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Preliminary Findings for a Prediction Model of Road Surface Macrotexture

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Abstract

The aim of this work is to present a prediction model of macro-texture based on bituminous mix properties. Following a review of existing prediction models where an in-depth critical analysis has been performed, several statistical models are presented where the macro-texture expressed in terms of mean texture depth depends on bituminous mixtures volumetric and grading properties. Different mixtures have been examined and experimental data have been derived from several technical papers or from ad hoc field and laboratory investigations. Data have been combined in order to obtain a more general prediction model, which presents a high level of applicability.

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Keywords: Surface texture; tire-road friction; prediction model; mean texture depth.

1. Introduction

The wearing course, which constitutes the top layer of the flexible road paving, is responsible for providing sufficient friction between tire and road. This phenomenon is ensured by a surface texture that, in agreement with the standards ISO [1] is described with two different scales: the micro-texture, with a range of wavelengths $\lambda < 0.5$ mm and the macro-texture with a range of $0.5 \text{ mm} < \lambda < 50$ mm. The first domain is directly related to the mineralogical nature of the aggregates used in the mixtures and it contributes to the friction by means of molecular adhesion and by penetration of residual water film. The macro-texture domain is instead dependent on particle size distribution of the aggregates and on the compaction energy exerted to the mixture; it contributes to the friction by means of tire's hysteresis, and its presence ensures the effective drainage of rainwater. For safety reasons it is important to have a tool for macro-texture's prediction, that is able to provide an indicative macro-texture's value, depending on grading and volumetric characteristics of the mixtures, at design stage. This tool may be effectively used by pavement contractors in order to fulfill hot mix asphalt performance related specifications and to avoid detrimental pay adjustment factors [2].

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The purpose of this work is to develop a macro-texture's prediction model, able to estimate the Mean Texture Depth (MTD) that according to ASTM E965 [3], is defined as average pavement macro-texture depth, calculated using the volumetric technique [4].

It has to be reminded that laser profilometer may provide an estimation of macro-texture derived from digital road profile named the Mean Profile Depth MPD [5], that may be converted to an equivalent volumetric macro-texture value named the Estimated Texture Depth (ETD) by the following relationship [5]:

$$ETD = 0,8 \cdot MPD + 0,2 \quad (1)$$

where MPD and ETD are expressed in mm.

There is an estimate of the Mean Profile Depth value too, named Estimated Profile Depth (EPD), defined in ASTM E1845 [5].

In the followings, a general overview of existing models, a description of experimental data, proposal of new empirical models and a final comparison between existing and new models are reported.

2. Macro-texture existing prediction models

Following an extensive research in the technical literature, several macro-texture predicting models have been identified. All these models are empirical and they use several functional form to correlate macro-texture to volumetric and grading bituminous mixture's properties.

2.1. Nchrp model (1999) [6] (NCHRP)

This model was developed within a study, funded by the National Cooperative Highway Research Program (NCHRP), aimed at defining methods and specifications to detect and measure segregation of hot-mix asphalt. The model, shown in Equation (2), consists of a linear combination of four different mixture's variables, including Coefficient of Curvature and Coefficient of Uniformity. Both coefficients represent a measure of uniformity in aggregate distribution; in particular the C_c , when it doesn't belong to the range 1÷3 it represents the absence of some size's diameters, or in other words, it indicates abrupt changes in slope of the grading curve. C_u , when is low (close to one), indicates a uniform grading.

The model was obtained using several cores, taken from twelve different hot-mix asphalt's test roads. The device used to measure the macro-texture is Rosan Laser profilometer.

$$ETD = 0,01980 \cdot MS - 0,004984 \cdot P_{4,75} + 0,1038 \cdot C_c + 0,004861 \cdot C_u \quad (2)$$

Where:

ETD = Estimated Texture Depth from sand patch test [mm] [5];

MS = Maximum Aggregate's Size [mm] (defined as the smallest sieve through which 100 percent of the aggregate sample particles pass [7]);

$P_{4,75}$ = the percent Passing the 4,75 mm sieve [%];

C_c = Coefficient of Curvature = $(D_{30})^2 / (D_{10} D_{60})$ [8];

C_u = Coefficient of Uniformity = D_{60} / D_{10} [8];

Where D_{10} , D_{30} and D_{60} [mm] are the particle diameter values corresponding to 10%, 30% and 60% passing on the grading curve respectively.

