Development of a Fundamental Skid Resistance Asphalt Mix Design Procedure

Sullivan, B.W. [1]

[1] *Pavement Management Service, Sydney, Australia*

ABSTRACT

Traditionally, when designing asphalt mixtures for skid resistance, designers have relied upon two measures: the Polished Stone Value (Polished Aggregate Friction Value), and the mixture gradation type. However, the use of these arbitrary measures can and have, somewhat clouded the fundamental issues related to skid resistance, of whether a vehicle can stop in the required time/distance or whether a vehicle can negotiate a curve safely.

Recently a method has been developed and published that uses the International Friction Index (IFI) to determine a design vehicles stopping distance and potential for loss of control. This method relies on the use of the both the International Friction Index macro and micro-texture measurements of a pavement surface to calculate a vehicle stopping distance requirements.

This paper presents a method for estimating the macro-texture in terms of the Mean Profile Depth determined from the aggregate gradation and binder content, with the micro-texture determined from the Polished Aggregate Friction Value (PAFV) of the coarse aggregate.

The measured Polished Aggregate Friction Value and the determined Mean Profile Depth are then used in terms of the International Friction Index macro and micro-texture measurements along with the International Friction Index, friction curve, to determine the calculated design stopping distance. An iterative procedure is then used to determine the required combination of both macro and micro-texture required to meet stopping distance requirements; these values are then used to determine the required aggregate type and gradation and binder content for the asphalt surfacing layer.

1 INTRODUCTION

With the increasing realization that pavement surface characteristics play an important part in road safety more agencies are specifying minimum requirements for surface friction, in most cases these requirements are specified in terms of surface macro texture and surface micro texture. For example New Zealand now requires that all surfaces placed on the National Highway system have a surface texture of at least 0.6mm, while most agencies specify a minimum micro texture of the aggregate in terms of the polished stone value, or the polished aggregate friction value. However, the use of these arbitrary measures can and have, somewhat clouded the fundamental issues related to skid resistance, of whether a vehicle can stop in the required time/distance or whether a vehicle can negotiate a curve safely. Additionally, the use of these arbitrary specifications are leading to the limiting of asphalt surfacing that is available to the engineer to maintain pavements, leading to increased construction and maintenance cost. Furthermore the use of more open graded mixtures required by these standards means that less stability is achieved by the aggregate skeleton, which in-turn leads to a less durable mix than standard dense graded mixtures.

Recently a method has been developed and published that uses the International Friction Index (IFI) to determine a design vehicles stopping distance and potential for loss of control. This method relies on the use of the both the International Friction Index macro and micro-texture measurements of a pavement surface to calculate a vehicle stopping distance requirements. As this method can be used to calculate the required stopping distance it is proposed that a design stopping distance be used to cover the design of both, macro and microtexture requirements of asphalt mixtures, rather than specifying both. The advantage of this method is that a lack of macro-texture can be substituted by increasing micro-texture and vice-versa giving significantly more options to the maintenance engineer.

For design of asphalt mixtures it is proposed to incorporate the macro-texture in terms of the Mean Profile Depth (MPD) determined from the aggregate gradation and binder content, with the micro-texture determined from the Polished Aggregate Friction Value (PAFV) of the coarse aggregate. An iterative procedure is then used to determine the combination of macro and microtexture required for meeting the stopping distance requirements, these values are then used to determine the required aggregate type and gradation and binder content, in the design process.

2 THEORETICAL BACKGROUND

2.1 FRICTION

It well known and has been established that to develop friction between a tyre and a road surface it is necessary to first displace the lubrication water film that is between them. As identified by Galloway[1] The displacement of this water can be broken into two phases:

1. The bulk removal of water through both the, tyre tread and drainage channels in the surface itself. Obviously, this is a time dependant and is related to the size of the drainage channels.

2. The penetration of the remaining water film by high pressure at the asperities of the fine texture of the surface aggregate.

The friction forces between the two surfaces is then developed by two principal components:

1. Shearing of adhesion developed between the tyre and the road surface. In this process the adhesion between the tyre and the road surface needs to be broken by shearing forces and it is these shearing forces that give rise to friction. The adhesion developed between the contact points between the tyre and the road surface, is the normal form of friction between two surfaces.

2. Energy loss through inelastic deformation of the tyre rubber (Hysteresis energy loss), for this type of energy loss it is not necessary for the surface to come into contact. A coarse macro texture generally produces large deformations and thus, larger amounts of energy loss. For this energy loss there may not necessarily be contact between the tyre and pavement surface.

