DEVELOPMENT OF TESTERS FOR MEASURING SKID RESISTANCE AND TEXTURE OF PAVED SURFACES, AND THEIR APPLICATION FOR DETERMINATION OF THE INTERNATIONAL FRICTION INDEX (IFI)

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Abstract: The International Friction Index (IFI) consists of a Friction Number (F60) and a Speed Constant (Sp). F60 indicates friction at a slip speed of 60 km/h. On the other hand, Sp indicates the speed dependency of the friction coefficient and is influenced by the macrotexture of the pavement.

This paper describes the development of two testers which can measure the skid resistance and the macrotexture of pavement surfaces, and their application for estimating the IFI. The Dynamic Friction Tester (DF Tester) was developed for measuring the coefficient of friction and its speed dependency of the pavement surfaces. The Tester is a disc-rotating type which measures the friction forces between road surfaces and three rubber sliders attached to the disc. The DF Tester was standardized as ASTM Standard E 1911-98. Another device developed is the Circular Texture Meter (CT Meter) which measures the macrotexture profiles on a circular track of 142 mm radius using a laser displacement sensor. The CT Meter is a portable device and is able to measure on the same circumference where the DF Tester measures the coefficient of friction. It has proven that the developed two testers were successively used to predict the two components of IFI.

1. INTRODUCTION

The friction characteristics of roads and runways play an important role in road and airport safety. Road and runway surfaces must ensure adequate levels of friction and skid resistance for the vehicles traveling on them. Many devices for measuring skid resistance and texture have been developed, but they vary widely from country to country. The International Experiment by PIARC was conducted in 1992 for the purpose of comparing and harmonizing the test results obtained from various testing devices. As a result, the International Friction Index (IFI) was developed for converting results measured by different devices to a common scale. The IFI consists of two components, the Friction Number (F60) and the Speed Number (Sp), and is reported as IFI (F60, Sp).

The Friction Number, F60, indicates friction as a slip speed of 60 km/h. There are several methods to measure friction. One is to directly measure the coefficient of friction between tires and road surfaces [ASTM E-274, 1999]. Another method is to measure the coefficient of friction between rubber sliders and road surfaces as in the case of DF Tester [ASTM E-1911, 1999] and British Pendulum Tester [ASTM E-302, 1999]. The Speed Number, Sp, indicates the speed dependence which can be determined from the macrotexture of the pavement. Macrotexture is defined as the components of the profile which have wavelengths of 0.5 – 50 mm [ISO 13473-1, 1997] and it is measured by such devices as the Laser Profilometer, the Volumetric Method and Outflow Meter. The macrotexture is an important factor that determines the speed dependency of friction coefficient.

The Dynamic Friction Tester (DF Tester) was developed for measuring the coefficient of friction and its speed dependency of the pavement surfaces. DF Tester is a disc-rotating type which measures the friction forces between a surface and three rubber sliders attached to the disc. The disc rotates horizontally at a linear speed of about 90 km/h to 10 km/h under a constant load, so the DF Tester can measure the skid resistance at any speed in this range with a single measurement [Saito et al., 1996]. The DF Tester participated in the International Experiment in 1992 and was proven that the measurements by DF Tester could predict the F60 quite well [PIARC, 1995]. Based on this result, the DF Tester was standardized as ASTM Standard E 1911-98 in 1998 [ASTM, 1999].

The Circular Texture Meter (CT Meter) is a profiling device that measures macrotexture profiles on a circular track of 142 mm radius using a CCD laser displacement sensor. The CT Meter is a portable device and is able to measure macrotexture on the same circumference where the DF Tester measures coefficient of friction. Before the development of the CT Meter it was not possible to measure the macrotexture at exactly the same location as the coefficient of friction is measured

In this paper, it is attempted to describe the IFI, the steps for determining the two parameters of F60 and Sp, the development of the DF Tester and the CT Meter in detail, and the prediction of IFI from the measured values by the DF Tester and the CT Meter. It was proven that the developed testers were successively used to predict the IFI (F60 and Sp) quite well.

