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The Effect Of Surface Texture On Skid Resistance Of Asphalt Pavements

Abhirup Basu Roy Chowdhury

MSc., Department of Civil Engineering,
Nottingham Transportation Engineering Centre, University of Nottingham,
Nottingham, United Kingdom

***Abstract:** One of the most important factors contributing to road traffic accidents in today's busy world is lack of adequate skid resistance on roads. Adequate friction at road-tyre interface reduces skidding in both wet and dry weather conditions. As typical maintenance policies are costly and disruptive, the situation cries out to construct pavements sufficiently skid resistant in the first place. This thesis analyses the influence of Mean Texture Depth (MTD), aggregate size, spacing between aggregates (edge-to-edge), on Skid Resistance. Finally, the effect of friction on Braking Distance was investigated. Additionally, the influence of varying void contents is considered. British Pendulum Test and Sand Patch Test were performed to account for micro and macrotexture of the samples respectively. The research used asphalt concrete slabs manufactured in the laboratory with varying void content and cores from a certified engineering company. The results are presented and analyzed. In most of the cases, the cores produced justifiable results, where Skid Resistance in terms of both MTD and friction coefficient decreased with increasing spacing (edge-to-edge) and decreasing aggregate size. But, the results obtained in some cases while studying the slabs were not as expected.*

Nevertheless, through this study, economically and technically, the optimal choice of asphalt mix, gradations, aggregate size, spacing and MTD could clearly be recommended considering the UK specifications for minimum skid resistance on roads.

***Keywords:** Skid Resistance, BPT, Aggregate Size, MTD, Braking Distance*

I. INTRODUCTION

Skid resistance is such an important characteristic property of a pavement, which is to be considered in this era of great concern about road traffic safety, accidents, and injuries, and also when Hot Mix Asphalt (HMA) is to be designed. As roads and road networks are inevitable means of transport ever since, Skid Resistance, today, is one of the most noteworthy chapters of pavement engineering. It is due to the fact that there is a high correlation between low skid resistance (especially in wet weather conditions) and the accident rates. It has been shown, that friction at the interface of the vehicle tire and the pavement surface play a significant role in reducing crashes (Hall et al., 2009), and that, most of the skid-related accidents and injuries occur when the road surface is wet (Flintsch et al., 2012). So, it can be said that the pavement surfaces with low skid resistance have had much more accident rates and casualties when compared with the pavement surfaces with high skid resistance.

Studies by Kamel and Musgrove (1981) revealed that some 54 percent reduction of accidents in wet weather and about 29 percent reduction on total were possible when a pavement of high skid resistance was used. This fact was seconded by Masad et al. (2007). It is also known from the studies, that the skid resistance of a pavement surface is associated with two main characteristic properties, and they are the microtexture and the macrotexture of the pavement. Briefly, it can be said that microtexture depends mainly on the aggregate shape, its characteristics, mineralogy, and the macrotexture is dependent on mix properties, aggregate gradation, etc. (Masad et al., 2007). The Macrotexture of the pavement surface is held as one of the prominent contributory factors towards road traffic accidents (Kwang et al., 1992). The researchers also did state that the Microtexture is yet another dominant factor in determining the resistance of a road surface to skidding, at a lower speed. More specifically, it was said that in bituminous surfacing, resistance to skidding is characterized by resistance to the polishing of the aggregates. From here on, the concern about the aggregates starts.

The literature review in aims to gain knowledge on skid resistance, and how it depends on the surface texture characteristics and to explore them vividly. The review also discusses various methods and techniques to measure Skid Resistance, and highlights the specifications, given by Design Manual for Roads and Buildings (DMRB) HD 36/06 and Transport Research Laboratory (TRL, 1969).

II. PROBLEM STATEMENT

Skid Resistance is the measure of the counteraction of a pavement surface against vehicular skidding. The texture of the pavement plays a huge role in that action. Though the researchers of the past proved the fact that the aggregate properties have a drastic influence on skid resistance after performing studies with the Polished Stone Value, none of them supplied the experimental information of how the friction coefficient (μ) is affected when aggregate with different types of stone sizes are used. The braking distances depending on the friction coefficient were predicted, but the dependency of the prediction of the Braking Distance on aggregate size was not vividly addressed (only names of different aggregates were used, not the characteristics). So, the concept of 'μ' is not very clear yet, and it throws up questions like, what is the influence of stone size, gap and void ratio on Wet Skid Resistance of Asphalt Pavements? How do they impact on the Prediction of Braking Distance? The project aims for a deeper investigation.

III. AIMS AND OBJECTIVES OF THE RESEARCH

A. AIMS OF RESEARCH

The purpose of this research is to carry out an extensive analysis on how –

- ✓ The friction coefficient, 'μ' varies with stone (aggregate size).
- ✓ Various stone size effects the Prediction of Braking Distance.
- ✓ The combination of aggregate gap and size affect the skid resistance of a pavement surface.
- ✓ Mean Texture Depth (MTD) affects skid resistance.

B. OBJECTIVES OF RESEARCH

The above-mentioned aims will be achieved by:

- ✓ Using the British Pendulum Tester for testing the test samples of the road surface with different stone sizes, which are to be made as well as retrieved from a certified engineering company.
- ✓ Performing Sand Patch Test on the road surfaces, made in the laboratory and retrieved.
- ✓ Analysing and assessing the behaviour of coefficient of friction, 'μ' and Braking Distance (DF) with respect to void ratio, maximum aggregate size, spacing between aggregates (edge-to-edge).
- ✓ Relating 'μ' with MTD and analysing the effect of Macrotexture.

IV. RESEARCH METHODOLOGY

The first stage of the research methodology is to test the retrieved cores in British Pendulum Tester (BPT), and get the British Pendulum Number (BPN), which would be an indicative aspect in calculating 'μ'.

The second stage is to make Asphalt Concrete slabs with different gradations and void contents and tested in BPT.

Sand Patch Test will be carried out on retrieved cores and laboratory made cores to get the texture depth, which is the function of the diameter of the sand encountered (see Sand Patch Test method described in Literature Review). Sand Patch Test is carried out to get an idea of the Macrotexture, which is directly related to the Skid Resistance.

The acquisition of the graphical-empirical analysis to correlate BPN, Texture Depth, 'μ', 'DF', the spacing between aggregates (edge-to-edge) and Maximum Aggregate size and MTD for laboratory made samples requires specimen preparation, for which:

- ✓ Gradations are adjusted in a calculative way for 14mm, 10mm and 6.3mm stone slabs to get the gradations as close to the specified mid-range as possible.
- ✓ Void contents are made varied which are 5%, 9% and 13% (three of each type, total nine). This is done to get enough data and to widen the sample range.

For the calculation of 'μ' and 'DF', the equations from a previous study (Burlacu et al., 2013) are used. Finally, the laboratory made slabs are to be tested in BPT and Sand Patch and the results to be presented and analysed.

V. SCOPE OF WORK

The research is limited to the following:

- ✓ Testing of some 18 cores retrieved from a certified engineering company. British Pendulum Test and Sand Patch Test to be done.
- ✓ Testing of nine Asphalt Concrete slabs made in the laboratory. Here again, BPT and Sand patch to be performed.

A range of 18 cores is sufficient to test on, and as far as the variety is concerned, they were all anonymous, and could not be gathered under one single category. Though, the exact mix for each core and their properties could not be found out, they are tested however to achieve the primary aims of this dissertation – friction related to aggregate size and spacing (material or mix is not the concern of this dissertation). Nine laboratory made slabs were tested. There, the void ratio (5%, 9%, and 13%) with the gradations of 6mm, 10mm and 14mm were selected as the parameters, which reflect one the aims of this research. For the inputs and outputs of the lab made (controlled) slabs.

VI. LITERATURE REVIEW

A. SURFACE FRICTION

Hall et al. (2009) define pavement friction as the force that counteracts the relative motion developed between the pavement surface and the tyre of a vehicle. This force generates as the result of rolling or sliding of tyres on the pavement surface. This resistive force, μ, equals to the ratio of the tangential frictional force (F) at the interface of the tread rubber of a vehicle tyre and the horizontal surface to the normal or vertical force (Fw), given by –

$$\mu = F/ Fw \quad (1)$$

The term, 'skid resistance' has a close association with the term 'surface friction' OR 'pavement friction', and in fact so close that it is hard to treat them differently.

Pavement friction as said by Hall et al. (2009), is the result of such an interaction between the key components of frictional force, which is considerably complex. The two key components are 'Hysteresis' and 'Adhesion'.

ADHESION: It is the frictional property that turns up because of the interlocking phenomenon of the pavement surface and the vehicle tyre, i.e., when there is a contact between the two.

HYSTERESIS: It is the frictional property which results from the loss of energy due to the ample deformation of the tyre of the vehicle. In another way, this deformation can be referred to as the enveloping action of the vehicle tyre around the pavement surface texture.

Hall et al. (2009) agreed the fact that both the above-mentioned components are dependent mostly on the characteristics of the surface of the pavement, and that, the total friction equals to the addition of the values of adhesion component and hysteresis component.

$$F = F_A + F_H \quad (2)$$

Where, F_A = Adhesion, F_H = Hysteresis

B. SKID RESISTANCE

Mayora et al. (2009) termed Skid resistance as the contribution of the pavement surface in developing friction. In other words, the term 'skid resistance' refers to the impact of roughness between the vehicle tyres and the pavement or road surface, and is measured on the wetted pavement or road surface. (German Asphalt Pavement Association et al.). The roughness is affected by the properties of the surface course, and the surface texture (microtexture, macrotexture, and megatexture), which is influenced by traffic and the environmental factors (Drüschner et al., 2006).

According to Els et al. (2006), after the completion of the roadwork, and the finished road been accepted, the roughness is influenced mostly by the texture of the surface achieved during the paving process, and while it is being used, the properties of the mixture and its components, like aggregates come in the picture mainly because of the traffic factors and weather conditions.

Cement Concrete and Aggregates Australia (2002) defines skid resistance as the ability of a surface to provide friction to the reference tyre or slider usually measured when wet, which is pretty much same as the definition given by German Asphalt Pavement Association. Moreover, like German Asphalt Pavement Association, Cement Concrete and Aggregates Australia states that skid resistance depends primarily upon surface macro and microstructure. There are other parameters as well, they will be talked about in the sections ahead.

C. RELATIONSHIPS WITH MICRO AND MACROTEXTURE

There are relationships between the surface texture properties and frictional components of the pavement surface (Adhesion and Hysteresis), which influence the Skid Resistance to a great extent. It is because of the fact, that as Skid Resistance is very much dependent on the surface microtexture and macrotexture (de León et al., 2003) the factors or the components which are strongly related to them will certainly have an effect on the Skid Resistance as a whole.

Flintsch et al. (2003) say that the macrotexture is the one which provides the hysteresis component. He also suggested that due to this fact, rapid drainage of water from the pavement takes place. As a result, an improved interaction between the tire and the surface is achieved, and hence Skid Resistance becomes favourable and good enough.