2.1.1 International Friction Index Equation

In the early 1990's the PIARC harmonization experiment [2] developed a method by which the effect of increasing water film thickness (as a function of texture) could be used to determine the reduction in available effective friction as a function of the surface-tyre slip speed. This equation is shown following:

$$\mu_i = \mu_{60} e^{(\frac{60 - v_i}{Sp})}$$

Where:

- μ_i is the coefficient of friction at slip speed v_i
- Sp is the speed constant, which is directly related surface macro-texture
- μ_{60} is the coefficient of friction at a slip speed of 60km/hr

The advantage of this equation is that coefficient of friction at any slip speed can be obtained.

2.2 USING THE IFI VALUES TO DETERMINE STOPPING DISTANCE

Recently Sullivan [3] published a method that uses the IFI Friction model to calculate vehicle-stopping distance under a "panic" braking situation (i.e. full wheel lock). In this process the slip speed, v_i , is equal to the vehicle speed.

By then Using the IFI equation and the equations of motion, the distance traveled in the interval *(ds),* for small velocity change (*dv*) can be found, (simplifying by assuming constant friction across the small interval), is given by.

$$ds = \frac{vdv - dv^2}{g\mu_{60} e^{(\frac{60 - v}{Sp})}}$$

The total stopping distance for a vehicle at any given initial speed can then be solved by numerical integration between the initial vehicle speed and zero.

2.3 ASPHALT MIXTURE DESIGN AND MACRO AND MICRO-TEXTURE

2.3.1 Traditional Approach to Incorporating Friction in Asphalt Design

As shown previously the design of asphalt mixtures for fiction in terms of stopping distance requires the use of both a macro and micro-texture measurement. Traditionally, when designing asphalt mixtures for skid resistance, designers have relied upon two measures for both micro and macro-texture: an accelerated laboratory aggregate polishing test, the Polished Stone Value (PSV) or Polished Aggregate Friction Value (AFV), and adjusting the mixture gradation type.

The PSV is a accelerated laboratory test that is designed to simulate the polishing of coarse aggregate by traffic on the road. It has been shown by numerous researchers, such as a study by the TRRL[4], that the PSV relates very well to in-service low speed friction values.

Currently there is no test to determine in-service texture of an asphalt mixture in the laboratory, therefore, the design for texture is typically based on historical information from the typical textures achieved from dense, gap or open graded aggregate gradation. The major disadvantage of this method is that the designer is not able to see if small changes in gradation and/or binder contents will effect texture requirements, this is especially important if there are specifications in place, so the designer tends to err on the side of safety and designs a more open gradation and thus a less durable mixture.

2.3.2 Aggregate Gradation

Aggregate gradation affects nearly all aspects of asphalt design from stability to modulus and most importantly for the purpose of this paper, the surface texture; coarser gradations create more Voids in the Mineral Aggregate (VMA) which leads to a less regular surface texture. Ideally for every aggregate source there is a gradation that will produce a maximum density and have air voids approaching zero and thus texture measurements approaching zero. Any deviation from this maximum density will then produce a mixture with a higher VMA, as the matrix will be less dense which in turn produces higher texture.

Numerous researches have proposed an ideal gradation for maximum density, of these probably the most widely known and used is Fullers curve proposed by work completed by Fuller and Thompson [5]. The equation for Fullers maximum density curve is:

$$P = 100\left(\frac{d}{D}\right)^n$$

Where d is the diameter of the sieve size, D is the maximum size of the aggregate in the mix and P is the percent passing the sieve or the percent finer than the sieve diameter.

The studies of Fuller and Thompson [5] suggested the power coefficient, n, should be 0.5 when maximum density is achieved. In the 1960’s the American FHWA modified Fullers curve and suggested a value of 0.45 for the power coefficient, this value has now became the standard to compare all gradations.

As suggested any move away from the maximum gradation will produce a higher VMA and thus higher surface texture for a given asphalt volume, however, any move away from the maximum density line will also produce a less stable mixture, which needs to be considered in the design process.

2.3.3 Affect of Change in Gradation on Asphalt Properties

When designing asphalt mixtures care must be taken to ensure the chosen gradation will provide sufficient VMA, so that the binder content needed for durability will not cause bleeding problems and mixture stability problems, this level is commonly referred to as the critical air void level. It has been empirically known for some period and has been recently shown experimentally by Sullivan[6] that this critical air void level is typically below 3%, at air void levels below this the stability of asphalt mixtures significantly decreases. This is why mixtures produced at the maximum density line should be avoided. Ideally, a design asphalt mixture will need to have at least 4%, at refusal or maximum gyrations, to limit bleeding and ensure mixture stability in the field. However, to meet stopping distance requirements most likely any mixture will need to have a target air voids significantly higher than the critical air void content. As a mixture near the maximum density line, would tend to produce a texture in the vicinity of 0.3-0.4mm and would need to be compensated for with a significantly higher PSV.