2. INTERNATIONAL FRICTION INDEX

Since there are three basic types of friction measuring systems: fixed slip, side force and locked wheel, it is recognized that a macrotexture parameter would be required to harmonize the results. PIARC has developed a Friction-Slip Speed Model (PIARC Model) as shown in Figure 1 and determined the Golden Values for Speed Number (GS) and for the Friction Number (GF60) based on the results of the International Experiment.

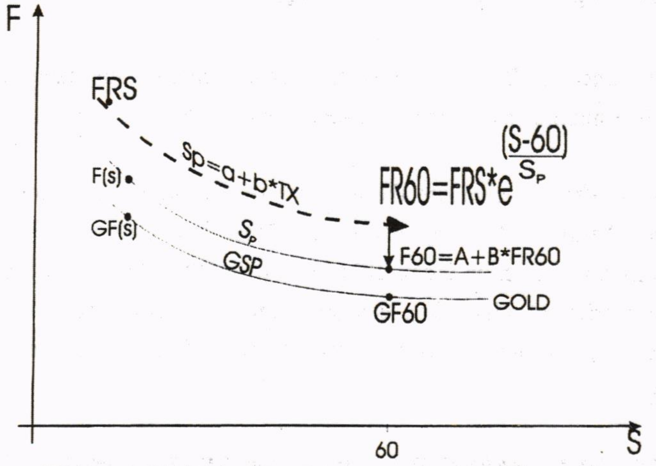


Fig. 1 Friction – Slip Speed Model (PIARC Model)

The following steps are taken to estimate the value Sp of GS and the value F60 of GS60 from macrotexture and friction measurement devices:

1. Calculate Sp using equation (1) from a macrotexture measurement (TX).

$$Sp = a + b \cdot TX \qquad (1)$$

where a and b are constants for a specific macrotexture device and TX is the macrotexture measurement reported by the device.

2. The friction measurement reported by device at Slip Speed S is converted to its value (FR60) at slip speed of 60 km/h using equation (2).

$$FR60 = FRS\ e^{(S-60)/Sp} \qquad (2)$$

where FRS is the friction reported by the measurement at a slip speed, S.

3. Calculate Friction Number F60 using equation (3).

$$F60 = A + B \cdot FR60 \quad (3)$$

where A and B are constants for a specific friction measurement device.

When IFI (F60, Sp) is determined, the friction value F(S) at any speed S can be calculated with F60 and Sp by using the following equation.

$$F(S) = F60 \cdot e^{(60-S)/Sp} \quad (4)$$

The regression constants A, B, a and b were only determined for each device which participated in the International Experiment [PIARC Report, 1995].

The PIARC Model is used to compute the estimate of the Speed Constant (Sp) and the estimate of Friction Number (F60) at 60 km/h. These two estimated values are then reported as the International Friction Index, IFI (F60, Sp). When the IFI values are reported, the estimated golden friction value, F(s), can be computed at any other slip speed (S) of interest by using Eq. (4). If one wanted to know F(S) for 120 km/h, one would simply use 120 for S in Eq. (4).

3. DEVELOPMENT OF DYNAMIC FRICTION TESTER (DF TESTER)

3.1 Description of DF Tester

When a rubber tire pressed to the surface with the constant load W is pulled at the speed of V, a friction force F is created. When F can be measured, friction coefficient μ can be obtained using the following equation;

$$\mu = F/W \quad (5)$$

When W is constant, μ is proportional of F.

On the basis of this principle, the Dynamic Friction Tester was developed. It can measure a given F of tire rubber and a linear speed V (rotating speed of a disc) by loading the rubber sliders attached to a rotating disc against the surface with a constant load W. The DF Tester consists of a horizontal spinning disc fitted with three spring loaded sliders which contact the paved surface as the disc rotational speed decreases due to the friction generated between the sliders and the paved surface. A water supply unit delivers water to the paved surface being tested. The torque generated by the slider forces measured during the spin down is then used to calculate the friction as a function of speed.

