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Aggregate Angularity on the Permanent Deformation Zones of Hot Mix Asphalt

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Abstract**—**This paper presents a method of evaluating the effect of aggregate angularity on hot mix asphalt (HMA) properties and its relationship to the Permanent Deformation resistance. The research concluded that aggregate particle angularity had a significant effect on the Permanent Deformation performance, and also that with an increase in coarse aggregate angularity there was an increase in the resistance of mixes to Permanent Deformation. A comparison between the measured data and predictive data of permanent deformation predictive models showed the limits of existing prediction models. The numerical analysis described the permanent deformation zones and concluded that angularity has an effect of the onset of these zones. Prediction of permanent deformation help road agencies and by extension economists and engineers determine the best approach for maintenance, rehabilitation, and new construction works of the road infrastructure.

Keywords**—**Aggregate angularity, asphalt concrete, permanent deformation, rutting prediction.

I. INTRODUCTION

THE nature of construction materials makes it impossible to design a road pavement which does not deteriorate in some way with time and traffic; hence the aim of accurate structural pavement design is to limit the level of distress. An asphaltic concrete mixture is comprised of 90% aggregate. The other 10% are the air voids and binder content [1]. From these ratios aggregate has a significant role in controlling rutting.

The research focused on the aggregate coarse particle angularity which is defined within the imaging system analysis as being variations at corners, that is; variations superimposed in the aggregate shape [2].

Since the 50's, several methods have been proposed to quantify the form, angularity, and surface texture of aggregate particles [3]. These standardized test methods do not classify all aspect of the aggregate shape. However some researchers have found significant disadvantages of using this test in particle classification [3]-[5]. The measurement and classification of angularity is a phenomenon being examined in the last decade by automated imaging systems. Aggregate Imaging System (AIMS) characterizes the shape of fine and coarse aggregates. It has the ability to analyse the angularity of fine and coarse aggregates [6]. Interesting correlations have been found between aggregate angularity quantified by AIMS and mixture performance [2].

There are many factors that determine the behaviour or performance of a flexible road pavement. One of these performance indicators is the rutting in asphalt-concrete pavements. Permanent Deformation or rutting is caused by the densification and movement of materials under repeated loads, and also might result from lateral plastic flow under the wheel track [7], [8]. It is also described as a pavement condition indicator defined as a 10 mm rut or the first appearance of wheel track cracking. This distress occurs primarily by shear failure in HMA [9].

The properties of coarse aggregate materials (physical shape) significantly affect both the strength and stability of asphalt mixes. In an evaluation of the influence of coarse aggregate shape on the strength of asphalt concrete mixtures, it was concluded that cubical particles possessed the best rutting resistance compared to the other shapes [10]. This means that coarser and high angular aggregates are expected to perform better than low angular aggregate and by extension the finer gradation mixes.

The proper selection of materials is one of the most important tasks in developing an asphalt mixture that shows improved resistance to permanent deformation [11]. Different types of aggregate such as limestone, basalt, dolomite, gravel, granite and traprock have been used for production of asphalt concrete. The high stability has been achieved in using limestone aggregate as compared to basalt aggregate [12].

The prediction of permanent deformation is a complex problem, requiring detailed knowledge of materials state, elastic and plastic deformability and viscosity of pavement materials. As depicted in Fig. 1, there are three distinct stages in the relationship between load repetitions and permanent deformation, which were primary, secondary and tertiary stages. It was also reported that of the design models only the initial and secondary permanent deformation stages are used for predictions [13].