While design of asphalt mixtures for friction requirements will most likely not involve mixtures near the critical air void level, It can not be emphasized enough that any movement of the mix gradation away from the maximum density line to increase texture, it will also increase air voids in the mixture, which in turn: reduces mix stability, increases aging, increases permeability and reduces fatigue life. Therefore, when designing an asphalt mixture, for friction, any significant departure from the maximum density line will need to be compensated for by changing binder contents and/or changing binder grades. While this is of no concern in the US where there are over 20 binder grades available and less of a concern in Australia, this presents a significant problem in New Zealand, which is limited to practically one binder grade. Therefore, if the regulatory authorities are going to continue to specify higher texture requirements, to obtain the stability and durability from the asphalt mixture a larger range of binders will need to be made available.

This concept is demonstrated in Figure 1 following, which schematically shows the effect of changes in the VMA on the asphalt mixtures properties. It is all of these effects need to be to be considered when changing mixture gradations and weighed up against the required performance. In the figure the arrow indicates the increasing tendency of the material property.

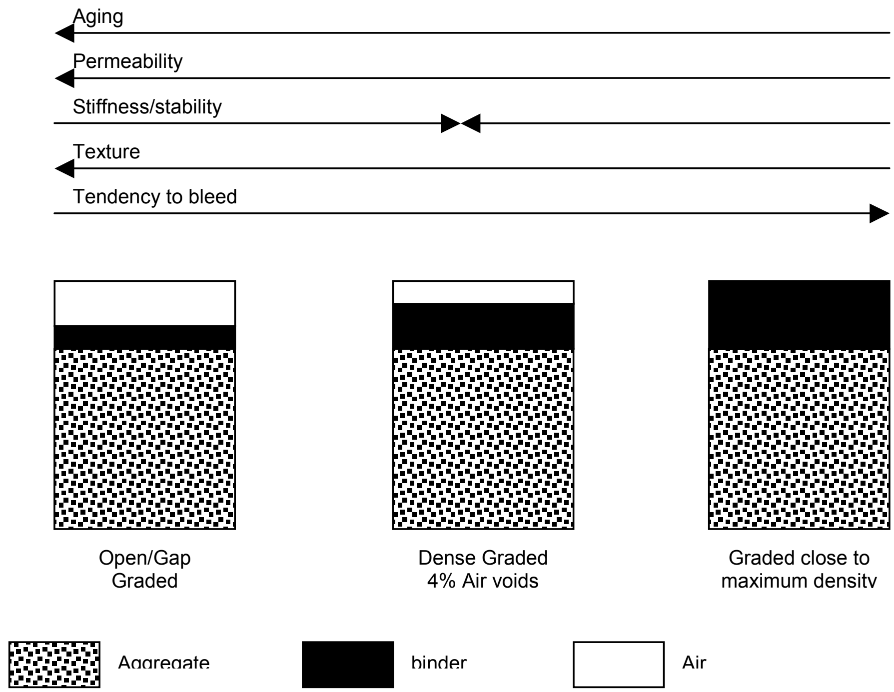

Figure 1 Phase Diagrams

2.3.4 Binder Effects on Texture

As introduced previously, the addition of higher binder contents into asphalt mixtures has the effect of filling more of the VMA, and thus, higher binder contents will produce lower textured mixtures as surface irregularities are smoothed out by binder.

Thus any method used to predict in service surface texture measurements from the mixture volumetric's must also have some measure of the binder volume. Ideally, this would be percent effective binder by volume (total minus the % absorbed), however, the standard still predominating in the asphalt industry is the percent binder by weight, and will therefore to be used in the interim to estimate in service binder content.

Conceptually the approach should be to take the volume of effective binder away from the voids in the mineral aggregate, corrected by some constant.

3 METHOD FOR DETERMINING THE REQUIRED MIXTURES MACRO AND MICRO-TEXTURE

3.1 ESTIMATING IN-SERVICE ASPHALT MICRO TEXTURE

As previously mentioned the most common method in place for determining the micro texture of an asphalt mixture is based on polished aggregate testing, either PSV or PAFV. This test is designed to simulate the polishing of an aggregates fine texture in service and has been found to correlate well to in-service low speed texture measurements.

3.2 ESTIMATING TEXTURE DEPTH FROM MIX GRADATION AND BINDER CONTENT

As previously mentioned there is currently no laboratory test to predict in service texture measurements it was therefore decided to investigate the effect of mix gradation and binder content on the in-service surface texture measurements from 17 of the 46 NCAT accelerated pavement performance site test cells.