In this case, the model suggests that the estimated texture depth increases with MS , C_c and C_u , according to expectations. Indeed macro-texture increases with maximum size of aggregates used in the mix and with gap-graded and non-uniform grading curve. It can be observed that no one volumetric variable appears in the model and this may be represent a weak point of the model itself. According to the specific mixtures examined (conventional grading) it can be further suggested that the equation yields a good estimate of the macro-texture

for the dense mixes but cannot appropriately predict the macro-texture for the Stone Mastic Asphalt (SMA) and Open Graded Friction Courses (OGFC) mixes.

2.2. Virginia model 1 and model 2 (2001) [9], [10] (VTI1, VTI2)

Similar work at the Virginia Tech Transportation Institute (VTI) (Davis et al., 2002 [9]; Flintsch et al., 2003 [10]) investigated the possibility of predicting field macro-texture based on mix properties determined from laboratory-compacted specimens. In these studies, twelve different samples were collected during placement of the wearing surfaces of the Virginia Smart Road and further specimens were prepared in the laboratory using VDOT mix design compaction procedures. These mixtures were composed by traditional wearing course, SMA and OGFC and the macro-texture was measured by means of laser profiling devices.

The model 2, shown in Equation (4) is the evolution of the model 1, shown in Equation (3):

$$EPD = -3,596 + 0,1796 \cdot MNS + 0,0913 \cdot PP200 - 0,0294 \cdot VTM + 0,1503 \cdot VMA \quad (3)$$

$$EPD = -2,896 + 0,2993 \cdot MNS + 0,0698 \cdot VMA \quad (4)$$

Where:

EPD = Estimated Profile Depth [mm] [5];

MNS = Maximum nominal size [mm] (defined as the largest sieve that retains some of the aggregate particles but generally not more than 10 percent by weight [7]);

PP200 = Percent passing the # 200 sieve (0,075mm) [%];

VTM = Total voids in the mixture [%] (defined as that part of the compacted mixture not occupied by aggregate or asphalt expressed as a percentage of the total volume);

VMA = Voids in the mineral Aggregates [%] (that are the air-void spaces that exist between the aggregate particles in a compacted paving mixture, including spaces filled with asphalt).

Although the first model has $R^2 = 0,97$, and the second has $R^2 = 0,96$, the authors showed some criticism of model 1 (Equation (3)), observing that the signs of coefficients related to the VTM and PP200 were inconsistent, in fact MPD was expected to increase with higher VTM and decrease with amount of filler which tends to fill voids between the larger particles. Therefore the model in Equation (4) was preferred and reported in later publications too. Confirming expected results, model 2 suggests that the estimated profile depth increases both with MNS, which can be linked to the maximum aggregate's size, than with, VMA that is directly linked to global porosity of the mixture.

Although prediction models were obtained from measurements on laboratory compacted specimens, it isn't clear if VMA and VTM, to be used in the model, had to be refer on field or laboratory derived properties.

2.3. Sullivan model (2003) [11] (Sullivan)

Sullivan developed a method for estimating the macro-texture in terms of the Mean Profile Depth as a function of aggregate gradation and binder content. Experimental data were derived from road trials carried out by National Center for Asphalt Technology (NCAT). NCAT test sections used were composed by: semi-grenue conventional, stone mastic asphalts (SMA) and open graded mixtures.