3.2 Apparatus and Test Method

The measuring instrument consists of a main body and a control unit. A portable personal computer or an X-Y plotter can be used to record the data. Figure 2 shows the DF Tester measuring unit, consisting of a fly wheel and disc which is driven by a motor. Three rubber sliders are attached to the disc by leaf springs. The sliders are pressed on the test surface by the weight of the device through three rollers. Each slider is loaded to 11.8 N by the leaf springs. The disc and the fly wheel are connected by a spring balance mounted along a circle on which the rubber sliders are fixed. Due to the forces on the rubber sliders, displacement occurs in a spring balance.

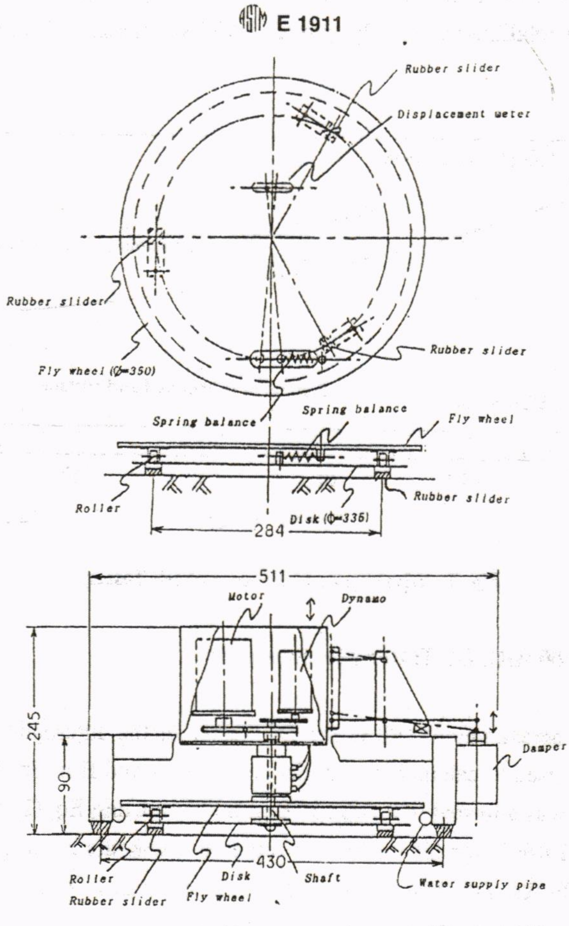


Fig. 2 The General Mechanism of Dynamic Friction Tester (dimension in millimeters)

The displacement is converted to an electrical signal through a displacement transducer with an accuracy of $\pm 1\%$ of all scale attached to the opposite side of the disc. This signal is output through a slip ring and brush, both of which are mounted on a driving shaft. The speed of rubber sliders is measured from the output of a rotational speed dynamo.

The test method uses a disk that spins with its plane parallel to the test surface. The fly wheel and disc with three rubber sliders start to rotate without contact with the pavement surface, and the water supply is started. When the rotational velocity of the disc reach to over 90 km/h, the disc is lowered to contact the test surface and friction measurement is started. The torque signal is monitored continuously as the disc rotation velocity is reduced to a measurement of friction between the sliders and the test surface. The torque signal is reduced to a measurement of friction by converting the torque to the force on the sliders and dividing by the weight of the disc and motor assembly. The friction is recorded continuously as shown in Figure 3. The friction at 20, 40, 60 and 80 km/h is recorded and the friction – speed relationship may be plotted [ASTM Standard Test Method E 1911-98, 1998].