3.2.1 NCAT Test Track

The NCAT test track is an accelerated loading facility constructed near Auburn, Alabama. The NCAT test track consisted of 46 mixes on a 1.7 mile oval installed in 200ft test sections, to facilitate meaningful field performance comparisons, between laboratory testing conducted on samples made before, during and after construction to facilitate practical lab to field performance correlations.

For the field validation of the proposed methodology; seventeen NCAT test mixture were used to assess the validity of predicting in place surface texture from both mix gradation and binder content. The NCAT test sections used are shown in Table 1 following, for the dense graded asphalt mixtures three typical gradations were used:

- Through the restricted zone (TRZ),
- above the restricted zone (ARZ)
- and, below the restricted zone (BRZ).

Additionally, stone mastic asphalts (SMA) and open graded mixtures were examined. All binders used in the asphalt were Superpave performance graded binders. The PG76-22 and the PG70-28 binders were modified asphalt binders. Table 2 lists the mixture properties (Air Voids and Binder Content), binder type, mix gradations and the mixture design method used for each test cell.

Table 1 NCAT Mixture Gradations

	PERCENT PASSING										
US	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Metric	25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.074
E4	100	100	95	75	42	29	23	18	13	8	4.6
E9	100	100	97	85	64	49	36	27	18	10	5.2
N1	100	100	100	92	69	52	33	22	15	10	6.7
N11	100	100	97	80	52	37	30	24	18	11	7.2
N12	100	100	96	73	32	23	21	19	17	14	11.8
N13	100	100	99	74	30	25	23	21	17	13	11.5
N3	100	100	99	91	68	51	33	22	15	10	6.5
N5	100	100	99	84	52	38	26	18	14	11	8.3
N7	100	100	98	83	52	36	24	17	13	10	7.8
N9	100	100	99	87	57	40	26	19	14	11	8.8
S2	100	100	100	96	67	41	29	22	15	10	8.4
S6	100	100	95	87	74	53	41	33	24	12	5.9
W2	100	100	98	77	35	24	17	15	13	12	10.7
W3	100	100	98	68	19	13	11	10	9	8	6.8
W4	100	100	95	66	23	14	13	12	11	10	8.6
W5	100	100	95	67	22	15	12	11	11	10	8.5
W8	100	100	99	80	33	25	22	20	18	15	12.9

Table 2 NCAT Test Cells Volumetrics and In Service Texture

Cell	Mix Volumetric's		MTD (in)	MIX DESIGN METHOD
	Air Voids	Binder Content		
E4	3.8	4.7	0.026	Super Pave
E9	4.4	5.4	0.02	Super Pave
N1	2.5	7.4	0.016	Super Pave
N11	3.4	4.3	0.027	Super Pave
N12	2.7	6.2	0.038	SMA
N13	4	6.8	0.046	SMA
N3	3.2	7.6	0.009	Super Pave
N5	3	6.9	0.011	Super Pave
N7	2.1	6.9	0.023	Super Pave
N9	3.2	6.7	0.018	Super Pave
S2	4.7	6	0.019	Super Pave
S6	4.5	6.2	0.012	Super Pave
W2	3.8	8	0.029	SMA
W3	11	7.6	0.052	OGFC
W4	11	6.1	0.06	OGFC
W5	11	6.2	0.06	OGFC
W8	3.5	7.5	0.032	SMA

The results of the accelerated pavement testing showed that all of the mixtures on the NCAT test track were extremely stable nearly all of the asphalt mixtures and exhibited less than 5mm rutting after $8x10^6$ ESAL's. It has been shown by

Galloway[1] that when trying to calculate skid resistance properties on less stable mixtures a measure of stability will be of benefit and should be included, therefore this method is not recommended to be used on unstable mixtures.

3.2.2 Weighted Distance From Maximum Density Line

The results of this study found that the assessment of the in-service macro-texture in terms of the MPD could be accurately estimated by use of a weighted mean distance from the maximum density line, with the addition of binder content.

In this process the weighted distance from the maximum density line, is found by summing and weighting each of the sieve sizes distance from that of the maximum density line, for all gradations used in the mix design, and is found from:

$$\Omega = \sum \left(\left\{ \left[\left(\frac{SivS}{MaxAgg} \right)^{0.45} \times 100 \right] - \% pass \right\} \times SivS \right)$$

Where:

Ω = Weighted Distance from the Maximum Density Line

SivS = Sieve size

MaxAgg = Maximum Aggregate Size in Mix

%pass = percent of mixing passing the sieve size

To develop an equation to predict the in-service MPD the weighted distance from the maximum density line and the percent binder by weight, were combined in numerical optimization process with the in-service MPD. The results of the optimization are shown graphically in Figure 2 and as can be seen very good correlation was achieved for the 17 sites examined.