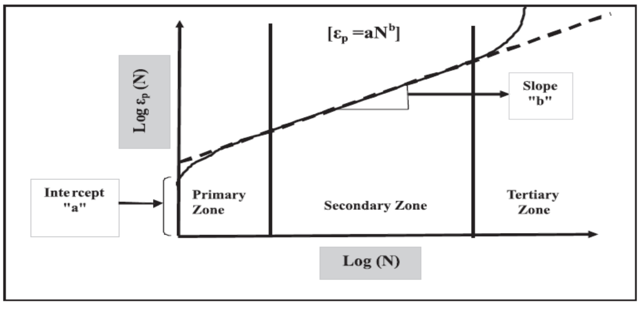

Fig. 1 Relationships between load repetition and strain [14]

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Within this study the first two stages of Permanent Deformation (Primary and Secondary) were examined. A large number of different permanent deformation models such as MEPDG, NCHRP 1-40B and VESYS are already available, but given the same input data, they produce different output (predictions). It is important that these models are easily adjustable in accordance to available historical data and the engineer's knowledge of local materials and environmental effects. The available permanent deformation prediction models have several limitations in that most of them involve large simplifications (e.g. in material behaviour), some of them contain input factors that are difficult to quantify and most are not comprehensive enough (does not consider all influencing factors).

Regarding rutting prediction models found in the Mechanistic Empirical Pavement Design Guide (MEPDG) and by extension National Cooperative Highway Research Program (NCHRP) 1-40B, has specific parameters and do not need to run laboratory testing. It is worth noting that not requiring laboratory testing is both advantageous and disadvantageous, because while it makes the models simple to implement, not using laboratory characterizations of HMA mixes may lead to inaccurate rutting prediction. This research study provides evidence of the variability of the predictions between existing models, as well as a comparison between existing models predictive data and this study data (with the adjustment of aggregate angularity property).

In spite of an enormous effort that has been made in the pavement engineering field, it still is not possible to make accurate and precise prediction of pavement life. Preservation of road infrastructure asset requires a systematic approach such as performance modelling to help in the development of tactical and strategic plans. Pavement performance predictive models allow the forward prediction of future condition based on present condition under a defined range of scenarios [15].

II. MATERIALS AND TESTS METHODS

A. Material

Natural Quartzite and Crushed Limestone were the two types of aggregate used in this study. The aggregates produced their respective gradations as shown in Table I. The mixes are dense graded mixes; however they were classified under three categories which were governed by coarse aggregate angularity within the mix (low, medium and high angularity). Trinidad Lake Asphalt (TLA) was the study binder. Aggregate abrasion test evaluated the wear potential of each type of aggregate.

B. AIMS Imaging System Test

Aggregate Imaging System (AIMS) was used for imaging analysis to characterize the angularity characteristics of coarse aggregate particles. The test samples were prepared with varying coarse aggregate angularity properties such as low, medium and high. The classification properties of both quartzite and limestone coarse aggregate particles for the mixes and also the identification of the angularity designations are shown in Table I.

TABLE I
PROPERTIES OF COARSE AGGREGATE MATERIALS

Aggregate Type	Abrasion (wear %)	Coarse to Fine Ratio	Angularity ID	AIMS Aggregate Angularity Number	MIX ID
Quartzite (Q)	44%	46% to 54%	Low	<2999	QL
			Medium	3000–5999	QM
			High	>6000	QH
Limestone (L)	30.5%	48% to 52%	Low	<2999	LL
			Medium	3000–5999	LM
			High	>6000	LH

C. Mix Design and Performance Test

All mixes met the road agency standards of acceptable limits of mix properties. The blend of aggregates for both material types used in the various mixes had no statistical significant difference between the two gradations (p=0.929>0.05 mean; p=0.937>0.05 standard deviation); therefore the research aim of aggregate type effect was accurately examined.

Permanent Deformation resistance of the mixes was evaluated using the procedure of the repeated loading dynamic creep test. The applied test stress was 200 kPa. The testing cycle stops after 3,000 loading applications. The equilibrium test temperature was 35^{o}C.