Flintsch et al. (2003) again suggest that as the surface microtexture provides the direct tyre-pavement contact, it is related with the adhesion. It is due to the fact that adhesion is the result of an interlocking action of the pavement surface and the tyre, where the surface microtexture is concerned, where it is susceptible to the micro-level roughness of the aggregate particles (Hall et al., 2009).

D. EFFECT OF SKID RESISTANCE ON ROAD SAFETY

Skid Resistance OR Pavement Friction is one of the most influencing factors of accidents on roads and is exceedingly associated with road safety. Studies confirm that each year an apprehensive number of people die due to skid resistance related road accidents. It is revealed from the study, that friction between tyre and surface of the pavement is a critical factor in reducing the traffic related deaths and injuries (Flintsch et al., 2012). Studies also showed that most of the skid resistance related accidents occur on the wet road surface, where there is a considerable lack of skid resistance as the surface friction drops below a certain or specified value.

Another study in the Czech Republic shows that, in the years 2003 and 2004, the total number of accidents on the 1st class road network was 800. In fact, 24% of accidents were localised on 6% of the road length that exhibited unacceptable and dangerous skid resistance (Kudrna et al., undated).

Andriejauskas et al. (2014) assert that skid resistance is an important element of road safety, especially in wet weathers, or when anyhow the road surface is wet. It was also determined that, on the wet road surface of horizontal curves, peak accident risk is where the skid resistance coefficient is

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0.25. It was calculated that the accident risk on the road surfaces with a coefficient of skid resistance below 0.45 was 20 times that on the roads with the coefficient of skid resistance above 0.60. It could also be noted that the risk of accidents becomes almost undeviating after the range of 0.35-0.45 Skid Number because the polishing of road surface reaches a limit. Hence, the criticality lies at anything smaller than that.

E. THE FACTORS ON WHICH SKID RESISTANCE DEPENDS

Friction depends on the interaction between the tyre and the pavement surface (Flintsch et al., 2012). And since, the terms 'Friction' and 'Skid Resistance' are immensely related to each other, today engineers and researchers all over the world have tried to identify a number of factors mainly on which Skid Resistance and tyre-surface friction interaction depends. They can be categorised as:

- ✓ Pavement surface characteristics.
- ✓ Vehicle operations.
- ✓ Characteristics of the tyre.
- ✓ Environmental and natural factors.

Under the above-mentioned factors, there can be a number of discussions on each, which are often inter-related, and lead to a chain of investigatory and critical analysis by either testing in field or testing under laboratory conditions, or both.

Skid resistance of wet road surface decreases with the increase of driving speed, think Andriejauskas et al. (2014), and hence according to him, pavement texture becomes such a property of pavement, on which skid resistance depends mainly. The researchers are also very clear on the fact that texture of the pavement surface further depends on the design of asphalt mixture, the composition of aggregates, materials of the pavement, size and shape of aggregate, bitumen binder content, etc.

F. PAVEMENT SURFACE CHARACTERISTICS

From the studies and researches performed most recently and in recent past, it is revealed that Pavement texture is undoubtedly the most important and considerable factor associated with tyre-pavement friction interaction and skid resistance. It is true from the science and the behaviour of friction, that a pavement surface is an acceptable one if it proves to provide enough skid resistance to stop a vehicle from skidding and to stop it safe when brakes are applied in normal as well as in a panic situation. Now while talking about the pavement surface characteristics, it can be said from various studies performed at World Road Association, that there are three texture levels on pavements which indicate different effects of pavement friction and its performance (Fuentes et al., 2009). Those can be categorised as follows:

- ✓ Microtexture
- ✓ Macrotexture
- ✓ Megatexture

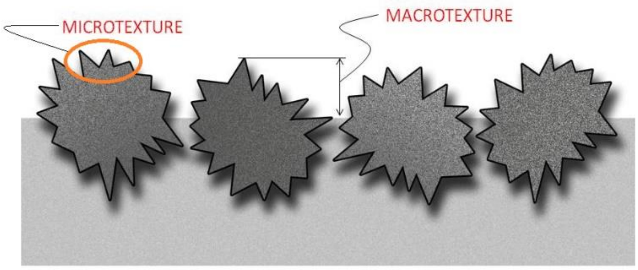

Figure 1: Illustration of Microtexture and macrotexture

G. MICROTEXTURE

It can be described as a function of aggregate asperities. Usually, its magnitude range is 1 to 500 □m (0.5mm). The function of microtexture is to provide adhesional friction at the interface of the tyre and the pavement when there is still a contact between the tyre and the asperity tips (Fuentes, 2009). The microtexture of a pavement surface is defined as the quality of the surface roughness on sub-visible level or when the microscope is used to study that (León et al., 2003). Mayora et al. (2009) believe that microtexture is such a property of a pavement surface texture that has a major contribution to skid resistance in case of low-speed transportation. In wet weathers or in the wet road surface, the involvement of microtexture takes place during its penetration through the film of water on the road surface, which has a negative result, i.e., the skid resistance reduces. Generally, microtexture is not measured in the field, but instead, measurement devices like British Pendulum Tester (BPT), Dynamic Friction Tester (DFT), etc. are used to measure friction at low speeds. (Flintsch et al., 2003).

H. MACROTEXTURE

The large particles of the paving mixture are responsible for the macrotexture of a pavement surface (León et al., 2003). It can also be described as a function of the arrangement and orientation of aggregates in the pavement surface. As suggested by Mayora et al. (2009), drainage convenience and paths which allow the water on the pavement surface to drain out of the road-tyre interface. Usually, its magnitude ranges from 0.5mm to 50mm (Fuentes, 2009). In general, methods for measuring macrotexture are Sand Patch test and the Circular Texture meter. (Flintsch et al., 2003).

Texture Depth: According to DMRB, the texture depth is a measure of the macro-texture and is an influencing factor on skidding on wet roads.

HD 36/06 states the two forms of surface texture as:

- ✓ Positive texture: In the case of a typical surface dressing or hot rolled asphalt with chips, it is defined as a number of angular peaks above a datum level.
- ✓ Negative Texture: In the case of a typical thin surface course systems and porous asphalt, it is defined as a network of depressions or series of grooves below the general level.

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I. METHODS AND TESTS USED TO MEASURE SKID RESISTANCE

The microtexture cannot be measured in field conditions, hence it is measured in laboratory conditions. There can be a good many methods and test techniques to measure the skid resistance of a pavement surface in terms of surface texture (microtexture and macrotexture) (Lu et al., 2006). Some of them can be discussed as follows:

a. BRITISH PENDULUM TEST

The British Pendulum Tester (BPT) is a pendulum impact-type test device, which measures the loss of energy when the edge of a rubber slider is propelled over a simulated or collected pavement surface sample (Lu et al., 2006). The British Pendulum Tester measures the skid resistance related to the microtexture of the road surface. Lu et al., (2006) believe that one of the biggest advantages of this test is the convenience to use the device both in the field and in the laboratory. It is confirmed from the studies that too much-polished aggregate caused by the polishing action of traffic, makes the road surface more slippery, especially in wet condition, and this can prominently be a cause of the increase in the number of skidding accidents (Northstone (NI) Ltd. Quarry and Asphalt Division). Burlacu et al. (2013), gave the formula for calculating the friction coefficient (μ) from British Pendulum Tester as –

$$\mu = \frac{M(H-h)}{PL} \qquad (3)$$

μ = coefficient of friction between surface and slider

M = effective weight of the arm (swinging)

H = initial height of the centre of gravity in the released position

H = height of the centre of gravity at the highest point of the swing after slider passes over the test surface

P = average normal load between slider and surface

L = Sliding distance

Figure 2: A British Pendulum Tester

b. POLISHED STONE VALUE (PSV)

It can be said that the polished Stone Value (PSV) is the measure of the extent of an aggregate's resistance to the action of polishing. This value is determined by standard polishing the aggregate first, and after that testing, it with the British Pendulum (BPT), to obtain its PSV (Summers, 2015). The property by virtue of which a good PSV is obtained is referred to as its Microtexture. Hence, it can be said that, the aggregates that retain a considerable Microtexture after the polishing process are the ones which have good skid resistance, and have a high Polished Stone Value. This test is of utmost importance for a road surface aggregate to undergo (Burlacu et al., 2013).

c. SIDEWAYS–FORCE COEFFICIENT ROUTINE INVESTIGATION MACHINE (SCRIM)

It is another prominent method of measuring skid resistance in terms of the macrotexture. The working principle of a SCRIM tester is that a freely rotating wheel fitted with a standard smooth tyre is inclined at an angle of 20 degrees to the direction of motion of the test vehicle. This generates a measurable sideways force on the surface. The Sideways-force Coefficient (SFC) is the ratio of the force developed at the right angles to the plane of the axis of the wheel to the load on the wheel (Tinni, 2010). The pavement is always tested with a sprayed film of water immediately under the test wheel so as to simulate the wet weather conditions. As the vehicle moves forward, the test wheel slides on the wet road surface. This action generates a force, which is related to the wet skidding resistance of the road surface. The disadvantage of using SCRIM is that it is not suitable for laboratory experiments.

d. SAND PATCH TEST

The sand patch test method measures the macrotexture depth (average) of a pavement surface concerned with skid resistance because the knowledge of the pavement macrotexture characterises the pavement surface texture as a whole. This test has a volumetric way of measuring the macrotexture of a pavement. Briefly, it can be said that in this study, a volume of glass beads which is known, is evenly spread over a portion of a pavement surface (which is aimed to study) in a circular fashion, where the glass beads fill the voids on the surface at that particular portion of the pavement. Department of Transportation, Minnesota says that the average value of the diameter of the circle is taken into account after measuring the diameter on four axes, so as to obtain the Mean Texture Depth (MTD).

e. GRIP TESTER

Another device for measure skid resistance in terms of friction is the Grip Tester. It is commonly used in European Countries. The working principle of a Grip Tester is that, a lightly braked test wheel is made to rotate and maintains a constant slip, to ensure a contrast between the velocity of the wheel with which the friction is tested, and the speed of the tester itself. Hence, this device is depicted as a fixed slip device, where the slip ratio remains usually between 10 – 20 percent. The friction obtained is then related to antilock braking (Steven et al., 2006).

There are various tests and methods which are used for measuring the skid resistance of pavement surface related to texture properties. It is also true and evident that each one of them has a significant correlation with others (Steven et al., 2006). But it can be derived that the use of The British Pendulum Tester will be the most relevant and useful one, as it is the most widely used device to determine the Skid Resistance in terms of Polished Stone Value (PSV) of Aggregates (Mahmoud et al., 2007). Moreover, it is portal and repeatable.