From the results of the optimization the texture depth, in terms of MPD (mm), can then computed using the weighted distance from the maximum density line and the binder content, by:

$$MPD = 0.025\Omega^2 + 0.037\Omega - 0.0265 P_b + 0.052$$

Where P_b is the percent binder by weight.

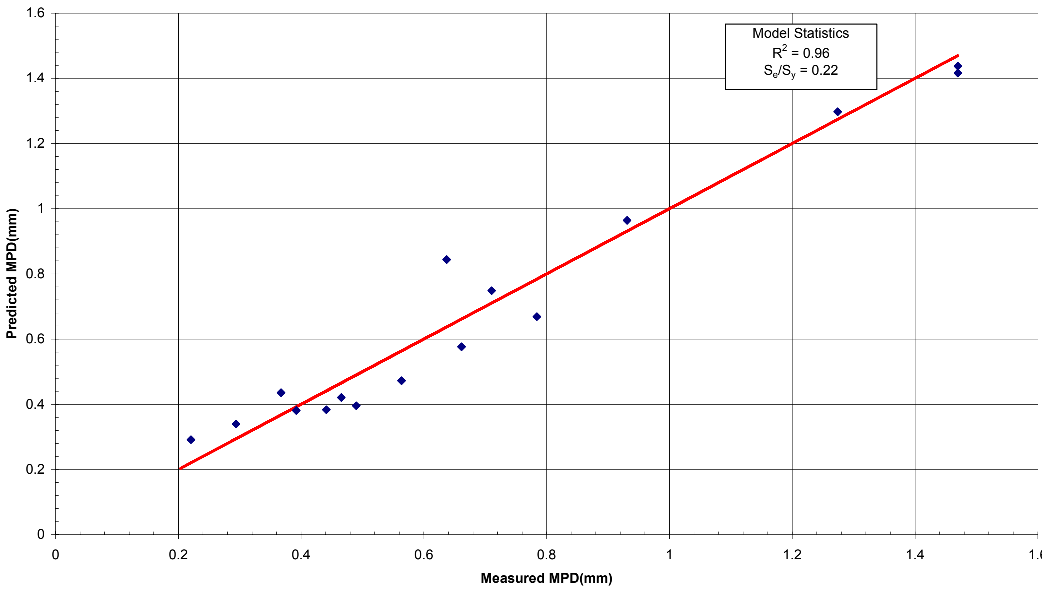

Figure 2 Results of Optimization

4 CALCULATING STOPPING DISTANCE OF DESIGN VEHICLE

With the design micro and macro-texture of the proposed mixture it is then possible to determine the required stopping distance of the design vehicle using the MPD and PAFV, from the IFI friction curve and the harmonization procedure presented in ASTM E1960 [7].

The numerical approach for the determination of the vehicle response is presented in §4.1 following, which can be used to determine the response of the design vehicle at any given initial speed, using the asphalt mixtures design parameters. Alternatively, this process has been solved for initial vehicle speeds of 60, 80 and 100kmhr^{-1} and is presented in §4.2 in Figures 4, 5 and 6 respectively.

4.1 CONVERTING VALUES TO IFI FRICTION VALUES

As the PAFV and the MPD are not in the IFI standard units (F_{60} and S_p), the first step required in the process is to convert the measured PAFV and the determined MPD to the IFI friction values in accordance with ASTM E1960[6]. In this process firstly, the MPD depth is converted to the IFI Sp value by:

$$S_p = 14.2 \times 89.7(MPD)$$

Where:

S_p = the speed constant.

The next step is to use the PAFV to determine the friction at the IFI common friction value of F60, predicted using the S_p determined in the previous step.

$$F60 = 0.008 \times \left(PAFV \times e^{\left(\frac{-50}{S_p}\right)} \right) + 0.056$$

To calculate the total stopping distance for a vehicle at any given initial speed, the stopping distance equation of §2.2, can then be solved by numerical integration between the initial vehicle speed and zero.

N.B. The IFI is based on a treadles test tyre, if the calculation of stopping distance is to be with any other sort of tyre an adjustment of the speed constant needs to me made.

4.2 STANDARD VEHICLE RESPONSE CHARTS

To aid in the process, the procedure for calculating the vehicle response in accordance with §4.1 has been solved for initial vehicle speeds of 60, 80, and 100kmhr^{-1} and are presented in Figures 3, 4 and 5 respectively. These charts can then be used to determine the design vehicles response, for the designed mixture.