As for the Virginia 's model, the macro-texture is expressed in terms of the EPD and is shown in Equation (5):

$$EPD = 0,025 \cdot \Omega^2 + 0,037 \cdot \Omega - 0,0265 \cdot Pb + 0,052 \quad (5)$$

Where:

EPD = Estimated Profile Depth [mm] [5];

Pb = Percent Binder content by weight [%] [12];

Ω = Weighted Distance from the Maximum Density Line [mm] that is:

$$\Omega = \sum \left(\left[\left\{ \left(\frac{SivS}{MS} \right)^{0,45} \cdot 100 \right\} - \%pass \right] \cdot SivS \right) \quad (6)$$

SivS = Sieve size [mm];

MS = Maximum Aggregate's Size [mm] [7];

%pass = percent of mixing passing the sieve size [%].

The new descriptive parameter for aggregate gradation, Ω , can be considered as a measure of a weighted mean distance from the maximum density line. As suggested, any shift from the maximum gradation will produce a higher VMA and thus higher surface texture for a given asphalt mix, however, any shift from the maximum density line will also produce a less stable mixture, which needs to be considered in the design process. If this interpretation of the variable Ω is accepted, the absolute value should be applied to each element of the summation. The model indicates a growth of macro-texture with the fairly increase of Ω (and then with the voids of the mixture) and a decrease with the increase of the bitumen's content, which tends to fill the voids.

It is necessary to observe that the use of model produces inconsistent estimates of macro-texture values. This leads to believe that there are problems of interpretation of input data or that the model itself may be severely biased.

2.4. Hanson - Prowell model (2004) [13] (H&P)

Several predicting models relating macro-texture with mixture's properties have been provided by the authors. Among these, the following has been reported since it can be used for a wide range of mixtures, although it was calibrated without OGFC and Novachip mixtures.

Mixture grading properties is expressed by means of the Fineness Modulus (FM) that is calculated by summing the cumulative percentages retained on the 0,15; 0,30; 0,60; 1,18; 2,36; 4,75; 9,5; 19,0; 37,5; 75 and 150 mm sieves and dividing by 100 [7] and it can be considered as the integral of the complementary area underlying grading curve. An high FM indicates a curve characterized by the presence of large grains, conversely a low FM, a curve with high presence of filler. The second order polynomial relationship between FM and MTD derives from the Sand Patch test is shown in Equation (7), based on the data from the 2000 NCAT Test Track.

$$ETD = 0,6421 \cdot FM^2 - 5,235 \cdot FM + 11,224 \quad (7)$$

Where:

ETD = Estimated Texture Depth [mm] [3];

FM = Fineness Modulus [7].

2.5. Goodman-Hassan-Abd El Halim model (2006) [14] (G-H-A)

Goodman – Hassan – Abd El Halim model is based on a linear relation between ETD_{field} (characteristic of the estimated texture in situ) and four different mixture's variables: Fineness Modulus, Voids in the Mineral Aggregate, percent of aggregate passing the 4,75mm sieve and Bulk Relative Density, defined as the ratio between specific weight of the aggregates and that of bitumen [15]. It was obtained using thirty-six cores, taken from traditional wearing course and measured by sand patch method.

The resulting linear model is shown as Equation (8):

$$ETD = -0,24 + 0,981 \left(\frac{FM \cdot VMA}{P_{4,75} \cdot BRD} \right) \quad (8)$$

Where:

ETD = Estimated Texture Depth [mm] [3];

FM = Fineness Modulus [7];

VMA = Voids in the mineral Aggregates [%];

$P_{4,75}$ = Percent Passing the 4,75 mm sieve [%];
 BRD = Bulk Relative Density [15].

As it can be seen, this model suggests that increased macro-texture may be achieved through use of gap-graded aggregates (increasing FM), increase of void (increasing VMA), use of coarser mixes (increasing aggregate retention on the 4,75 mm sieve) or decrease of compaction effort (reducing density).