J. FACTORS AFFECTING SURFACE TEXTURE

It could be said by going through the past research papers (Hall et al., 2009) that, some of the factors that have an effect on the surface texture of pavements have a strong relation with binder, aggregate and its characteristics, and sometimes with mix properties of the surface material. They can be described as follows:

- ✓ Maximum Dimensions of Aggregate – The size of the largest aggregates in the pavement is responsible for providing the dominant macrotexture, if the aggregates are closely packed and evenly spaced in the mixture.
- ✓ Type of Coarse Aggregate – This influence the surface texture, because the selection of the type of coarse aggregate will control the material of stones used, the angularity, the shape, and also the durability of aggregate.
- ✓ Binder Viscosity and Content – Binders which have low viscosities are likely to cause much more bleeding than that which have higher viscosities and harder grades. This is an important factor because bleeding results in a massive depletion or even complete loss of microtexture and macrotexture from the pavement surface.

From the discussion above, it can be summarised that pavement design involves the utilisation of proper materials and aggregates to achieve a high level of performance from the perspective of skid resistance, which significantly depends upon the pavement surface characteristics, i.e., the macrotexture and the microtexture. It is also very clear now, that the types of aggregates in the surface mixture directly affects the microtexture, and the gradation and size of the aggregates affect the macrotexture of the pavement surface (Hall et al., 2009).

K. ADVANCES ON SKID RESISTANCE

Researchers, scholars and organisations who considered skid resistance as an important aspect of pavement engineering, and an influencing factor on road safety, found the lack of it on the pavement surface as a sinister issue, and performed studies, both in the field and in laboratory conditions. The research and advances that are discussed in this section mainly focus on how aggregate properties, like texture, shape, gap and polishing cycle affect skid resistance.

a. DEPENDENCY ON AGGREGATE SHAPE

Studies by Masad et al. (2007) revealed the connection of aggregate texture to the skid resistance of the pavement where image analysis was used for the study of aggregate shape, in which a new method was developed, called Micro-Deval, to measure the effect of the texture of coarse aggregate texture on skid resistance. The results were varying, depending on texture levels of aggregates.

Masad et al., 2007 described the dependency of Skid Resistance with respect to the Skid Number (SN). But, what seems to be the most curious after going through that work, is the variation of ‘µ'with different stone shapes, which was not presented in that work.

b. PREDICTING BRAKING DISTANCE

Burlacu et al. (2013) predicted braking distance depending on the Polished Stone Value of the aggregates in the wearing course, where it was found that though indeed there is a relation between the PSV and the friction coefficient, it varies depending on the type of asphalt mixtures, and other conditions like traffic. He found it difficult to give some clear ideas concerning the relation between PSV and friction coefficient (µ). He also highlighted that an equivalent relation could not be established between those two values. Hence, this cries out for the need to find the change of ‘µ’ with varying stone sizes.

An equation was used to calculate the Braking Distance, which is –

$$DF = \frac{V_i t}{3.6} + \frac{V_i^2 - V_f^2}{254(\mu_1 \pm i)} \qquad (4)$$

Where,
DF = Braking Distance
V_i = initial speed in km/hr
V_f = final speed in km/hr
μ_1 = longitudinal frictional coefficient
i = slope
t = reaction time

Burlacu et al. (2013) finally came up with the results and graphs for braking distance values, depending on the friction coefficient and considering several other factors like driving speed, driver reaction time and slope. But the properties (size, shape, and gap) of each type of aggregate were not specified.

c. DEPENDENCY OF SKID RESISTANCE ON GAP OF AGGREGATES

According to the findings of Fwa et al. (2003), skid resistance indeed depends on the properties of aggregate, and thus the skid resistance properties of the aggregate are the dominant factors in providing a skid-resistant asphalt pavement surface. Fwa et al. (2003) in the research experimented with two types of pavement aggregate, granite and steel slag aggregate, and a set of fabricated portland cement mortar specimens with different patterns of sliding contact surface. Specimens with different aggregate gradations (dense-graded, gap-graded and open-graded) were studied and the effect of aggregate spacing and gap width on skid resistance, keeping the aggregate size constant was found out.

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He studied their effect on both dry and wet friction in terms of British Pendulum Number and compared the results.

Fwa et al. (2003) found that the rates of reduction of frictional resistance were not uniform for the two types of aggregates, with increasing gap width between aggregates in both the conditions (dry and wet). From this, it was suggested that the issue - how the aggregate gap width affects the skid resistance, is very much dependent on the aggregate type used for the surfacing course. Hence, it was implied that the gradation of aggregate has a huge effect on the skid resistance.

On total, it can be said that friction is inversely proportional to the width of the aggregate gap. But, what remained as a gap was that the effect of the combination of aggregate size and aggregate gradations did not come up truly in that research, and so, further research is needed.

d. RELATIONSHIP WITH POLISHING CYCLE

Masad et al. (2009) in their study, measured and analysed the behaviour of friction with several types of devices when different aggregates and mixture types were used for the asphalt mix. There, it was indicated that the British Pendulum Number values decreased when there was an increase of polishing cycles for almost all the aggregates. Even though that conclusion was converged, there were variations in results within them. In the study, 4 types of aggregates were used (El Paso, Beckman, Brownwood, and Brownlee). The graphs of British Pendulum Values for each were plotted against Polishing Cycles, and they came up with varying results.

It could be derived from that study, that different aggregate has different level of resistance to the effect of polishing caused by the traffic. Hence, of course, have variations in British Pendulum Number (BPN).

VII. EXPERIMENTAL WORK

A. PRELIMINARY TESTS

A set of preliminary experiments was carried out to observe the practicality of the project and the experiments and to get the very idea of the agreed dissertation. British pendulum Test and Sand Patch Test were carried out on six out of eighteen cores retrieved from an engineering company. The purpose of both preliminary and main tests is to:

- ✓ Find the relationship between Braking Distance (DF), the British pendulum Number (BPN) and the coefficient of friction, ‘μ’.
- ✓ Find the relationship between gap width of aggregates (edge-to-edge) and the coefficient of friction, ‘μ’.
- ✓ Find the relationship between 'μ', max. aggregate Size and the gap width between aggregates, i.e., how they act combinedly.
- ✓ Find the relationship between mean texture depth (MTD) and the coefficient of friction, ‘μ’.

Six retrieved cores were tested on to get a much clearer idea of the mechanism of the tests, and also to obtain some data to see whether they justify the theory available in the literature. However, the hurdle was to adjust the sliding distance of the pendulum arm to be 127mm. Initially, due to the complex setup of the British Pendulum Tester, the sliding distance of 127mm could not be maintained precisely, as a result, the outcome was misleading. Immediately after that, the BPT was mounted on some wooden blocks with flat surface and a platform was made to make the sliding distance exactly 127mm. It was done with utmost caution and the level of the apparatus was adjusted by the bubble adjuster.

B. CORES RETRIEVED FROM SITE

Eighteen (18) cores with no pre-knowledge of their mix design, AVC, aggregate size, spacing of any kind between aggregates are retrieved from a certified engineering company for the study.

Figure 3: Asphalt Cores retrieved from site

C. LABORATORY MADE SAMPLES

VOID CONTENT: Nine slabs are made with each stone size, i.e., 6.3mm, 10mm and 14mm with void content of 5%, 9% and 13%. The purpose of this is to get a relation between the void content and the friction coefficient, ‘μ’, and also to get a larger variety of materials to test. The bitumen grade is kept standard, i.e., 40/60 pen.

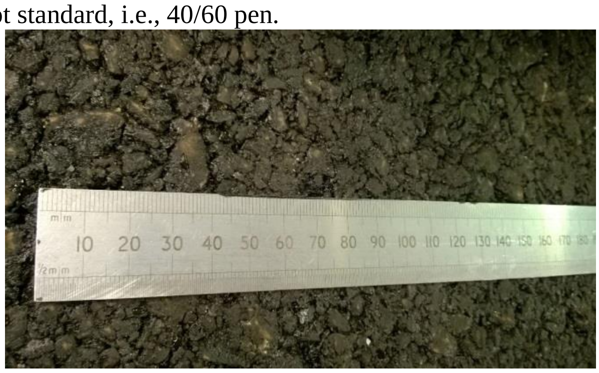

Figure 4: Asphalt concrete slabs made in laboratory

D. SAMPLE PREPARATION

For lab made slabs, void content has been an influencing factor on asphalt mixture, and followingly on the spacing between stones. Moreover, in the current research, the increase in void content increased the MTD of the lab made slabs, which reveals that void content does influence on the aggregate spacing and texture.

PREPARATION OF SLABS: Nine slabs of dimensions $306 \times 306 \times 50\ mm^3$ were manufactured for TAV – 5%, 9% and 13% and compacted to the target density using rollar compactor. The mixing temperature for the mixes was 160° C.

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Burdon Hill granite was used as the aggregates for all the slabs.

DENSITY: The maximum density was determined by the mathematical procedure through the BS EN 12697, part 5 (2009). The maximum density can be calculated by the mathematical procedure as:

$$\rho_{mc} = \frac{100}{(p_a/\rho_a)+(p_b/\rho_b)} \quad (5)$$

Where,

ρ_{mc} = maximum density of the material by calculation, in megagrams per cubic metre (Mg/m^3)

ρ_a = apparent density of the aggregate, in megagrams per cubic metre (Mg/m^3)

p_b = the proportion of binder in the material in percent (by mass)

ρ_b = density of the binder at 25 °C, in megagrams per cubic metre (Mg/m^3)

$p_a + p_b$ = 100 % (by mass)

Also, the bulk densities of the specimens were determined by the dry method through the BS EN 12697, part 6 (2012).

The dry bulk density can be calculated as:

$$\rho_{b\,dry} = \frac{m_1}{m_1 - m_2} \times \rho_w \quad (6)$$

Where,

$\rho_{b\,dry}$ = dry bulk density in megagram per cubic metre (Mg/m^3)

m_1 = mass of the dry specim in gram (g)

m_2 = mass of the specimen in water in gram (g)

ρ_w = density of water at test temperature in megagram per cubic metre (Mg/m^3)

THE AIR VOID CONTENT: The air voids content of asphalt mixtures was calculated using the respective maximum and bulk densities based on the previous calculations. The air voids percentage in the mixture can be calculated as:

$$V_m = \frac{\rho_m - \rho_b}{\rho_m} \times 100\ \%\ \text{(v/v)} \quad (7)$$

Where,

V_m = the air voids content of the mixture (v/v)

ρ_m = the maximum density of the mixture, in kilograms per cubic metre (kg/m3)

ρ_b = the bulk density of the specimen, in kilograms per cubic metre (kg/m3).

E. SAND PATCH

The sand Patch Test is performed on all 18 retrieved cores and the nine slabs made in laboratory. Texture depth is given by the formula –

$$Texture\ Depth = \frac{4V}{\pi d^2} \quad (8)$$

Where,

V = Volume of sand used (ml)

d = Diameter of the sand patch (in mm)

Texture depth practically depends on stone size, the spacing of stones (edge-to-edge), and combinedly could be said that the orientation of the aggregates present in the surface layer is the factor on which mean texture depth depends. It can be said quite evidently, that bigger the spacing between aggregates, smaller the diameter. The orientation of the aggregates depends on the void content, and that's the reason void contents are controlled for the Asphalt Concrete slabs made in the laboratory.