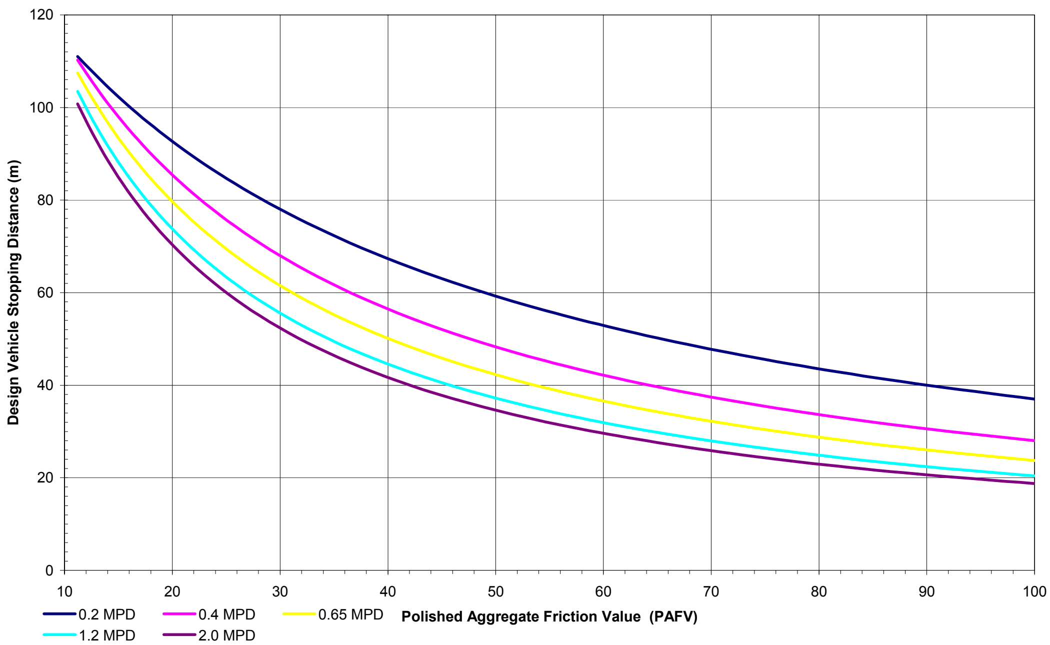

Figure 3 Design Vehicle Response 60km/hr

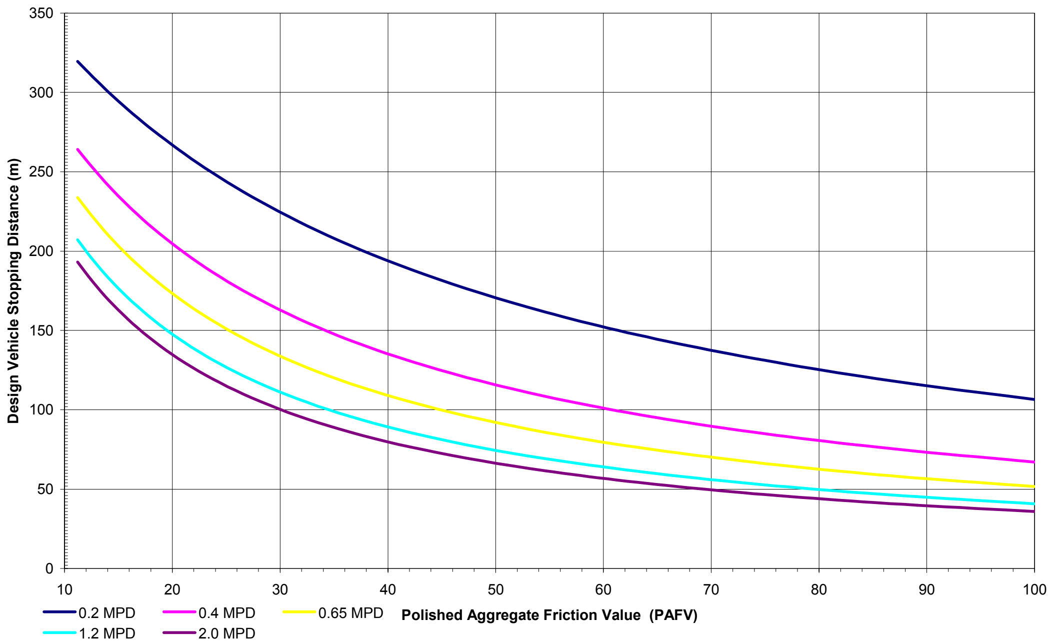

Figure 4 Design Vehicle Response 80km/hr

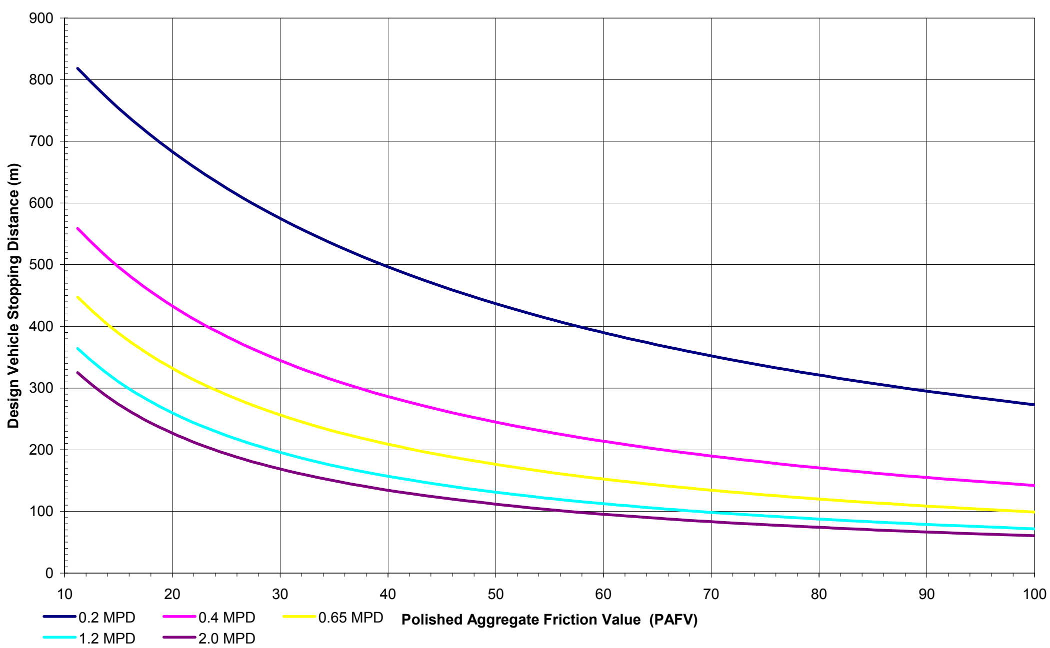

Figure 5 Design Vehicle Response 100km/hr

4.3 THE DESIGN PROCESS

The process for designing an asphalt mixture for frictional requirements is shown in Figure 6 following, to aid in interpretation this process can be broken into two phases:

1. Determining the mix gradation and binder contents that will give adequate friction. In this process, the vehicle response determined by using either, §4.1 or 4.2, is then compared to that of the desired or design response. If the response is larger (i.e. greater stopping distance) than the desired response; the MPD will need to be increased by opening the gradation i.e. increasing the weighted distance from the maximum density line. Or alternatively, a coarse aggregate with a higher PAFV may also be used, or alternatively a process of increasing both the PAFV and MPD may be employed. This process is repeated until the desired stopping distance is achieved for a range of binder contents.

2. Determining if the binder contents/types that will give adequate stability. This process requires the gradation and binder content range previously determined that would achieve a required stopping distance to be tested for stability. From the results of the combined mix gradation and binder contents, a range of binder contents is achieved that will give an adequate stopping distance. Using the design binder contents the stability of the mixture is determined by a stability test (Marshall or Superpave). If the stability is less than the required level, for all binder contents an increased binder grade is then chosen and the process repeated.