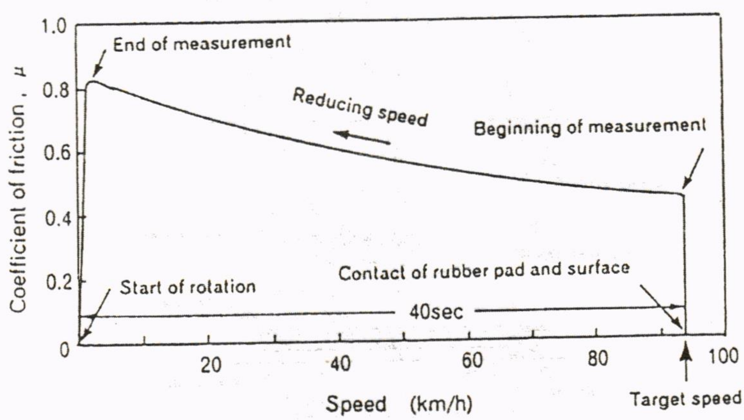


Fig. 3 Measurement Process of DF Tester

3.3 Prediction of F60 with DF Tester Measurement

Using the friction measurement (FRS) for DF Tester in the International Experiment, the PIARC Model was used to calculate the model constants A and B in Eq. (3). First the value FRS for DF Tester was adjusted to a slip speed of 60 km/h using Eq. (2) to get FR60 for each site. Then using FR60's for all the sites a regression was done using Eq. (3) to find the constants A and B for DF Tester. For DFT the constants A and B in Eq. (3) were determined with high correlation coefficient as following:

$$F60 = 0.081 + 0.732\, DFT_{20} \qquad (R = 0.96) \qquad (6)$$

where DFT_{20} is the DF Tester measurement at the speed of 20 km/h

Based on the results, DFT_{20} is recommended for predicting the F60. The DF Tester is single out since it is small and can easily be shipped to a location where there is no equipment that participated in the Experiment [ASTM Standard Practice E 1960-98, 1998].

4. DEVELOPMENT OF TESTER FOR MEASURING MACROTEXTURE

4.1 Macrotexture Measurement

The practice of measuring pavement macrotexture has been a common practice in Europe for many years. Recognition of an importance of the role of pavement macrotexture in providing adequate skid resistance has been increasing in the United States. The implementation of the International Friction Index (IFI) requires the measurement of friction and macrotexture data. Historically macrotexture data have been measured using a volumetric technique. This basic method consists of spreading a known volume of material (sand, glass beads, or grease) on the pavement and measuring the area covered. Dividing the volume by the area provides the Mean Texture Depth (MTD). Variations of this method are referred to as the "Sandpatch". The current ASTM Standard [ASTM Standard Test Method 965-96, 1999] requires the use of glass spheres instead of sand (see Figure 4).

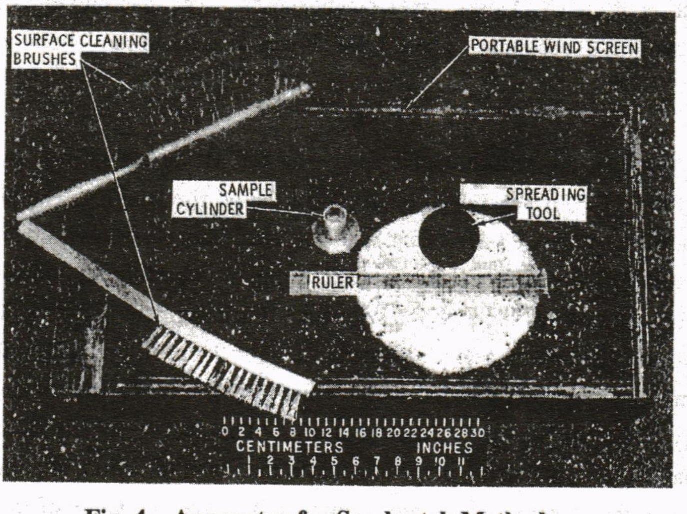


Fig. 4 Apparatus for Sandpatch Method

4.2 Relationship Between the Speed Constant (Sp) and Macrotexture Measurements

In the International Experiment it was found that when the MTD by the volumetric method produced a good regression equation as following

$$Sp = 113.6\ MTD - 11.6 \qquad (7)$$

where MTD is expressed in mm and Sp is in km/h.

The result for constants a and b are given in the ASTM Standard Practice for calculating the IFI [ASTM Standard Practice E-1960, 1999].