III. RESULTS AND ANALYSIS

A. Aggregate Angularity on Permanent Deformation

The results obtained from the dynamic creep test as shown in Figs. 2 and 3 show that all the mixes whether or not the aggregate type or coarse angularity changes it still exhibited the theoretical behaviour mentioned by [13]. However the tertiary stage was not evident in the measured or predictive results of the research. Mixtures with aggregates that have low resistance to wear (quartzite) have very low resistance to permanent deformation as compared to limestone material which has a high wear resistance. Even if the mixes were of different categories of angularity (low, medium, high) the results showed that the type of aggregate significantly affects the resistance to permanent deformation.

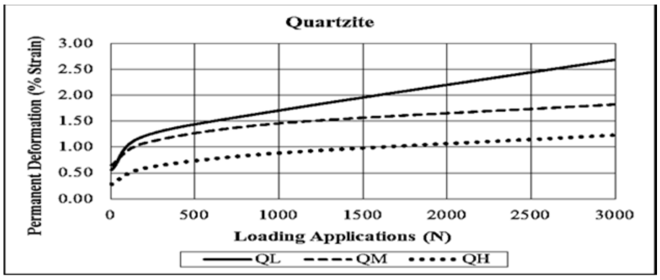

Fig. 2 Quartzite aggregate angularity on permanent deformation

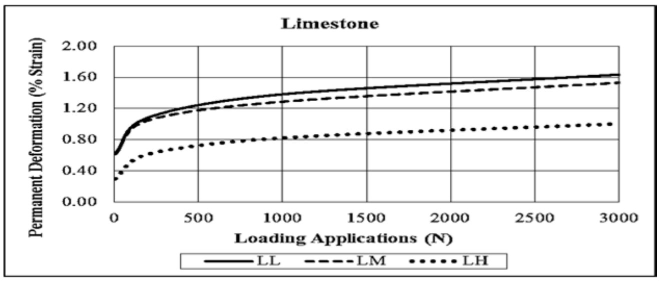

Fig. 3 Limestone aggregate angularity on permanent deformation

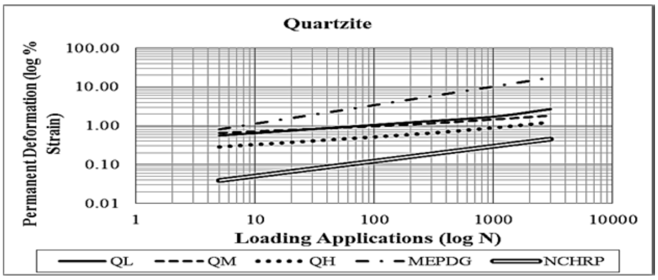

Fig. 4 Quartzite predictive and measured permanent deformation

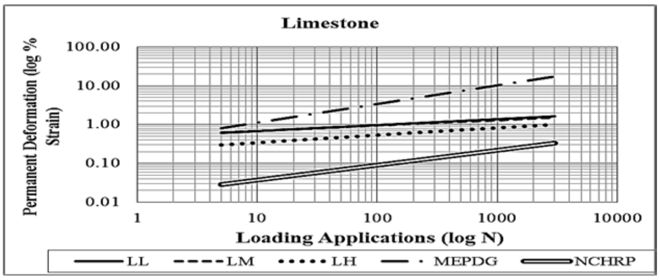

Fig. 5 Limestone predictive and measured permanent deformation

B. Aggregate Deformation Prediction and Measured Data

The results in Figs. 4 and 5 show that the high angular aggregates have higher resistance to rutting, unlike medium and low which has almost the same measured values with each other. As the angularity of coarse aggregate changes to be more angular, the internal resistance increases and the HMA mix improves its capability of carrying traffic load. The high angularity particles possess the highest deformation resistance, followed by medium and low angular particles. It appears that an HMA mix can be made more stable and resistant to deformation by specifying the coarse aggregate angularity. Fig. 3 also shows a comparison of the results of two permanent deformation prediction models when compared with the actual measured laboratory results. Although the NCHRP model has a model input for angularity (F_{index} and C_{index}), the model still underestimates the percentage of deformation in an HMA mix while the MEPDG overestimates deformation when compared to the measured values. This could be that these models lack a more rigorous variable which accounts for the potential aggregate particle angularity.

