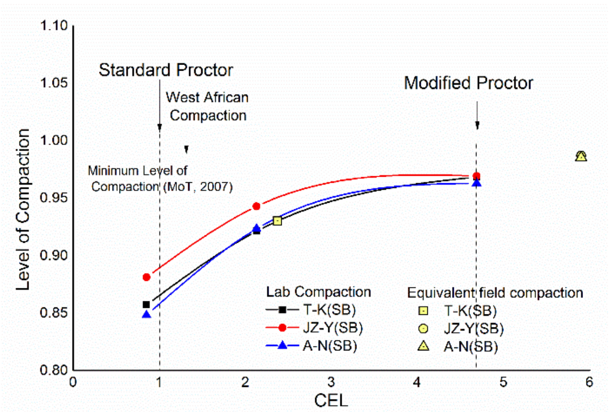

Figure 4. Variation of Level of Compaction with CEL.

It may be noted that using fresh samples and adding the equivalent amount of water to attain w_{opt} in one step gives only about 0.967 of the MDD achieved when the water is added incrementally with sample reuse. This observation is consistent with previous results (Hammond 1970, Ampadu et al 2015) for lateritic soils and suggests that re-compaction gives higher dry densities than using fresh samples, but Gidigasu (1976) has cautioned that this may not be a general trend and will depend on whether the particle crushing leads to improved grading.

3.3 *Effect of Compaction on Particle Crushing*

The amount of particle crushing occurring during compaction of a soil sample is defined by the particle size distribution before and after compaction as shown in Figure 2. However, the challenge has always been how to adequately include the crushing which occurs in the various soil fractions into the measurement. A number of different approaches have been used in different studies. Lee and Farhoomand (1967) in their study of the plugging of dam filters used the ratio of the particle size corresponding to 15% passing (D_{15}) before and after testing to define particle crushing. Sanders (1980) during laboratory and field compaction of natural gravel base and sub-base layers of a highway, used the ratio of D_{50} to define particle crushing while Patakiewicz and Adamska, (2017) used D_{10} and D_{60} as defined in the Uniformity Coefficient before and after compaction. Gidigasu and Dodgbey (1980) used the percentage retained on 2mm as a measure of particle crushing during laboratory compaction of lateritic gravel and quartzitic gravel. These approaches define crushing by only one or two points on the grading curve. However, there are approaches which integrate all sieve sizes to define crushing, but they are not commonly used, mostly because of the complexity involved in their usage. These include the approach by Hardin (1985) where he introduced the relative breakage index as the ratio of the total breakage to the breakage potential and needed to determine the area between and under the grading curves in order to evaluate the crushing. Marsal (1967) presented a simplified approach in which the particle breakage index (B_g) is defined as the sum of the positive of the change in percentage retained on the same sieve size before and after the test. B_g varies from 0 for no breakage to 1 for all particles broken to size below the smallest sieve size used.

In this study, crushing is defined in terms of the Marsal breakage index. However, because the mechanisms of particle crushing for larger particles are different for those for smallerparticles, the crushing is also examined in terms of the change in gravel content (i.e. percentage retained on 2mm) and in fines content (percentage passing 0.075mm). The crushing is examined in terms of the changes in gravel and fines contents rather than the absolute values because as a result of the need to sieve samples through 20mm before conducting laboratory compaction, the initial grading curves for laboratory and for field samples are not the same. The dependence of LC on particle crushing as defined by the change in fines and gravel contents is illustrated in Figure 5 wherethe change in percentage of gravel and of fines are plotted against the level of compaction achieved for both laboratory compaction and for field compaction.

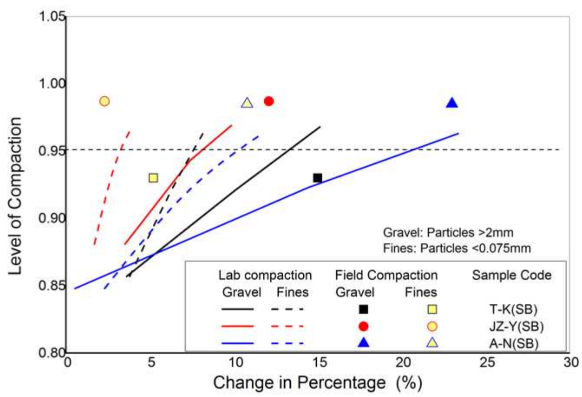

Figure 5. Variation of particle crushing with LC for laboratory compaction and the equivalent field compaction

It can be seen that for levels of compaction exceeding about 0.86, the laboratory compaction gravel crushing curves lie to the right of the equivalent laboratory compaction fines crushing curves and also that the field compaction gravel crushing points alsolie to the right of the equivalent field fines crushing points. This indicates that both laboratory and field compaction lead to higher particle crushing for the gravel fraction than for the fines fraction. It can also be seen that for the same level of compaction, the field compaction fines crushing points are all on the left of the laboratory fines compaction crushing curves, indicating that for the same level of compaction, field compaction leads to less generation of fines than the equivalent laboratory compaction. However, the trends in the changes in the gravel fraction for field and for laboratory compaction is not clear.

The variation of LC with Marsal Breakage Index is plotted in Figure 6 to examine the crushing over a large range of sieve sizes. The trend in the laboratory test results is that there is an initial low B_g of up to about 0.10 associated with low LC of the order of 0.85. Between B_g values of about 0.10 to 0.20 the LC increases dramatically to about 0.95. Beyond a B_g value of about 0.20, there is little further increase in LC. The field compaction is associated with high B_g values of between 0.217 and 0.261. The results suggest that for the same level of compaction, field compaction leads to similar (JZ-Y(SB) and A-N(SB)) or higher (T-K(SB)) levels of particle crushing as defined by B_g. This observation seems to fit the compaction mechanism suggested by Guyon and DuTroadec (1994) that the larger particles break down first (by fracture because of presence of natural cracks) into smaller particles which improves the grading leading to a rapid increase in LC. With increased LC arising from better packing of soil grains further crushing (by attrition and abrasion arising from the rolling and slippage) leads to only very small increases in LC.