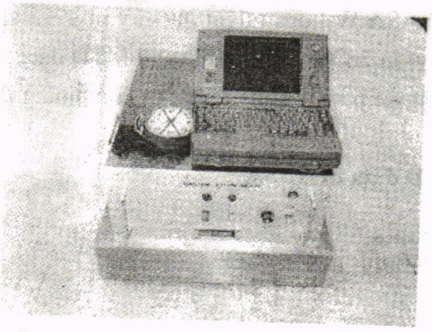
5. DEVELOPMENT OF DEVICE FOR MEASURING MPD

5.1 Description of the CT Meter

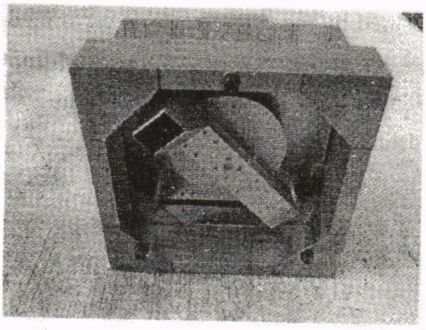
A new device for measuring Mean Profile Depth (MPD) called the Circular Texture Meter (CT Meter) was introduced in 1998. The CT Meter shown in Picture 1 measures 40×40×27 cm and weights 13 kg. As shown in Picture 2, the CCD laser displacement sensor is mounted an arm that rotates on a circumference of 142 mm radius and measures macrotexture on the same circular track where the DF Tester measures the coefficient of friction [Henry et al., 2000]. When measurement is started, the CCD laser displacement sensor rotates. Measured values of profile height are read into a personal computer through RS232C cable after one rotation of the CCD laser displacement sensor. The macrotexture of pavement can be measured within 40 seconds. The CT Meter can be used in the laboratory as well as in the field.

The circumference of the profile measured by the CT Meter is 892 mm and the sampling interval is set to be 0.871 mm, which is 1/1024 of the profile length. The profile measured is divided into 8 segments (A-H) each length of 111.5 mm, as shown in Figure 5 (a). A linear regression of the profile values for each segment is performed and regression line is subtracted from the profile values of the segment. Each segment is further divided into two equal lengths of 55.75 mm and the maximum value of the profile is determined for each of the 55.75 mm sub-segments as shown in Figure 5 (b). These two values are averaged arithmetically to obtain the mean segment depth. The average of all eight segments, the average of the two arcs which are perpendicular to the travel direction, and the average of the two segments in the travel direction are computed. The average value of the mean segment depths for all segments of the measured profile is used to obtain the Mean Profile Depth

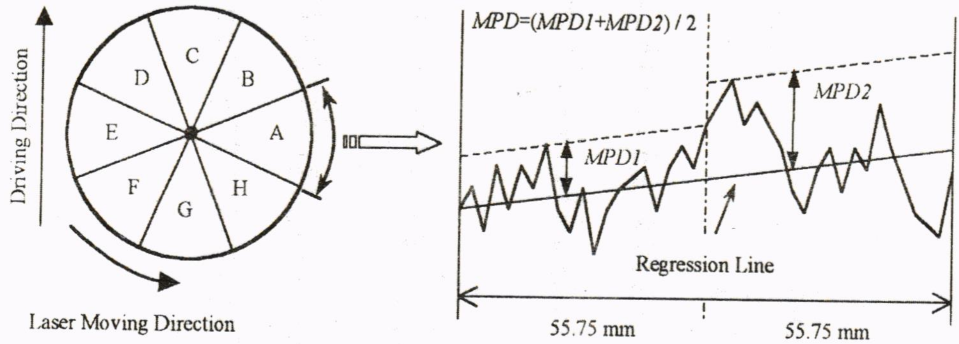
(MPD). The CT Meter is controlled by a notebook personal computer which also performs the calculations and stores the mean profile depth of each segment.



Pic. 1 General View of CT Meter



Pic. 2 Laser Displacement Sensor



(a) (b)

Fig. 6 Calculation of MPD from CTM measurement

The specifications of the CT Meter are given in Table 1.