The main characteristics of all the models are summarized in the following table (Table 1) and figure 1:

Table 1 Existing Models characteristics

Name	Sample Size	R^2	Parameters	Range of Variation	MTD [mm]	Measurement method	Mix type
NCHRP	12	0,65	MS, $P_{4,75}$, Cc, Cu	12,5<MS<37 26< $P_{4,75}$ <70 0,5<Cc<14 25<Cu<156	0,3÷1,03	Laser profilometer Rosan	Semi-grenue
VTI1	12	0,97	MNS, PP200, VTM,VMA	9,5<MNS<12,5 1,1<PP200<10,5 0,8<VTM<22,4 14,8<VMA<34,4	0,94÷3,48	Laser profilometer	Semigrenue, SMA, OGFC
VTI2	12	0,96	MNS,VMA	9,5<MNS<12,5 14,8<VMA<34,4	0,94÷3,48	Laser profilometer	Semigrenue, SMA, OGFC
Sullivan	17	0,96	Ω , Pb	$-\Omega < -$ 4,3<Pb<8	0,009<MTD[in]<0,06	-	Semi-grenue
H&P	45	0,62	FM	3<FM<5,9	0,3÷1,6	Sand Patch Testing	Semi-grenue
G-H-A	36	0,95	FM, VMA, $P_{4,75}$, BRD	3,8<FM<5,5 15<VMA<21 24< $P_{4,75}$ <66 2,2<BRD<2,4	0,23÷1,9	Sand Patch Testing	Semi-grenue, OGFC

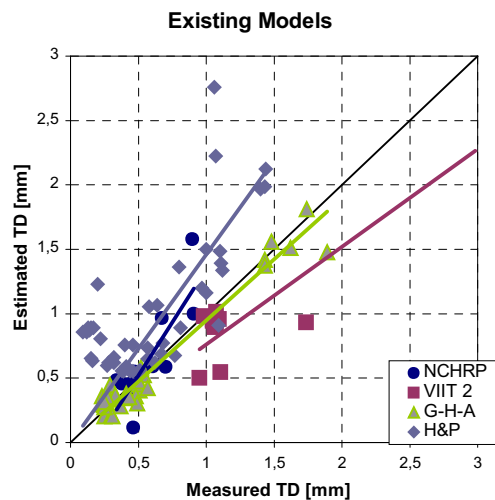


Figure 1 Graphical description of Existing Macro-texture prediction Models.

Observing the figure 1, it is possible to say that the Virginia’s model systematically underestimates the measured macro-texture; conversely, H&P model overestimates the measured macro-texture. The NCHRP model presents a good correlation for low macro-texture values, but overestimates the texture for high values. The Sullivan’s model isn’t reported because its results are inconsistent. The best model appears to be G-H-A, that are

calibrated with a large number of experimental data and is able to represent the behaviour of different mixture's type. Although the values of R^2 provided by the authors are high, it has to be observed that the amount of experimental points is rather low for each model.

3. Data collection and Analysis

As can be observed in the previous paragraph, most of models are based on a low sample size and, above all, they are based on a few mixture's types. For these reasons, it was necessary to combine and extend the overall amount of experimental data. The research was conducted examining several national and international technical papers [6, 9, 13, 14, 16, 17, 18, 19, 20, 21, 22, 23,24].

For each, experimental point were collected, when possible: measured macro-texture (by sand patch or laser device) grading curve, mix type, voids (field and/or laboratory), specific weight of the aggregates and of bitumen, percent binder content by weight, maximum aggregate's size and maximum nominal size. From experimental data were derived: fineness modulus, bulk relative density, coefficient of curvature, coefficient of uniformity and weighted distance from the maximum density line, Ω . The total number of collected data was 237, 169 are North American mixtures and 68 are Italian mixtures; an ANOVA (Analysis Of Variance) F test was performed, to compare the Variances of both populations of data. The F Test showed a substantial affinity, for independent parameters (Pb, VMA) and a satisfactory affinity for aggregated parameters (FM, Cc, Cu, Ω), between the two populations. For this reason both Italian and American data have been used for the calibration of models. It is necessary to highlight the high heterogeneity of data: there are laboratory samples and specimens cored from test tracks or roads open to traffic. Also the macro-texture was measured by means of various devices and using different procedures yielding different synthetic descriptive parameters that are been conveniently converted in terms of a unique parameter ETD.