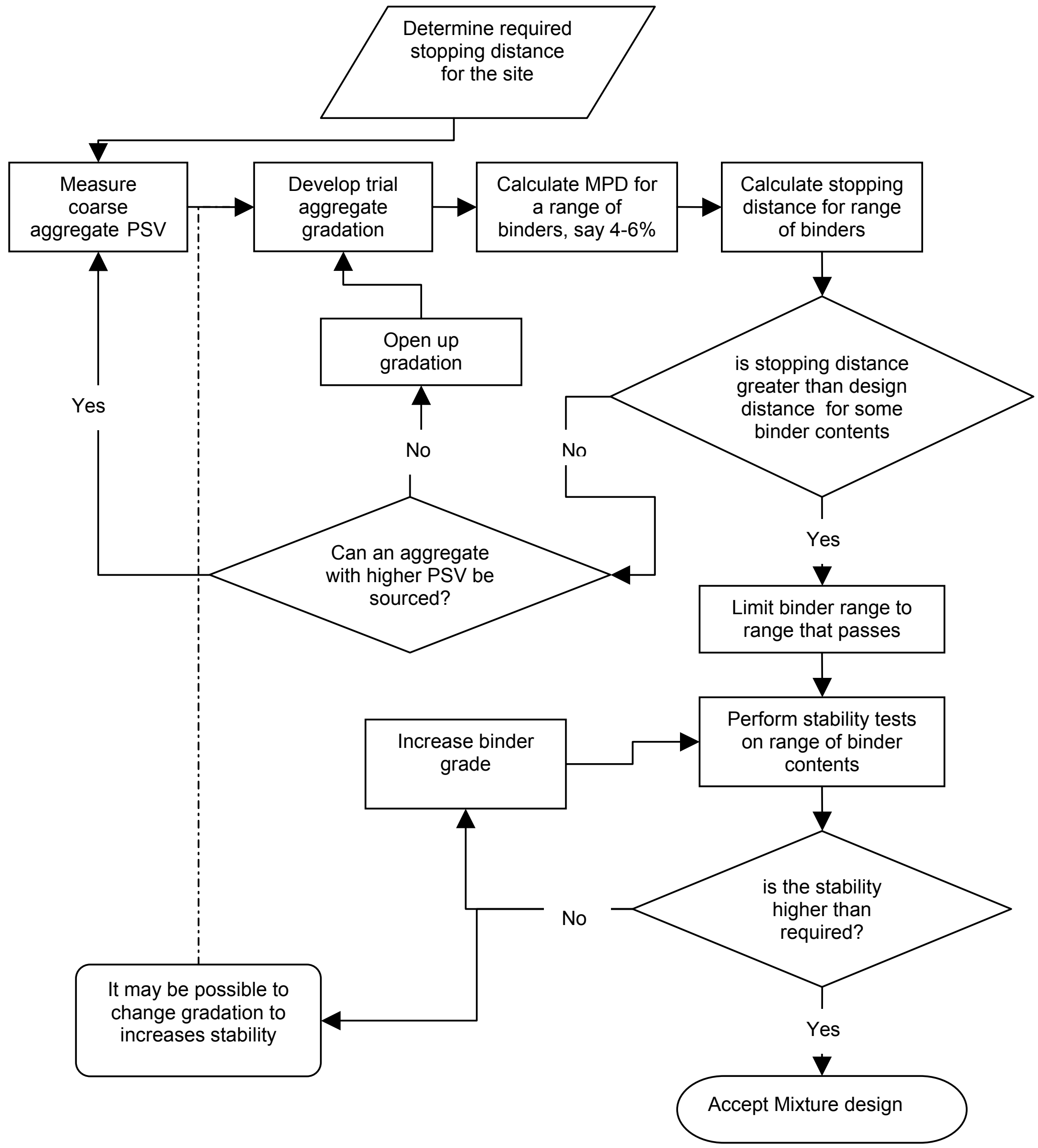

Figure 6 Flow Chart for Frictional Asphalt Mix Design

5 CONCLUSION

This paper presented a method for the design of mix gradation and binder content, together with the design mixtures coarse aggregate PAFV, to determine a design vehicles response under locked wheel braking, using the IFI friction curve and the IFI parameters (F60, S_p).

The measurement of pavement macro-texture is determined from the mix gradation and binder content in terms of MPD, which in turn is converted to the IFI macro-texture value of $S_{p.}$ The measurement of the pavement friction is determined from the

PAFV, which is then in turn converted to the IFI F60 value with the addition of the determined S_p.

The vehicle response under locked wheel braking is then determined using the IFI friction curve and the IFI values F60 and Sp. The approach adopted in this paper is that if the vehicle response (stopping distance) is greater than required, then either the mix gradation or the PAFV is modified by an iterative procedure until the desired response is achieved. The mix is then tested to ensure stability of the design mix is achieved if not an alternative binder grade is tested.

6 REFERENCES

1. Heaton B.S. *“Asphaltic Concrete Material Properties Influencing the Skid Resistance of Road Surfacing”* Engineering Bulletin CE9, University of Newcastle Faculty Of Engineering, 1979

2. PIARC *“International Experiment on Compare and Harmonize Texture and Skid Resistance Measurements”,* Association Internstionale Permanente Des Congres De La Route, Spain, 1995

3. Sullivan BW *“A Fundamental Approach to Skid Resistance Using IFI”,* 1st Annual Friction Testing Workshop, SACL, Sydney, 2003.

4. TRRL Trial from Heaton B.S. *“Asphaltic Concrete Material Properties Influencing the Skid Resistance of Road Surfacing”* Engineering Bulletin CE9, University of Newcastle Faculty Of Engineering, 1979

5. Fuller W.B. and Thompson S.E. *“The Laws of Proportioning Concrete”* Journal of Transportation Division, American Society of Civil Engineers, Vol.59 1907.

6. Sullivan B.W. *“Development of the Flow Number and Flow Time Simple Performance Test for Asphalt Mixtures”*, Arizona State University, Tempe Arizona, 2002

7. ASTM E 1960 *“Standard Practice for Calculating International Friction Index of a Pavement Surface”,* ASTM International, 2003