Table 1 Specifications of the CT Meter

Displacement Sensor	CCD Laser
Laser Measuring Range	65 - 96 mm (2.6 - 3.7 in)
Laser Spot Diameter	70 μm (2.75x10^{-3})
Wavelength	60 nm (2.36x10^{-6})
Measuring Radius	142 mm (5.6 in)
Samples per revolution	1024
Sampling Interval	0.9 ±0.05 mm (.035 ± 0.002 in)
Total Time per measurement	Approximately 45 seconds

5.2 Relationship Between MTD and MPD Measured by the CT Meter

The experiment for comparisons of MTD measured by Sandpatch Method and MPD measured by the CT Meter was performed at the NASA Wallops Flight Facility in 1998 and 1999 and at Sperenberg test track (Berlin, Germany) in 2000. The MPD and MTD data for 1998 and 1999 in NASA are given in Table 2. Figure 6 shows the result of combining the all data for three years.

Table 2 MPD and MTD data in NASA

Surface Wallops	MPD (mm) 1998	MTD (mm) 1998
A	0.5	0.47
B	1.82	1.62
C	2.11	1.95
D	0.68	0.56
E	1.11	1.01
F	2.01	1.76
G	2.7	2.21
K	0.65	0.48
KO	0.89	0.72
SO	0.48	0.5
S1	0.65	0.73
S2	0.82	0.7
S3	1.19	1.03
S4	2.43	2.31
S5	1.29	1.31
S6	1.15	1.04
MS1	0.57	0.47
MS2	0.69	0.52
MS3	0.62	0.5
MS4	1.44	1.55
WHITE PAN	0.31	0.27
RED PAN	0.5	0.44
BLUE PAN	0.58	0.64

Surface Wallops	MPD (mm) 1999	MTD (mm) 1999
A	0.47	0.5
B	2.15	2.07
C	2.04	1.88
D	0.53	0.57
E	1.75	1.48
F	1.88	1.79
K	0.49	0.46
KO	0.64	0.64
SO	0.57	0.7
S1	0.64	0.6
S2	0.88	0.74
S3	1.29	1.19
S4	2.36	1.97
S5	1.02	1.06
S6	1.05	1.04
MSO	0.44	0.51
MS1	1.16	1.18
MS2	1.26	1.33
MS3	1.12	1.27
MS4	1.4	1.58
WHITE PAN	0.14	0.22
RED PAN	0.34	0.44
BLUE PAN	0.5	0.61
SM WHITE	0.04	0.148

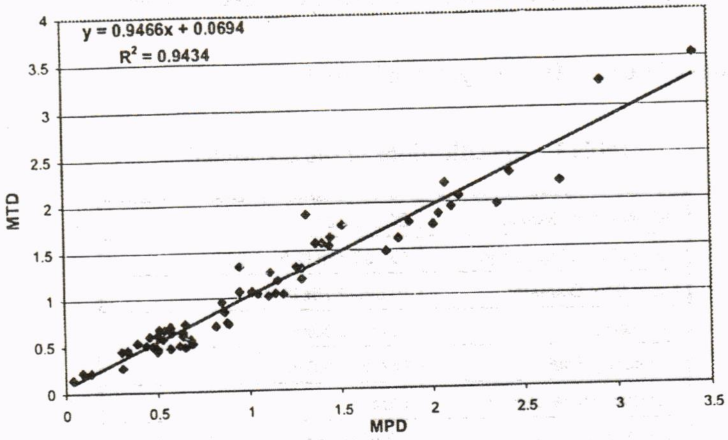


Fig. 6 MPD vs MTD for all data in 1998 – 2000

The resulting relationship is given for predicting MTD from CT Meter MPD measurements as follows [Abe, et al., 2000]:

$$\boldsymbol{MTD = 0.947\,MPD + 0.069} \qquad (R^2=0.97) \qquad (8)$$

where MTD and MPD are in mm.