From the total number of collected data (237):193 belong to semi-grenue grading curves, 14 to open graded mixtures and 30 to Stone Mastic Asphalt mixes. Furthermore:76 samples were compacted in laboratory and the remaining 161 were cored by roads.

4. Recalibration of existing models

Basing on a significant amount of data, a recalibration of existing models was undertaken. During this phase, the model layout and the independent variables, chosen by the authors, were kept unchanged, apart from Virginia and Sullivan's models where the dependent variable EPD was replaced by ETD by making use of Equation (1). Results from calibration are reported in the table below (Table 2).

Since the models are recalibrated with the same sample of experimental data, it is possible to obtain a direct comparison between the results that the models generate. As it can be observed from following Figure 2:

- the NCHRP, Virginia, Sullivan models systematically underestimate the real values of macro-texture;
- the Hanson & Prowell's model shows a good agreement for low macro-texture values, but a poor agreement with high macro-texture values;
- the recalibrated model that shows the best fitting was Goodman – Hassan – Abd El Halim model, although $R^2 = 0,5$ is considerably lower than $R^2 = 0,95$, obtained by the authors with 36 sample data; furthermore the model itself show a significant underestimation of macro-texture as the macro-texture itself increase.

Table 2 Recalibrated Existing Models

Name	Structure	Sample Size	R ²	P*	Range of Variation	MTD [mm]	Mix type
NCHRP	$ETD = 0,03119 \cdot MS + 0,00186 \cdot P_{4,75} + 0,0336 \cdot C_c - 0,00371 \cdot C_u$	236	0,11	0,18	9,50<MS<37,00 19,00<P _{4,75} <98,00 0,10<C _c <53,03 2,51<C _u <280,92	0,09÷3,79	Sem-Gre, SMA, OGFC
VTTI2	$ETD = 0,0292 \cdot MNS + 0,0288 \cdot VMA - 0,194$	227	0,06	0,26	4,75<MNS<25,00 7,20<VMA<44,12	0,09÷3,79	Sem-Gre, SMA, OGFC
Sullivan	$ETD = -1,78E(-06) \cdot \Omega^2 + 0,0019 \cdot \Omega - 0,083 \cdot Pb + 0,893$	171	0,12	0,24	3,98<Ω<866,23 3,30<P _b <10,70	0,09÷3,79	Sem-Gre, SMA, OGFC
H&P	$ETD = 0,15 \cdot FM^2 - 0,856 \cdot FM + 1,5267$	237	0,31	0,32	2,04<FM<6,25	0,09÷3,79	Sem-Gre, SMA, OGFC
G-H-A	$ETD = 0,088 + 0,85 \cdot \left(\frac{FM \cdot VMA}{P_{4,75} \cdot BRD} \right)$	227	0,50	0,71	2,04<FM<6,25 7,20<VMA<44,12 22,00<P _{4,75} <98,00 1,67<BRD<2,80	0,09÷3,79	Sem-Gre, SMA, OGFC