C. Permanent Deformation Zones

As shown in Fig. 1 the various zones of permanent deformation versus loading application can be modelled. Refer to (1), (2) and (3) which gives the mathematical explanation of the permanent deformation zones as previously mentioned.

Primary Zone:

$$\varepsilon_p = aN^b \tag{1}$$

Secondary Zone:

$$\varepsilon_p = dN + c \tag{2}$$

Tertiary Zone:

$$\varepsilon_p = fe^{gN} \tag{3}$$

Each equation parameters (a,b,c,d,f, and g) can be determined by regression analysis once the strain and load application cycle are known.

To determine the start of the secondary zone the use of numerical analysis can be employed. This paper employs the Newton-Raphson method, which is an iterative numerical method for finding the solution or roots of equations arising from differential equations. The Newton-Raphson method is based on the idea of linear approximation where the function must be differentiable. As mentioned previously the zones of permanent deformation can be represented mathematically, therefore using the combined (1) and (2) for secondary zone initial transition point, the algorithm developed. A concise explanation of the Newton-Raphson method used in this work is described in (4).

$$N_{n+1} = N_n - \left[\frac{aN^b - dN - c}{abN^{b-1} - d}\right] \tag{4}$$

Using an initial guess of 5 (N value), the following Table II shows results of aggregate type, the minimum and maximum strain and loading application of the transition point. The result in Table II shows that as coarse aggregate angularity increases so does the onset of the secondary stage. It also indicates a lower permanent deformation strain estimate for high angularity.

Various models such as the VESYS rutting prediction model, use the strain estimate at the 200th cycle to predict deformation depth with a pavement structure. However from the research algorithm the VESYS assumption can be affected by the type or abrasion property of the aggregate. Limestone which has a higher resistant to abrasion as compared to quartzite, has the 200th loading application cycle occurring in the primary zone while for quartzite it occurred in the secondary zone.

TABLE II
TRANSITION POINTS BETWEEN PRIMARY AND SECONDARY ZONE

Aggregate Type	Angularity #	Load Application, N_{sec}	Strain, $\varepsilon_{p,sec}$	Strain @ 200th cycle, $\varepsilon_{p,200th}$
Quartzite	2019 (low)	105.6	1.0818	1.1397
	6176 (high)	113.4	0.5371	0.5607
Limestone	2770 (low)	327.1	1.1712	1.0853
	6117 (high)	477.7	0.5417	0.4337

IV. CONCLUSIONS

If an asphalt mixture deforms (ruts), it is normally because the mixture has insufficient shear strength to support the stresses to which it is subjected to. Aggregates are responsible for minimizing shear failure within an asphalt concrete mix. From the experimental study conducted it can be concluded that the aggregate resistance to degradation (abrasion wearing) is significantly influenced by the aggregate type and by extension its morphological properties. HMA mix density and stability properties can be vastly affected by the aggregate type abrasion wear potential. The higher the abrasion wear resistance, the higher the mix density and greater stability properties when used within a mix.

The AIMS imaging system was shown to be a useful tool for quantifying the angularity characteristics of coarse aggregate. It quantifies the angularity as well as other shape properties for each individual particle within. The analysis of the angularity data is not subjected to human error which leads to more accurate results. For any given type of aggregate, an increase in the coarse aggregate particle angularity in a mix decreases its susceptibility to permanent deformation, while increasing stability potential.

The proposed algorithm for the estimates of onset of the secondary zone was used for different aggregate type with varying levels of coarse aggregate angularity. The existing predictive models did not accurately predict deformation of the mixes because the material properties input are subjected to a user bias test. The research procedure validate that the transition points of permanent deformation zone can be estimated using mathematical models that describe each zones.

The accuracy in the prediction of HMA mixes to permanent deformation can be obtained if prediction models take into account a more accurate or an additional variable for the aggregate particle angularity property.

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