In the International Experiment it was found that the volumetric mean texture depth (MTD) was highly correlated to the speed constant of the International Friction Index. It is found that the average of the MPD values for the eight segments using the CT Meter is extremely highly correlated with the MTD and can replace the volumetric measurement for determination of the MTD. It means that the MTD in Eq. (7) can be replaced by the recommended relationship for the estimate of the MTD from the MPD by the CT Meter in Eq. (8). The resulting relationship is recommended for the estimation of Speed Constant Sp:

$$\boldsymbol{Sp = 107.6\,MPD - 3.8} \qquad (9)$$

6. APPLICATION OF THE MEASUREMENTS BY CT METER AND DF TESTER

6.1 Calculation of IFI from the Measurements by CT Meter and DF Tester

The Friction Number and Speed Constant can be estimated from DFT_{20} measurements and CT Meter MPD measurements by using Eqs. (6) and (9), respectively.

$$F60 = 0.081 + 0.732\,DFT_{20} \qquad (6)$$
$$Sp = 107.6\,MPD - 3.8 \qquad (9)$$

When IFI (F60, Sp) is determined the friction value F(S) at any speed S can be calculated by using the following equation which is combined Eqs. (4), (6) and (9):

$$\boldsymbol{F(S) = 0.081 + 0.732\,DFT_{20}\,e^{(60-S)/(107.6\,MPD-3.8)}} \qquad (10)$$

6.2 Application to Pavement Management

If a pavement manager establishes management level for IFI: [IFI* (F60*, Sp*)], the requirements for a minimum texture level and a minimum friction measurement can be formulated for a particular device. For example it might be agreed that the management (minimum) levels are F60* = 0.30 and Sp* = 100 km/h. Then the criteria for minimum values of the DF Tester measurements at speed 20 km/h and the CT Meter measurements. The procedure to develop these criteria can be applied to any of the friction and texture systems that participated in the Experiment.

For developing these criteria, firstly select the management values for IFI*: F60* and Sp* and secondly substitute them in Eqs. (2) and (3), and solve for minimum required friction measurement and the minimum texture requirement. As a result, the following equations can be obtained:

$$FRS_{min} =((F60^* - A) / B)\, e^{(60 - S) / (a + b\, TX)} \quad (11)$$

$$TX_{min}= (S^* - a) / b \quad (12)$$

When the DF Tester values at 20 km/h (FR20) with MPD measured by the CT Meter measurement are applied to pavement management for the management levels of IFI* = [F60* = 0.3, Sp* = 100 km/h], the values of A = 0.081, B = 0.732, a = - 3.8, b = 107.6 and S = 20 are put in Eqs. (11) and (12). The resulting equations are as following:

$$FR20_{min} = ((0.3 - 0.081) / 0.732)\, e^{(60 - 20) / (107.6\, MPD - 3.8)} = 0.30\, e^{1 / (2.69\, MPD - 0.095)}$$

$$MPD_{min} = (100 + 3.8) / 107.6 = 0.96$$

The results are plotted in Figure 7. These relationships are convenient in the decision making process to establish tradeoffs between microtexture and macrotexture. Using Figure 9, one can determine the strategy to achieve the desired level of IFI*.

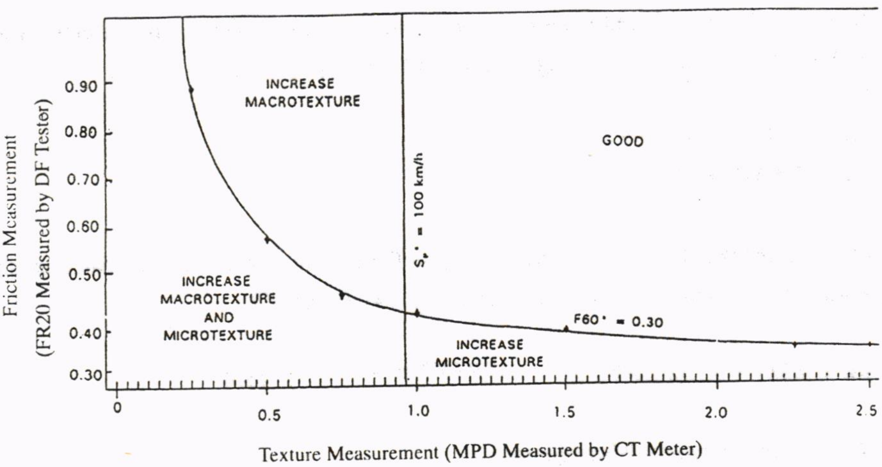


Fig. 7 Minimum DF Tester Values at 20 km/h vs MPD Measurement by CT Meter for IFI* = [F60* = 0.3, Sp* = 100 km/h]