* = Pearson's Coefficient

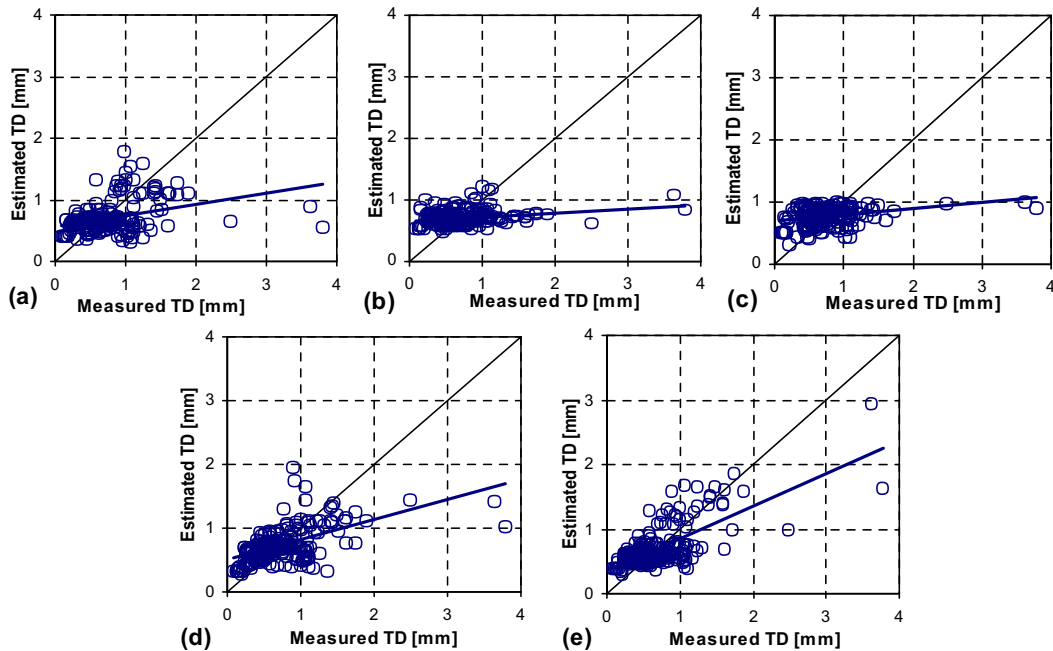


Figure 2 Estimated texture depth VS Measured texture depth according to NCHRP (a), VTTI2 (b), Sullivan (c), H&P (d), G-H-A (e) models.

5. Development of new models

Since results derived from recalibration were fairly unsatisfactory, a new model structure has been investigated. Following an extensive analysis, a multiplicative structure with different exponents for each variable (Equation (12)) was used:

$$ETD = a \cdot x_1^b \cdot x_2^c \cdot x_3^d \cdot x_4^e \tag{12}$$

where the independent variables are related to grading and volumetric properties of bituminous mixes.

A systematic study of all possible quadruples of independent variables was performed to identify the best fitting; two grading and two volumetric variables were kept for each attempt and were chosen between: VTM, VMA, FM, Pb, MS P4,75, Cc, Cu, Vb and Ω . Thirty different multiplicative models with four independent variables were studied and three different models were found: a general model, a SMA-OGFC model and semi-grenue model.

The final results are presented in the following: Table 3 and in figure 3:

Table 3 New models

Name	Structure: ETD [mm] =		a	b	c	d	e	Sa. Size	R ²	P *	Range of Variation	MTD [mm]	Mix type
General model	$a \cdot \frac{VMA^b \cdot Cc^d}{Pb^c \cdot P4,75^e}$	Value	1,287	1,40	0,786	0,105	0,899	228	0,54	0,26	12,3<VMA<44,1 22,0<P4,75<96,0 0,1<Cc<53,0 3,3<Pb<10,6	0,09÷3,79	Sem- Gre SMA, OGFC
		St. De.	0,64	0,12	0,18	0,03	0,09						
		Pr.Rej**	0,05	0,00	0,00	0,001	0,00						
SMA- OGFC model	$a \cdot \frac{VMA^b \cdot Cc^d}{Pb^c \cdot P4,75^e}$	Value	108,36	0,779	1,629	0,375	0,798	38	0,76	0,85	15,3<VMA<44,1 19,0<P4,75<91,0 71,2<Cc<53,0 4,7<Pb<9,5	0,40÷3,79	SMA OGFC
		St. De.	90,90	0,18	0,60	0,09	0,31						
		Pr.Rej**	0,240	0,00	0,010	0,00	0,015						
Semi- Grenue model	$a \cdot \frac{VMA^b \cdot Cc^d}{Pb^c \cdot P4,75^e}$	Value	1,849	0,429	-0,518	0,192	0,411	190	0,32	0,56	12,3<VMA<28,8 13,7<Cu<179,6 0,1<Cc<26,9 3,3<Pb<10,6	0,09÷1,61	Sem- Gre
		St. De.	1,13	0,17	0,19	2,77	0,15						
		Pr.Rej**	0,100	0,010	0,007	0,000	0,008						

** = according to test of the null hypothesis "Pr.Rej" represents the probability that the calibrated parameters are rejected in the proposed equations; in cases of "Pr.Rej" is close to 1, the parameter can usually be removed from the model without affecting the regression accuracy.