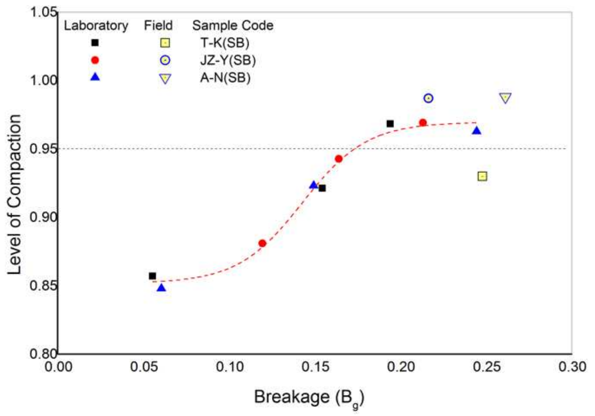

Figure 6. Variation of Marsal Breakage Index with LC for laboratory compaction and for the equivalent field compaction

3.4 *Effect of Compaction on CBR*

The variation of the soaked CBR strength of the compacted sample with LC is shown in Figure 7. The figure underscores the importance of ensuring high levels of compaction in order to improve the soaked CBR strength of subbase. In fact for JZ-Y(SB) and A-N(SB) compaction levels higher than 0.94 are required to achieve the minimum soaked CBR of 60 for G60 natural gravel sub-base. This suggests that achieving high levels of compaction may be an important consideration in utilizing material with relatively high PI values outside the recommended thresholds.

Figure 8 shows the variation of the soaked CBR with the breakage index Bg. It can be seen that there is a general trend of increasing soaked CBR with increasing B_g. However, it may be noted that for T-K(SB) with relatively low PI of 12 in the low rainfall zone, the minimum specified CBR of 60 is achieved at a relatively low level of Marsal particle crushing index value of about 0.10 but for JZ-Y(SB) and A-N(SB) with high PI values of 15 and 19 the minimum soaked CBR is attained at a relatively high level of particle crushing index value of 0.24.

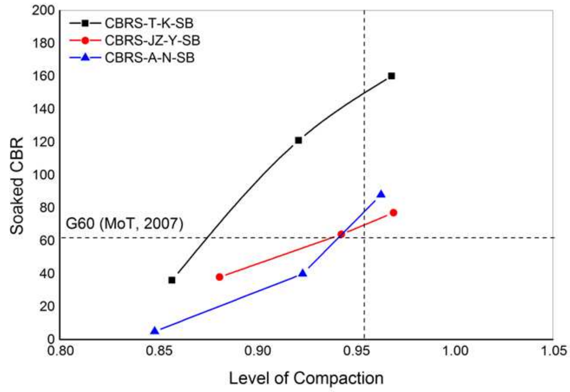

Figure 7. Variation of soaked CBR variation with level of compaction

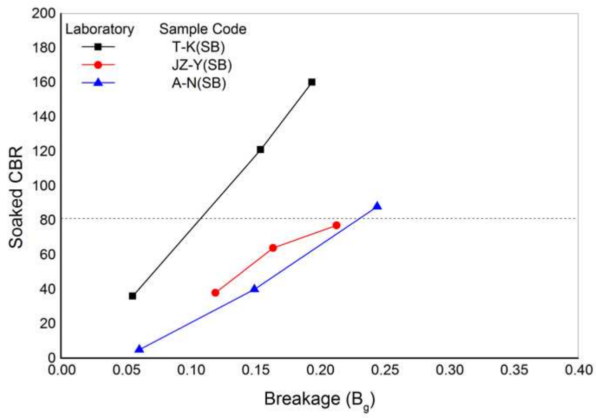

Figure 8. Variation of soaked CBR variation with particle crushing

4 CONCLUSIONS

This study aimed to investigate the level of particle crushing that occurs under laboratory compaction and to compare it with that which occurs under field compaction and to discuss the results in terms of the level of compaction achieved and the implications for the CBR strength on three road projects in different climatic zones of the country. Though the number of sites studied may be considered insufficient for definitive conclusions to be made, on a preliminary basis the main findings of this study include:

- The results suggest that in order to attain the minimum level of compaction of 0.95 specified for subbase, field compactive efforts equivalent to CEL of between 2.37 and 3.18 is required. However, most of the equivalent field compaction efforts actually being applied in the field far exceeds the CEL imposed by the Modified Proctor suggesting excessing compactive efforts are being applied in the field.
- For levels of compaction between about 0.86 and 0.99, both laboratory and field compaction lead to higher particle crushing for the gravel fraction than for the fines fraction as measured by the change in percentage retained on 2m and passing 0.075mm. For the same level of compaction, field compaction generates less fines than the equivalent laboratory compaction.
- The trend in the laboratory test results is that there is an initial low particle crushing as measured by the Marsal Breakage Index of up to about 0.10 associated with low levels of compaction of the order of 0.85. However, further increase in particle crushing from about 0.10 to 0.20 is

associated with a large increase in the levels of compaction from 0.85 to 0.95. Beyond particle breakage index of about 0.20, there is little further increase in the level of compaction.

- The field compaction is associated with high levels of particle crushing with Marsal breakage index values of between 0.22 and 0.26.
- The laboratory test results suggest that subbase material with relatively low PI in the low rainfall zones undergo far less particle crushing than the material with relatively high PI values in the moderate to high rainfall zones.

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