7. SOFTWARE DEVELOPMENT FOR EVALUATION OF PAVEMENT SURFACES

In this study, a software that can evaluate the friction quality of pavements from IFI which was calculated from the measured data by the CT Meter and the DF Tester has been developed. The software developed works in Windows98. The flow diagram of the software is shown in Figure 8. The software consists of three categories, i.e., a) Macrotexture Analysis, b) IFI Calculation and c) Friction Quality Evaluation. Friction Quality Evaluation can be done instantly on site by calculating the IFI of given pavements from the measured data of CT Meter and DF tester with this software [TAMAI, et al., 2001].

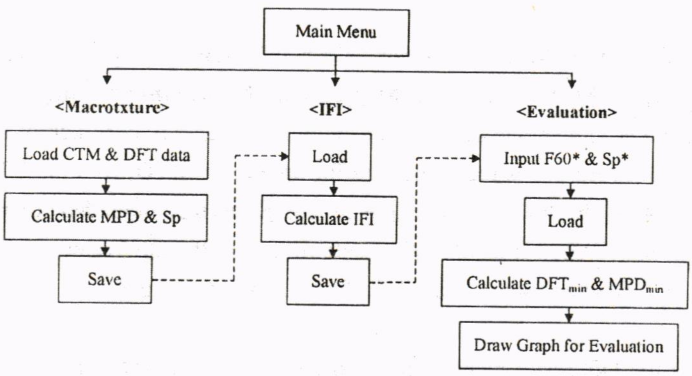


Fig. 8 Flow Diagram of the Software

8. CONCLUSIONS AND RECOMMENDATIONS

This paper describes the development of the DF Tester and the CT Meter which are able to measure the skid resistance and the macrotexture of pavement surfaces, and their application for pavement management. It has been shown that the measurements of two device can predict accurate values of the International Friction Index, IFI(F60, Sp).

It was already shown in the International Experiment that the F60 could be predicted with the DF Tester measurements at speed of 20 km/h using Eq. (6). The DF Tester is small and can easily be transported to a location where there is no equipment that participated in the Experiment. As a result, the DF Tester was standardized as ASTM Standard Test Method E 1911-98 in 1998.

The Circular Texture Meter (CT Meter) was developed for measuring macrotexture profiles on a circular track of 142 mm radius using a CCD laser displacement sensor. The CT Meter is a lightweight and portable device, and is able to measure macrotexture on the same circumference where the DF Tester measures coefficient of friction. In addition it is able to measure macrotexture within a short time (within a minute).

The CT Meter measures the profiles of a circle which is divided into eight equal segments (arcs). Two of these are approximately parallel to the direction of travel and two are approximately perpendicular to the direction of travel. The other four are approximately at ±45 degrees. Therefore, it is possible to measure macrotexture in any direction of travel.

Before the development of the CT Meter it was not possible to measure the macrotexture at exactly the same location as the coefficient of friction is measured. The macrotexture is an important factor that determines the speed dependency of friction coefficient. The CT Meter can be used in the laboratory as well as the field.

The Mean Profile Depth (MPD) produced by the CT Meter is highly correlated with the Mean Texture Depth (MTD). The ASTM procedure for determining the MPD is used to calculate the MPD as an average of the eight segments of the circular track of the CT Meter. Linear relationship in Eq. (8) is recommended for predicting MTD from the CT Meter MPD measurements. Also the linear relationship in Eq. (9) is recommended for predicting the Speed Constant, Sp. When IFI(F60, Sp) is determined by the DF Tester and the CT Meter, the friction value F(S) at any speed S can be calculated by using Eq. (10).

It is shown that the DF Tester measurements and the CT Meter measurements can apply to pavement management for the level of IFI* [F60*, Sp*]. The result show that it is possible to establish the tradeoff between microtexture and macrotexture in decision making. That is, one can determine the strategy to achieve the desired level of IFI*.

The software that works in Window98, can analyze macrotexture, calculate the IFI and evaluate friction quality has been developed. It is possible to evaluate the given pavement surfaces on site by using the personal computer.

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