Figure 5: Sand Patch Test in NTEC laboratory

For laboratory made slabs and cores, the diameter of the sand patch formed was measured in four different directions to get the mean diameter, and followingly, the Mean Texture Depth (MTD).

Example calculation of Mean Texture Depth (MTD):

The mean diameter of the sand patch formed on the surface of test specimen with spacing between aggregates (edge-to-edge) and stone size 8mm and 17mm respectively was found as 103mm. Equation 8 is used to calculate the MTD-

$$Texture\ Depth = \frac{4V}{\pi d^2}$$

$$= \frac{4 \times 10000\ mm^3}{\pi \times 103^2\ mm^2}$$

= 1.200 mm

The calculation of MTD for all other samples with their respective diameters formed in the sand patch test were calculated in the same way as shown above.

a. CORES RETRIEVED FROM SITE

The texture depth calculated from the diameter of the retrieved cores are as in the tabular format –

No.	Spacing of Stones (in mm)	Stone Size (in mm)	Diameter of the Patch (in mm)	Mean Texture Depth (MTD) in mm
1.	8	17	103	1.200
2.	6	18	125	0.815
3.	8	20	105	1.155
4.	6	18	101	1.248
5.	7	17	120	0.884
6.	4	12	100	1.272
7.	5	19	126	0.800
8.	4	17	116	0.948
9.	5	11	115	0.964
10.	8	15	115	0.964
11.	17	22	128	0.776
12.	11	20	88	1.644
13.	6	27	98	1.324
14.	4	11	120	0.884
15.	7	23	116	0.948
16.	4	13	99	1.300
17.	8	16	141	0.640

18.	7	15	113	1.000

Table 3: Mean Texture Depth of Cores Retrieved from Site (in mm)

b. LABORATORY MADE SLABS

Stone Size (in mm)	**Void Content (in %)**	**Diameter of Patch (in mm)**	**Mean Texture Depth (MTD)**
	5	200	0.640
		195	0.670
		180	0.786
		180	0.786
14	9	190	0.705
		185	0.744
		195	0.670
		195	0.670
	13	160	0.995
		170	0.881
		170	0.881
		170	0.881
	5	245	0.424
		240	0.442
		250	0.407
		250	0.407
	9	215	0.551
10		237	0.453
		205	0.606
		205	0.606
	13	193	0.684
		195	0.670
		190	0.705
		190	0.705
	5	275	0.336
		265	0.363
		285	0.314
		285	0.314
	9	273	0.342
		245	0.424
6		235	0.461
		250	0.407
	13	255	0.392
		220	0.526
		230	0.481
		235	0.461
		240	0.442

Table 4: Mean Texture Depth of Lab made slabs (in mm)

For all the laboratory made slabs, the diameter of the sand patch formed was measured in four different directions to get the mean diameter, except for the slab with 6mm aggregate size and 13% AVC, where the sand patch was measured in five directions so as to counteract the unclarity in the fourth measurement (refer to table 4 above).

F. BRITISH PENDULUM TEST

PRINCIPLE: According to BS EN 13036-4:2011, the British Pendulum Tester includes a slider, which is spring-loaded and made of standard rubber mounted to the end of a pendulum arm. When the pendulum arm is released from a horizontal position, the slider assembly passes over the test surface and the energy loss is measured by the reduction in length of the upswing using a calibrated scale.

Figure 6: British Pendulum Tester

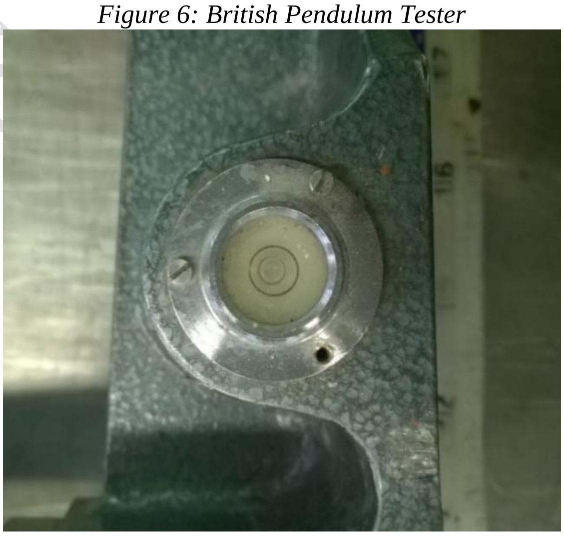

Figure 7: The Bubble adjuster of a BPT

Slider 55#61 was used for the test in this research. BS ISO 48:2007 lays out the conformities as follows –

Hardness:

Temperature	0°C	10°C	20°C	30°C	40°C
Hardness	54	54	54	54	54

LUPKE RESILIENCE: Chevalier Cleret (2013) defines Lupke Resilience of a vulcanised rubber as the very link between the energy restored by the material after deformation and the energy which had been provided to obtain the same deformation.According to BS ISO 4662:2009, the Lupke Resilience of slider 55#61 at different temperature is as follows –

Temperature	0°C	10°C	20°C	30°C	40°C
Resilience % (limits)	43-49	58-65	66-73	71-77	74-79
Resilience %	48	64	70	74	76

(mean results)						

BS EN 13036-4:2011 states that the slider should swing clear of the surface of the test specimen and the sliding distance should be of a fixed length of $126 \pm 1\ mm$. In this research, the sliding distance is taken as 127mm. A schematic diagram of the sliding distance is given below for the sake of visualisation of the action.

Also, the standard states that the slider assembly should be spring-loaded against the test surface of the specimen. The static force on the slider should be $22 \pm 0.5\ \mathrm{N}$. In this research, it is taken as 22N, and denoted by 'P'.

Calculation of 'μ'

The coefficient of friction, 'μ' is calculated using the following formula (refer to Fig.):

$$\mu = \frac{M(H-h)}{PL} \qquad (8)$$

where,

M = Effective weight of the swinging arm, 1.486 Kg

H = Initial height of the Centre of Gravity in released position

h = Height of the Centre of Gravity at the highest point of the swing after the slider has passed over the surface of the test specimen (as indicated by the pointer)

P = Static force on the slider, 22N

L = Sliding Distance.

In practice, the 'H' and 'h' were measured physically using a long ruler. 'H' is the height of the pendulum arm measured from the surface of the test specimen, whereas the 'h' is the height of the centre of gravity measured from the surface of the test specimen. Burlacu et al., 2013 say that the centre of gravity of the pendulum arm is the release catch itself and it is taken into account. Also, it is practically evident from the test that the pendulum arm swings as much as the pointer does and then strikes back the surface due to gravity, but on the other hand, the pointer stays as it is pointing the British Pendulum Number(BPN). So, it is indeed a fact that the pointer itself marks the height of centre of gravity after the swing – 'h' and is measured according to the BPN value obtained for individual specimens. This is one of the main factors which influences the calculation of 'μ'.

Retrieved Cores from the Site:

Water was sprayed over the surface of the test specimen so as to obtain the wet skid resistance, i.e., 'μ' (surface wet), but before that the specimens were tested dry to get 'μ' (surface dry). This was done so as to study the aims under two conditions of the specimen – dry and wet.

Example Calculation

The test specimen whose spacing of stones and stone size are 8mm and 17mm respectively, the 'H' is found to be 515mm, the BPN (surface wet) to be 71 and the corresponding 'h', 405mm (refer to Figure).

Therefore, from equations (3) and (6),

$$\mu = \frac{1.486 \times 9.81\ (515 - 406)}{22 \times 127}$$

$$= 0.57$$

'μ' for other samples with their respective variables is calculated in the same way as described above.

a. CORES RETRIEVED FROM SITE

No.	Spacing of Stones (in mm)	Stone Size (in mm)	BPN (dry)	BPN (wet)	μ (dry)	μ (wet)
1.	8	17	81	71	0.66	0.57
2.	6	18	76	60	0.62	0.51
3.	8	20	55	46	0.44	0.38
4.	6	18	93	70	0.75	0.58
5.	7	17	94	65	0.74	0.53
6.	4	12	74	67	0.60	0.50
7.	5	19	81	65	0.64	0.52
8.	4	17	90	79	0.70	0.63
9.	5	11	85	55	0.68	0.47
10.	8	15	64	41	0.53	0.35
11.	17	22	55	50	0.45	0.41
12.	11	20	84	62	0.66	0.50
13.	6	27	82	78	0.66	0.64
14.	4	11	86	72	0.72	0.59
15.	7	23	78	76	0.62	0.60
16.	4	13	75	65	0.61	0.53
17.	8	16	68	55	0.55	0.47
18.	7	15	66	61	0.54	0.50

Table 5- μ (dry and wet) calculated from BPN (dry and wet)

CALCULATION OF BRAKING DISTANCE (DF)

For retrieved cores and laboratory made slabs, DF has been calculated by the formula described in 6.11.2, given by Burlacu et al. (2013). The initial speed (V_i) and the final speed (V_f) were kept unchanged for each and every sample and were 70 Kmph and 0 Kmph respectively. The slope (*i*) is kept unchanged as well, and was 0% for all the cases. Therefore, the Braking Distance is calculated with only changing 'μ'. This point marks the criticality and significance of the friction coefficient in the calculation of DF.

Example Calculation

For the calculation of DF (wet and dry) of the first sample:

$$DF\ (dry) = \frac{V_i t}{3.6} + \frac{V_i^2 - V_f^2}{254(\mu_{dry} \pm i)}$$

$$= \frac{70 \times 2.5}{3.6} + \frac{70^2 - 0^2}{254\,(0.66 \pm 0)}$$

$$= 78 \text{ metres}$$

For all other samples (retrieved, laboratory made, dry and wet conditions), DF is calculated by the same equation with respective values of 'μ' (dry and wet).