As it can be observed the new proposed models are characterized by quite acceptable values of R² and Pearson's Coefficient, although they are not always satisfactory. It is worth to notice that the linear regression of data in the graphical representation of estimated vs measured values is closer to the bisector with respect to the recalibrated model previously showed (see figure 2). Not uniform source and nature of data may have affected the results. Furthermore, the effects of traffic compaction insofar it may affect the decrease of the mixture void and the reallocation of aggregate particles at the pavement surface has not taken into account.

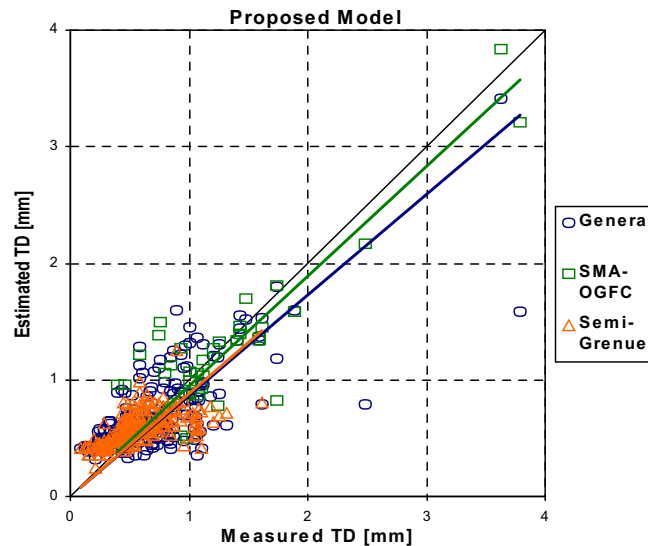


Figure 3 Graphical description of the new macro-texture predicting models.

6. Conclusions

The existing macro-texture prediction models, have limited validity range and, above all, lead to rarely satisfactory results. Following an extensive collection of experimental data, in order to increase the sample size. A recalibration of these model has been carried out, showing a drastic decrease of correlation coefficients R^2 . The most promising model appears to be Goodman – Hassan – Abd El Halim model, although its R^2 is greatly reduced. The new proposed models have a multiplicative structure with four independent variables, related to mixture's grading and volumetric properties. Following an extensive analysis, best fitting results have been obtained by using, as independent variables, VMA, Cc, Pb and P4,75. The obtained correlation coefficients R^2 and Pearson's Coefficients are mildly satisfactory, however they are not very high because of the possible following reasons:

- the measured macro-texture values, were recorded with different technique: both laser and standard volumetric (sand patch method) and then they were converted into a common synthetic descriptive parameter (namely the ETD) in order to harmonize them; conversion equation not always provide satisfactory results for each type of mixture examined;
- as far as the experimental investigations derived from road trials are concerned, there may be a mismatch between the point of extraction of the sample cores and the point of macro-texture measurements; this may affect somehow volumetric and grading properties of mixtures and therefore the reliability of the prediction model itself;
- furthermore, since, as previously highlighted, some macro-texture values have been derived from road sections exposed to the traffic, post-compaction phenomena induced by traffic actions exerted may have played a relevant role in the modifications of volumetric properties of the mixtures or/and in the partial re-allocation of aggregate particles thus affecting the goodness of fit of the model; it is worth to be noticed that this phenomena although is acknowledged in the technical literature, has not been adequately taken into account in all the studies investigated so far.

Further extension of sample size is needed in order to better investigate on the behaviour of non-conventional mixes (OGFC and SMA) with higher macro-texture values. However, although final results still remain fairly satisfactory, these models may represent an effective tool to predict macro-texture at an early design stage.

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