No.	Spacing of Stones (in mm)	Stone Size (in mm)	BPN (dry)	BPN (wet)	DF in metre s(dry)	DF in metres (wet)
1.	8	17	81	71	78	82
2.	6	18	76	60	80	86
3.	8	20	55	46	92	99
4.	6	18	93	70	74	82
5.	7	17	94	65	75	85
6.	4	12	74	67	81	87
7.	5	19	81	65	79	86
8.	4	17	90	79	76	79

9.	5	11	85	55	77	90
10.	8	15	64	41	85	104
11.	17	22	55	50	91	96
12.	11	20	84	62	78	87
13.	6	27	82	78	78	79
14.	4	11	86	72	75	81
15.	7	23	78	76	80	81
16.	4	13	75	65	80	85
17.	8	16	68	55	84	90
18.	7	15	66	61	84	87

Table 6: Braking Distance (dry and wet) calculated from μ (dry and wet)

b. LABORATORY MADE SLABS

Aggregate Size (in mm)	Void Content (in %)	μ (dry)	μ (wet)	DF in metres (dry)	DF in metres (wet)
		0.64	0.56	79	83
	5	0.68	0.52	77	86
		0.68	0.52	77	86
14		0.65	0.59	78	81
	9	0.65	0.59	78	81
		0.62	0.59	80	81
		0.59	0.54	81	84
	13	0.59	0.54	81	84
		0.59	0.54	81	84
		0.77	0.61	74	80
	5	0.77	0.61	74	80
		0.77	0.61	74	80
10		0.73	0.55	75	84
	9	0.78	0.50	73	87
		0.78	0.50	73	87
		0.63	0.60	79	81
	13	0.65	0.60	78	81
		0.65	0.60	78	81
		0.68	0.60	77	81
	5	0.70	0.57	76	82
6		0.65	0.63	78	79
		0.75	0.57	74	81
	9	0.72	0.60	75	81
		0.69	0.60	77	81
		0.65	0.51	78	86
	13	0.67	0.52	77	86
		0.67	0.53	77	85

Table 7: Aggregate size, void content (%), μ (dry and wet), DF (dry and wet)

Two consecutive readings of BPN were recorded at two arbitrary points on the surface of each and every test sample with different AVC and then those two readings were averaged. This was repeated thrice per slab (hence, three values of μ in every case).

VIII. OBSERVATION AND ANALYSIS OF RESULTS

The results of 18 retrieved cores from the site and nine slabs made in laboratory offering coefficient of friction 'μ', Braking distance (DF) and Mean Texture Depth (MTD) have been presented in this chapter. It can be noticed from the tables of results (table 5 and table 6) that different aggregate size and aggregate spacing (edge-to-edge) offer different skid resistance (surface wet) in terms of 'μ', following a variation in DF.

A. RETRIEVED CORES

a. RELATIONSHIP BETWEEN 'DF', BPN AND 'μ'

As the combined observation for both the preliminary and the main tests, it is observed that 15 out of 18 cores have 'μ' as 0.50 and below. The rest three cores produced a friction coefficient of 0.60 and greater. The observation is made from the point of view of 'μ' depending on wet BPN and DF depending on wet BPN, and the resulting trend lines which turned up are good enough to justify that the increase in BPN increases the skid resistance of the surface (may it be wet or dry). It is also observed that the increase in BPN (surface wet) is beneficial for the roadways and pavements in terms of safety as that minimises the Braking Distance (DF).

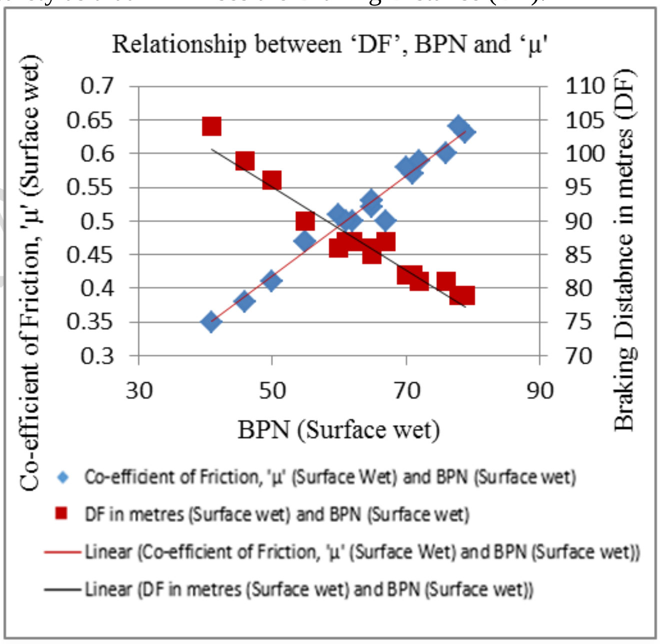

Figure 8: Relationship between 'DF', BPN and 'μ'

Though the normal trend of the UK so far is to measure the BPN and then consult the Highways agency specifications to declare a particular road safe or unsafe only in terms of BPN, this research pleads that calculating DF from 'μ' is also important for road safety.

b. THE RELATIONSHIP BETWEEN AGGREGATE SPACING, MAX. AGGREGATE SIZE AND 'μ'

This research focuses on the dependence of 'μ' on maximum aggregate size on the surface of the test samples and the edge-to-edge spacing between the aggregates. The results produced sensible trend lines. μ ranged from 0.35 to 0.64 depending on aggregate size and edge-to-edge spacing of aggregates. As observed from the results, for maximum samples, μ increased with the increase in aggregate size but

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some came up with anomalous behaviour and deviated from the fact that larger the aggregate size, more the skid resistance is. For example, for the sample with aggregate size of 15mm, μ was surprisingly 0.35, whereas, the sample with a stone size of 12mm produced μ as 0.50. From this observation, it could be said that though the aggregate size is an important factor which influences skid resistance, there are other factors as well which have an influence on surface friction. It could be said that possibly the polishing Stone Value (PSV) and the edge-to-edge spacing between aggregates are the very factors that are responsible for the anomalous behaviour of some specimens. The PSV test was not performed in this research, but the spacing of the aggregates on the surface of the test samples was taken into account.

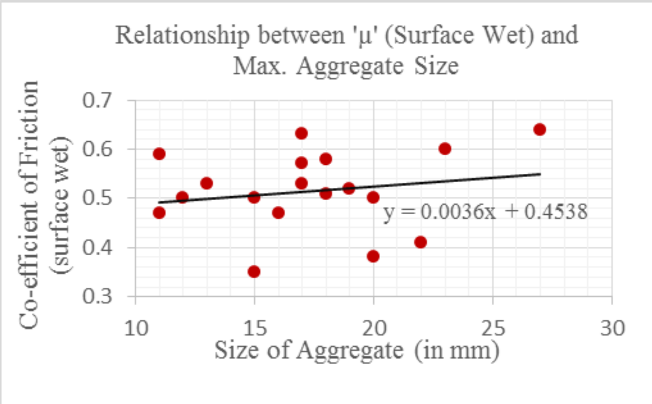

Figure 9: Relationship between 'μ' (Surface wet) and Max. Aggregate Size

The trend line of the result of μ depending on edge-to-edge spacing between aggregates was obtained and it was observed that in maximum cases, greater spacing led the decrease of skid resistance in terms of 'μ'. There again, there were some samples which showed anomalous behaviour. For example (refer to sample no. 9 of table-3), in the case of the sample with edge-to-edge spacing of 5mm produced a friction of coefficient (surface wet) of 0.47, whereas the sample with the spacing of 11mm produced a friction coefficient (surface wet) of 0.50. These results fail to justify the hypothesis that more the spacing is, worse the friction. But this was not the case for the dry surface of the same samples. The sample with 5mm spacing produced a friction coefficient of 0.68 and that with 11mm spacing produced 0.66.

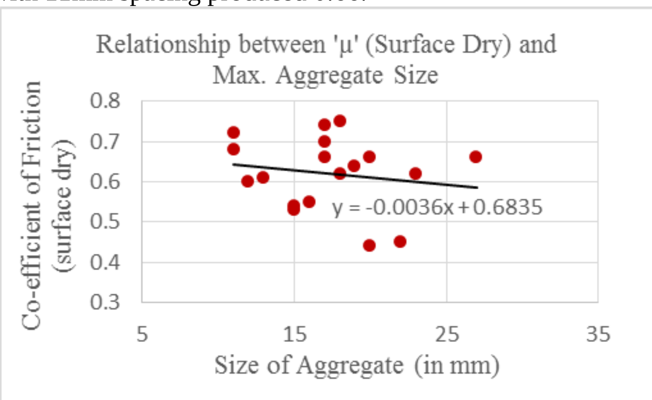

Figure 10: Relationship between Coefficient of Friction 'μ' (Surface Dry) and Size of Aggregates (edge-to-edge)

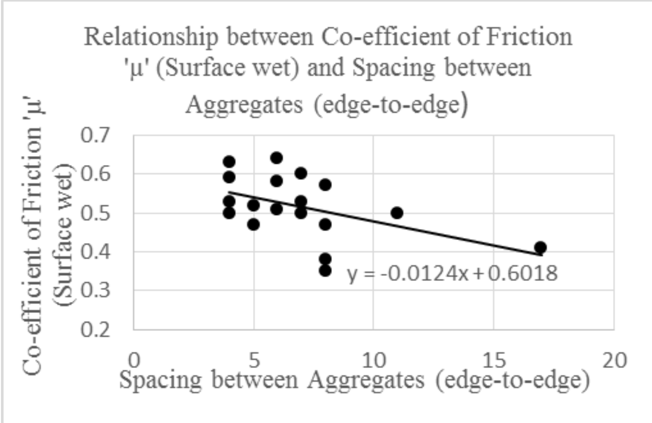

Figure 11: Relationship between Coefficient of Friction 'μ' (Surface wet) and Spacing between Aggregates (edge-to-edge)

It is speculated that it may be because the test (the swing of the pendulum in the case of BPT) was done in just two different points of the sample surface and not more. The Polishing Stone Value (PSV) is yet another factor that is speculated to be responsible for the unjustifiable behaviour of some samples. As the cores were collected randomly from an engineering company with no knowledge of their PSV, even a range of the same could not be comprehended. But, as the spacing of aggregates is not the sole factor that influences skid resistance, the maximum aggregate size on the surface comes in the picture. Considering the same example, the sample with an aggregate spacing of 5mm had a maximum aggregate size of 11mm and that of the sample with 11mm aggregate spacing was 20mm.

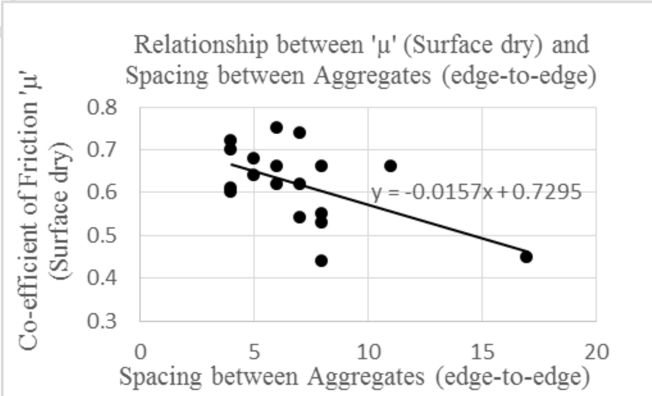

Figure 12: Relationship between Coefficient of Friction 'μ' (Surface dry) and Spacing between Aggregates (edge-to-edge)

For the case of 11mm aggregate spacing and 20mm aggregate size, in spite of having a considerably large spacing between aggregates, it is definitely the aggregate size that pushed up the wet skid resistance.There, the combined effect of the aggregate spacing and the aggregate size is noticed.

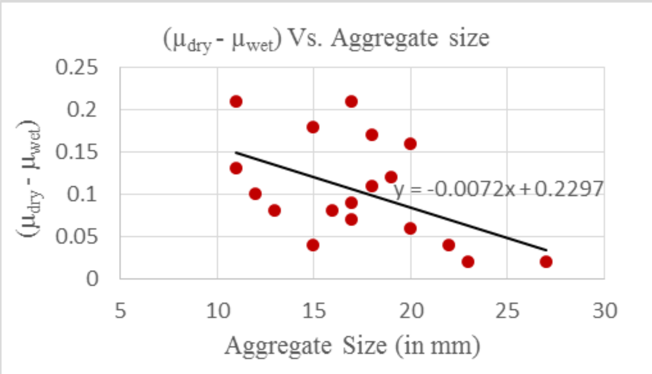

Figure 13: (µdry - µwet) Vs. Aggregate size

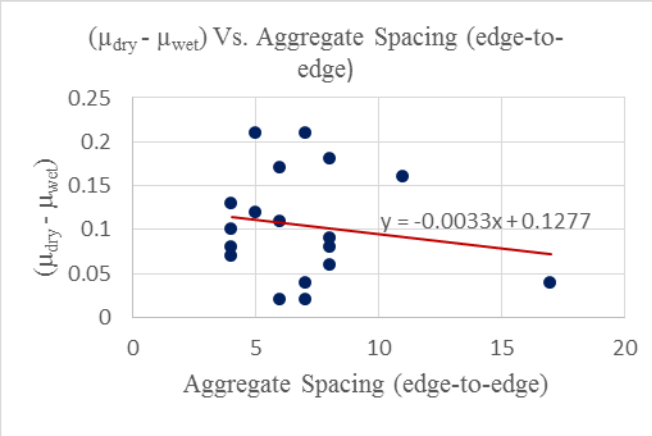

Figure 14: (µdry - µwet) Vs. Aggregate Spacing (edge-to-edge) in mm

c. *RELATIONSHIP BETWEEN COEFFICIENT OF FRICTION (µ) AND MTD (IN MM)*

A normal trend of increase in skid resistance (both wet and dry) in terms of coefficient of friction with an increase in Mean Texture Depth (MTD) was observed (see figure - 16), although the range was not too wide. Some specimens did show that to have high MTD alone does not make skid resistance better, but MTD too is dependent on aggregate size and spacing. Having large stone size quite obviously means high MTD, but there again, the spacing between the aggregates plays a crucial role in obtaining the same MTD. For example, in the case of the sample with aggregate size of 22mm and spacing of 17mm yielded an MTD of 0.776mm, whereas the sample with aggregate size of 11mm and spacing of 5mm yielded an MTD of 0.964mm. In fact, MTD influences the skid resistance drastically and it was observed that the results affect 'µ' both in dry and wet condition. The friction in dry and wet condition of the former one was 0.45 and 0.41 respectively and that of the latter one was 0.68 and 0.47 respectively. Though the maximum aggregate size of the former one was quite large compared to that of the latter one, the spacing of 17mm between the aggregates in the former one lowered down the friction than the latter one. It is definitely due to the reduced aggregate-tyre (slider in the case of BPT) interaction. The point here is to learn the contribution of not one alone but all the parameters in developing friction.

Thus, it could be noted that both the tests, i.e., British Pendulum and Sand Patch justify themselves to be related to each other in this dissertation.

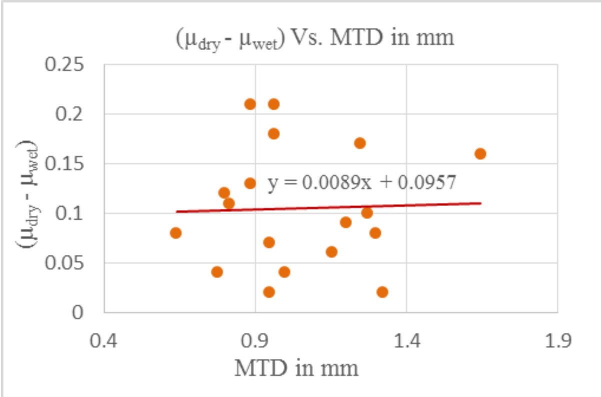

Figure 15: (µdry - µwet) Vs. MTD in mm

However, when the difference of dry and wet friction Vs. Aggregate Spacing (edge-to-edge) and MTD were plotted, no good relation was observed. The results were extremely scattered (refer to figure 14 and figure 15). Hence, they do not reveal anything specific or considerable.

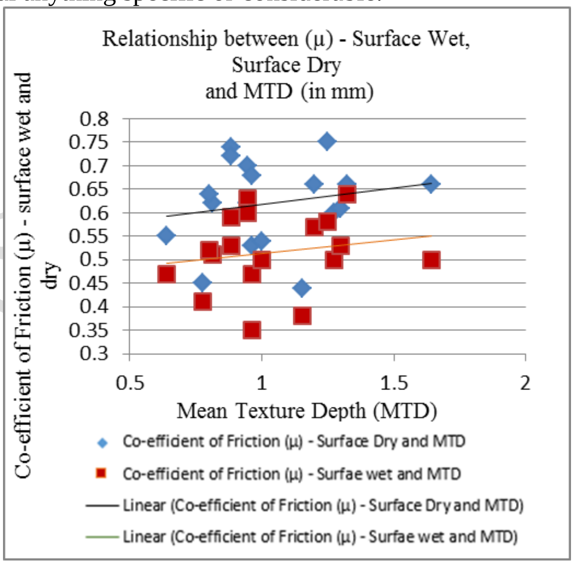

Figure 16: Relationship between Relationship between Coefficient of Friction (µ) - Surface Wet, Surface Dry and MTD (in mm) for Cores retrieved from site

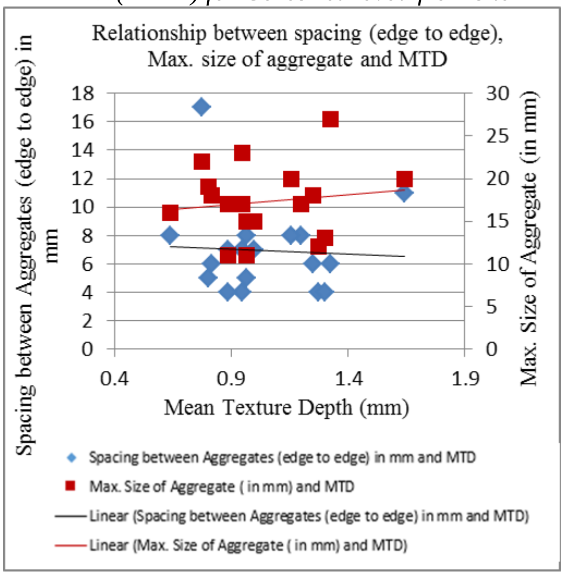

Figure 17: Relationship between spacing (edge to edge), Max. Size of aggregate and MTD

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B. LABORATORY MADE SLABS

a. THE RELATIONSHIP BETWEEN MAX. AGGREGATE SIZE AND 'µ'

The relationship that was obtained between Aggregate Size and 'µ' (surface wet) is rather complex. The friction in wet condition offered by the asphalt slabs with 14mm graded aggregates ranged from 0.52 to 0.59 across different void contents, which is surprisingly low for 14mm aggregates. Whereas, in the case of 10mm aggregates, it ranged from 0.50 to 0.61, which is because the 10mm gradation used was more compact than 14mm. The 10mm graded aggregates with considerable use of stone size between 8-10mm and 6-8mm, and adequate use of 4-6.3mm and 10-14mm made it equally skid resistant to the slabs with 14mm gradation. That is because the constant contact between the tyre (slider in case of BPT) and the stones help maintain the adequate friction, which on the other hand the slabs with 14mm aggregate gradation were lacking. In 14mm aggregate gradations, the mixes used up around 47% of stones alone between 10mm-14mm, while the other sizes of stone present in the mixes were awfully less in quantity. The large difference in stone sizes, that too with very little quantity of 4mm, 6.3mm and 8mm stones reduced the constant interaction between trye and the surface, and hence, reduced the friction. The friction co-efficient for 6mm aggregates ranged from 0.51 to 0.63. There again, the tyre-surface interaction was good enough to yield an acceptable range of friction. It was noted that the mixes with 6mm aggregate gradation used nearly 30% of stones ranging between 4-6.3mm, with an adequate amount of stones ranging from 2.8-4mm and 6.3-8mm.

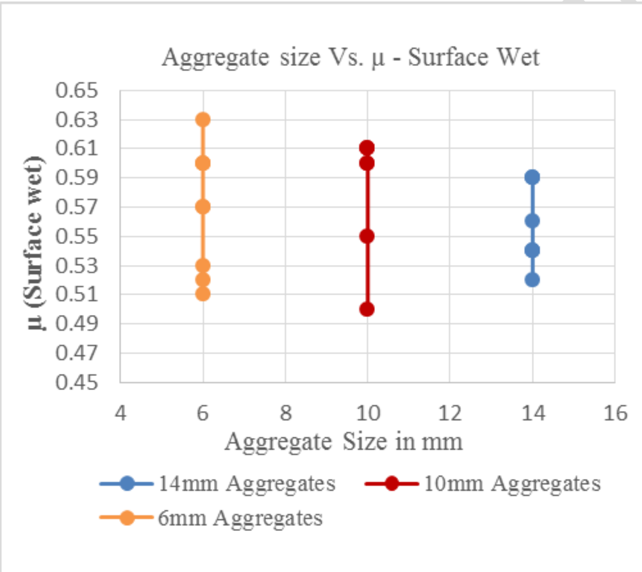

Figure 18: Aggregate Size Vs. 'µ' - Surface Wet for Lab made slabs

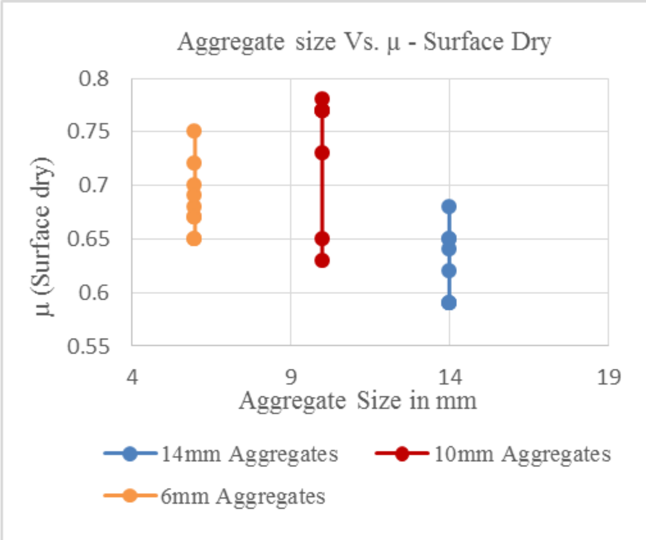

Figure 19: Aggregate Size Vs. µ - Surface Dry for Lab made slabs

In dry condition, almost similar thing was observed as it was in the case of wet condition. The friction coefficient of 14mm graded aggregates ranged from 0.59 to 0.68, whereas that of 10mm and 6mm graded ranged from 0.63 to 0.78 and 0.65 to 0.75 respectively. In here as well, the same explanation applies. However, the effect of water is noteworthy in wet condition. There, the surface of the slabs was lubricated due to water and hence, the friction fell down. The difference between friction in dry condition and friction in wet condition for 14mm, 10mm and 6mm ranged 0.07 to 0.09, 0.13 to 0.17, and 0.14 to 0.12 respectively. This indicates that the water film affected the 10mm and 6mm stones much more compared to 14mm stone grading. This is because of the fact that the big difference in stone size (as discussed earlier) made 14mm stone slabs more porous compared to 10mm and 6mm, and hence helped in drainage. So, the effect of water reduced and the friction in wet condition obtained actually was very close to that in dry, as observed.

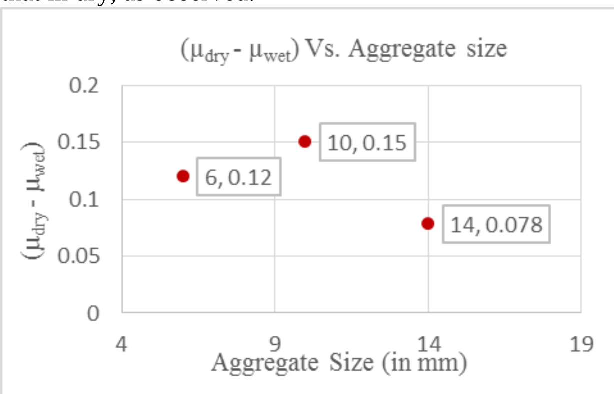

Figure 20: (μ_{dry} - μ_{wet}) Vs. Aggregate size for laboratory made samples

For the figure above, (μ_{dry} - μ_{wet}) for each aggregate size is calculated by averaging (μ_{dry} - μ_{wet}) across all the readings corresponding to all the void contents. The purpose of that is to account only for stone size in this case, and not void content (refer to table 4).

a. EFFECT OF VOID CONTENT

The tests revealed an intricate set of results when the effect of void content on surface friction was investigated. As discussed earlier, the slabs were manufactured with different AVC (5%, 9% and 13%), along with different aggregate size gradations (14mm, 10mm and 6mm). As void content influences spacing between aggregates (Hassn et al., 2016), the concept of void content was taken into consideration to study the effect of spacing between aggregates in the slabs. Tests were done in both dry and wet conditions. However, all the set of results were not in line with the theory that the spacing between aggregates reduces road surface friction.

In the case of 14mm aggregates in dry condition, when three readings of friction co-efficient after British Pendulum Test for each slab were averaged, the friction coefficient fell from 0.67 to 0.64 for 5% and 9% respectively, and then to 0.59 for 13%. These readings were absolutely justifiable. The 10mm aggregates yielded even more consistent results. From an average of 0.77 for 5%, the friction coefficient fell down to 0.76 for 9% and then further down to 0.64.

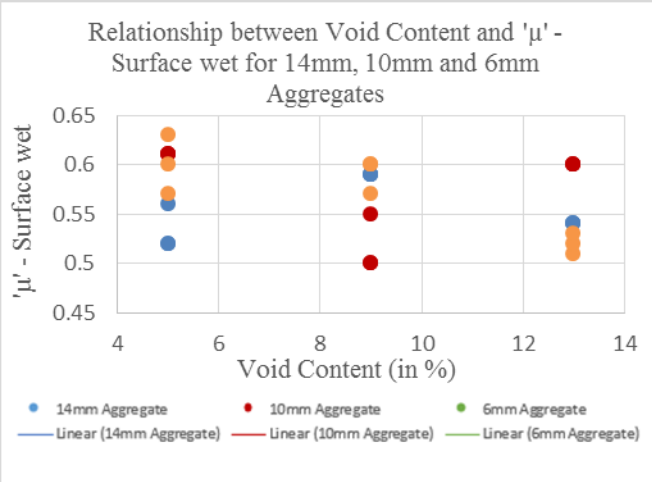

Figure 21: Relationship between Void Content and 'μ' – Surface Wet for 14mm, 10mm and 6mm Aggregates

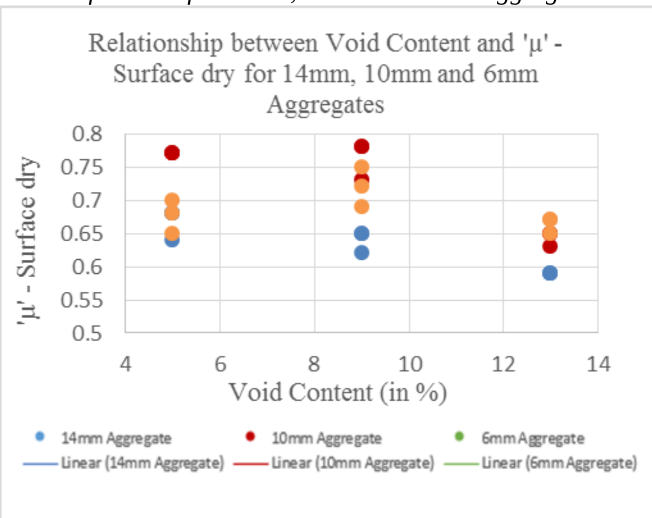

Figure 22: Relationship between Void Content and 'μ' – Surface dry for 14mm, 10mm and 6mm Aggregates

The reason why the coefficient of friction was much greater in the case of 10mm aggregates than 14mm is discussed, nevertheless, the effect of void ratio was clear – more the AVC, more the spacing, and hence, less the friction. On the other hand, the 6mm aggregates showed complex results. The average of the three readings of friction co-efficient for 5% AVC was 0.68, that of 9% AVC was 0.72, and that of 13% was 0.66. It was observed that this was the only case where the intermediate reading (9% AVC) rose up from that of 5% AVC to 0.72, and fell down again to 0.66. It could be explained that the former trend is due to the testing of specimens at only two points of the specimens, and not more than that. Had it been tested at more than two points, results might have come slightly different. The latter trend that was observed is definitely due to the increase in AVC, which reduced the interaction, and followingly, the friction.

In wet condition, a different trend was observed. Amongst 14mm, 10mm and 6mm, only the 6mm aggregate slabs showed consistent results, i.e., friction fell with an increase in AVC. For 14mm aggregates with 5% AVC, an average friction coefficient of 0.53 was obtained. The one with 9% AVC inflated slightly to 0.59, and then fell down to 0.54 for 13% AVC. The one with 10mm aggregate and 5% AVC yielded a friction coefficient of 0.61, then fell down to 0.50 for 9%, and finally accounted 0.60 for 13% AVC. This is likely due to the texture variation within the aggregates.

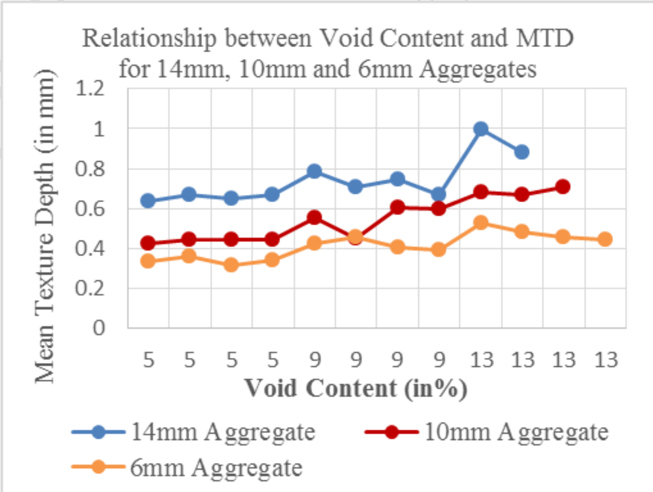

Figure 23: Relationship between Void Content and MTD for 14mm, 10mm, and 6mm Aggregates

As Masad et al., 2007 in his research found out the fact that aggregate shape and aggregate type (source) can indeed be significant in affecting skid resistance, it could be said, that for 10mm aggregate with 9% AVC that particular aggregate shape did not favour the skid resistance and along with the lubrication due to water, worsened it. But in the case of 6mm aggregate slabs, with truly compacted mix, the increase in AVC at an intermediate stage (9%) drained the water well and hence, the friction rose up from 0.53 to 0.59. But, in the case of the one with 13% AVC, the percentage of air voids proved to be little too much and along with the effect of smaller stone size (6mm) and lubrication due to water, lowered down the friction from 0.59 to 0.54.

b. EFFECT OF MEAN TEXTURE DEPTH

As observed in figure 25 and figure 26, with an MTD value of 0.55 for both wet and dry conditions, the 10mm aggregate slabs yielded the highest wet and dry friction of 0.57 and 0.72 respectively amongst 14mm, 10mm and 6mm aggregate slabs, when averaged across the values corresponding to 5%, 9% and 13% AVC. It is likely due to the orientation of the aggregates with favourable grading, rather than the Texture Depth that helped achieve a good friction. For 14mm and 6mm aggregates, although they have had revealed a drastic difference in the MTD, yielded similar friction coefficient in wet condition. this is probably again due to the orientation of the aggregates on the surface layer. It could be explained as, for 14mm aggregate slabs, due to testing at only two points, the pendulum of BPT swung clear at those points on the surface of the slab lacking interaction, which was exactly opposite in the case of 6mm aggregate slabs in dry condition. Despite 6mm aggregate slabs having considerably low MTD, offered friction which is equal to that of 14mm aggregate slabs, likely due to adequately good gradation. As a matter of fact, although the highest MTD was obtained in the case of 14mm aggregate slabs, their friction was the lowest in both dry and wet condition, which indicates that MTD is not the sole factor in increasing friction. The observations suggest that MTD did not have much effect on the friction in the lab made slabs, until the effect of water was studied. The (μ_{dry}-μ_{wet}) against MTD for 14mm, 10mm and 6mm indicate that the most affected are the 10mm aggregate slabs, and the least are the 14mm ones with highest texture depth (figure 24). Hence, MTD does have an impact on developing friction, which, in terms of water effect is noteworthy. It could ideally be said, that 14mm is certainly a choice because it retained the highest MTD (high MTD is good for skid resistance, as the theory suggests and that the effect of water is much lower), yet 10mm aggregates could also be used. For figure 26, MTD and (µdry-µwet) for 14mm, 10mm and 6mm slabs are averaged across all the values corresponding to all the void contents (refer to table 4).

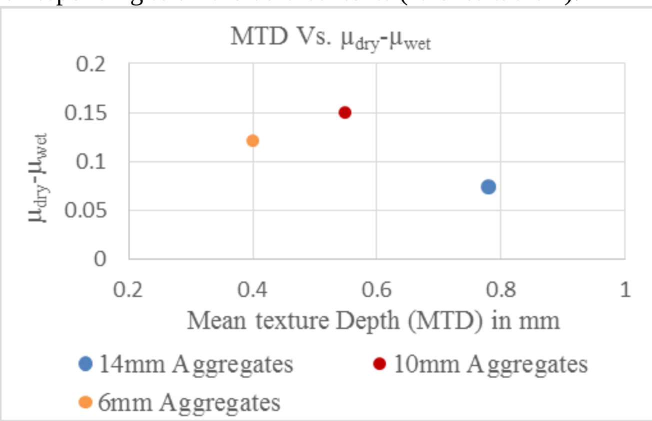

Figure 24: (μ_{dry} - μ_{wet}) Vs. MTD for laboratory made slabs

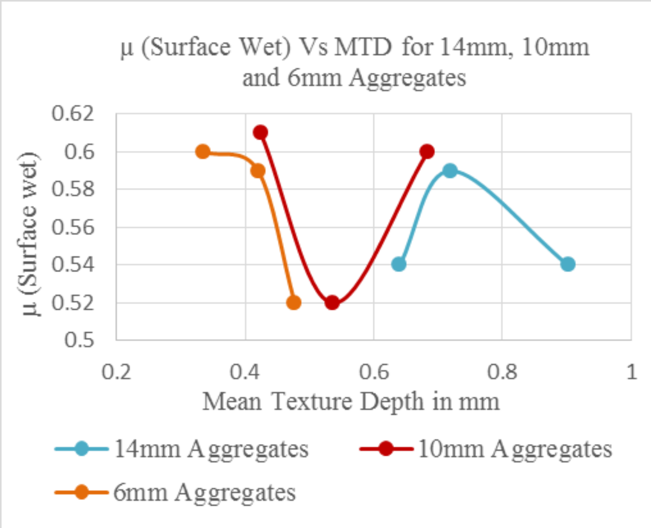

Figure 25: Coefficient of Friction (µ) - Surface Wet Vs MTD for 14mm, 10mm, and 6mm Aggregates

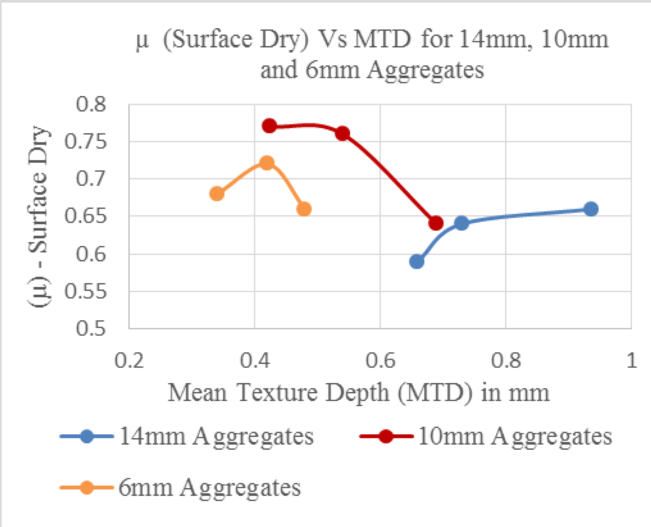

Figure 26: Coefficient of Friction (µ) - Surface Dry Vs MTD for 14mm, 10mm, and 6mm Aggregates

In figure 25 and figure 26, each point of each sample curve (14mm, 10mm, and 6mm) denotes the average of µ and MTD across each void content (5%, 9%, and 13%). Refer to table 4 and table 7.

IX. LIMITATIONS OF THE TEST

The British Pendulum Test was performed on the slabs at only two points on the surface of the slabs, and then the readings were averaged. But, in few cases, the value of friction coefficient corresponding to MTD did not come up as it was speculated from the axioms. Hence, it could only be explained that due to the lack of variation of testing points, the results showed a discrepancy in those few cases.

Another major problem was to accurately maintain the sliding distance of 127mm of the pendulum. Due to the complex setup of the machine, this sliding distance could not be maintained accurately at first go. In some cases, the pendulum arm swung too much clear off the surface of the cores, and in some cases, got stuck unnecessarily, which led to the misleading reading of the British Pendulum Number. For this, there was no such reason other than the inaccurate affair of installation of the tester. Hence, those readings were discarded, and the tester was re-installed with utmost accuracy and caution.

Figure 27: The Sliding Distance of 127mm

X. CONCLUSIONS

A. GENERAL

This project is a physical analysis of road cores and laboratory made samples using an apparatus called British Pendulum Tester and a low technology test - Sand Patch. Though Sand Patch is a low technology test, it is one of the most widely performed test to account for macrotexture, and hence reliable, as described in the literature. The study focuses on the effects of the following parameters on Skid Resistance of asphalt pavements:

- ✓ Stone (aggregate) size.
- ✓ Aggregate spacing (edge-to-edge).
- ✓ Mean Texture Depth (MTD).
- ✓ Void content.
- ✓ The combination of aggregate gap and size.

Preliminary tests were performed beforehand to understand the mechanisms affecting the measurement of the micro and macrotexture by BPT and Sand Patch Test respectively.

B. FINAL REMARKS

The tests revealed a mix of consistent and inconsistent results. As the cores retrieved from site were randomly chosen and there was no pre-knowledge of the asphalt mix, from the results, it can be concluded that the Skid Resistance of any type of asphalt mix usually increase with increasing aggregate size and decreasing edge-to-edge spacing. Though in some cases results were deviating which is suspected due to testing at one point on the surface of the cores. From the results, the exact favourable and viable aggregate size and spacing (edge-to-edge) could not be suggested as in some cases smaller stone size with bigger spacing yielded high friction. To investigate the effect of water, graphical representations of the difference between μ_{dry} and μ_{wet} against parameters like aggregate size, spacing (edge-to-edge) and MTD were studied. The considerable effect of water could only be observed in the case of aggregate size, where it was revealed that smaller the aggregate size, larger the effect of water on Skid Resistance. A normal trend of increase in skid resistance (both wet and dry) in terms of coefficient of friction with an increase in Mean Texture Depth (MTD) was observed although the range was not too wide. Some specimens do show that to have high MTD alone does not make skid resistance better, but MTD too is dependent on aggregate size and spacing.

When laboratory made samples with varying AVC were studied, it was found that the water film affected the 10mm and 6mm stones much more compared to 14mm stone grading. The readings obtained in dry condition, are absolutely justifiable, i.e., more the AVC, more the spacing, and hence, less the friction. The 10mm aggregates yielded even more consistent results. From an average of 0.77 for 5%, the friction coefficient fell down to 0.76 for 9% and then further down to 0.64. In some cases, the testing at only two points misled the results. In wet condition, only the 6mm aggregate slabs showed consistent results, i.e., friction fell with an increase in AVC. For both wet and dry conditions, as observed, with an MTD value of 0.55, the 10mm aggregate slabs yielded the highest wet and dry friction of 0.57 and 0.72 respectively amongst 14mm, 10mm and 6mm aggregate slabs, when averaged across the values corresponding to 5%, 9% and 13% AVC.

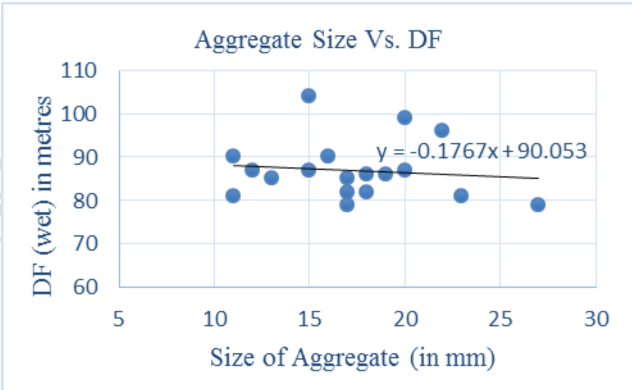

Figure 28: Relationship between Aggregate Size and DF (surface wet) for retrieved cores

The observations suggest that MTD did not have much effect on the friction in the lab made slabs until (μ_{dry}-μ_{wet}) was plotted against MTD for 14mm, 10mm and 6mm, which indicates that the water affected 10mm aggregate slabs the most, and the least are the 14mm ones (51% lesser than 10mm and 39% lesser than 6mm) with highest texture depth (figure 30). Hence, it is observed that MTD does have an impact in developing friction, which, in terms of water effect is noteworthy. As the Braking Distance (DF) has been calculated with only varying 'μ', it got accordingly reflected. Very obviously, for all retrieved cores and laboratory made slabs, more the friction is, lesser is the DF. Good correlation was observed between aggregate spacing (edge-to-edge), aggregate size and DF, i.e., DF reduced with the increase of aggregate size and decrease of aggregate spacing, although some samples have come up with unexpected results (see figure 28 and figure 29).

Therefore, it could be justified that larger aggregate size and smaller edge-to-edge spacing between aggregates are favourable and should be preferred. As all the parameters (aggregate size, edge-to-edge spacing, MTD and gradation) account for the texture of an asphalt surface as a whole, the effect of surface texture has been studied in this research, splitting the vast concept into different aspects.

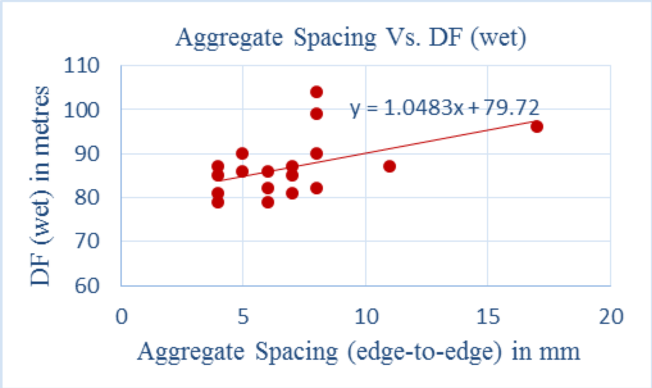

Figure 29: Relationship between Aggregate spacing (edge-to-edge) and DF (surface wet) for retrieved cores

XI. RECOMMENDATIONS FOR FUTURE WORK

Nearing the end of this research and after completing it, I felt the need of the following as future work in the area of skid resistance on asphalt pavements and would recommend:

- ✓ To study the effect of various tyre tread depth on skid resistance, which was not studied in this research. Hence, it needs to be studied to extend research on skid resistance of asphalt pavements.
- ✓ Image analysis of the test samples, which would help to increase the accuracy in the calculation of aggregate size and spacing between aggregates (edge-to-edge or centre-to-centre).
- ✓ The tests in this research are done at 25°C, hence, to study the effect of temperature of pavements on skid resistance, further tests need to be carried out at various temperatures.
- ✓ The effect of aggregate shape was not considered in this research. So, it is recommended to carry out further research taking aggregate shape (angularity and flakiness) into account.
- ✓ Tests should also be performed on roadways where traffic is present. Also, the effect of various speeds should be considered.

Last but not the least, it is recommended that British Pendulum Tests should be performed at minimum five points on the test sample.

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