

Assessment of the Indirect Tensile Test as a Support Tool for the Routine Quality Control of Asphalt Mixtures

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Abstract

Ecuadorian technical specifications recommend, but do not require, dynamic performance testing of asphalt mixtures beyond the elastic modulus, and the limited availability of dynamic testing frames further restricts its use. Earlier research in Ecuador proposed performance requirements based on Nottingham Asphalt Tester (NAT) results, of which the stiffness modulus proved the most representative. This work therefore determines and assesses the relationship between the dynamic indirect tensile stiffness modulus (ITSM) and the indirect tensile strength (ITS) measured in a monotonic test, both at 20°C, on Marshall specimens from dense mixtures produced by several plants, so that the requirements already established for ITSM can be transferred to routine quality control based on ITS. A statistical analysis of 292 paired values yielded a significant linear relationship ($r = 0.850$; $R^2 = 72.66\%$; slope 5.15986, 95% confidence interval 4.794 to 5.526). The intervals associated with the model were used to derive the ITS ranges linked to satisfactory and tolerable ITSM behaviour. ITS values above 1,400 kPa or below 950 kPa are taken as representative of inadequate mixtures, prone to cracking and to permanent deformation respectively. The criterion was verified on fifteen independent specimens from five plants on which the stiffness modulus was also measured: the rating derived from ITS matched that derived from the measured modulus in all five samples, the mean prediction bias (+ 137 MPa) was not statistically significant ($p = 0.243$), and every specimen fell within its 95% prediction interval.

1 Introduction

The indirect tensile (IT) test was first described in Brazil [1], and its use was initially confined to hydraulic concrete cylinders, extending only years later to asphalt mixture specimens. In the test, a cylindrical specimen is subjected to a compressive load distributed along two opposite generatrices until failure occurs. This loading arrangement produces a relatively uniform tensile stress perpendicular to and along the diametral plane containing the applied load, which generally leads to failure by splitting along that plane [2]. See Fig. 1.

The strength associated with failure is determined, according to ASTM D6931-17 [3], by the following equation:

$$ITS = \frac{2000 \times P_{max}}{\pi \times t \times D}$$

1

where ITS is the indirect tensile strength at failure (kPa), P_{max} is the maximum or failure load (N), t is the thickness of the asphalt specimen (mm) and D its diameter (mm).

Between 1980 and 2000 this test was widely adopted in several countries because of its simplicity and the representativeness of its results under realistic loading conditions. In the United States, a study by Baladi and Harichandran [4] proposed a more rational approach to asphalt mixture design based on the

IT test as a central tool. In the Superpave mix design method, developed within the Strategic Highway Research Program (SHRP) between 1987 and 1993, low-temperature cracking is evaluated by indirect tension through two procedures: creep compliance and indirect tensile strength [5].

In Spain, research conducted at a technical university applied the IT test to the field control of mixture placement [6]. Minimum values were recommended for the different mixture types evaluated. For D20 dense mixtures, similar to those most commonly used for wearing courses in Ecuador, minimum strengths of approximately 2,450 kPa are suggested for tests at 5°C. This criterion of minimum ITS values is also found for certain mixture types in the Italian specifications; for SMA mixtures, for instance, values above approximately 590 kPa are required at 25°C [7].

In the development of the IDEAL cracking test, which yields the so-called cracking tolerance index or CT index [8], a comprehensive analysis was performed of the parameters obtained from load–displacement curves in IT tests on 150 mm diameter cylindrical specimens, at 25°C and a deformation rate of 50 mm/min. Better cracking performance and, consequently, fewer field cracks are associated with higher CT index values. In a study conducted in Ecuador [9], the CT index determined under ASTM D8225-19 [10] was found to decrease in the more aged and stiffer mixtures, which generally exhibited higher ITS. See Fig. 2. In other words, specifying minimum ITS values alone would not guarantee control of cracking in the mixtures.

This reasoning, namely that a single limit is insufficient to control two opposing distress modes simultaneously, is the premise of balanced mix design (BMD), the framework that has organised much of the recent research in this area. AASHTO defines it as mix design based on performance tests carried out on appropriately conditioned specimens, addressing multiple distress modes and accounting for mixture ageing, traffic, climate and position within the pavement structure [11]; an associated specification [12] and the methodological framework developed under NCHRP Project 20 – 07/Task 406 [13] complete the standardisation of the concept. Within this framework, the use of the indirect tensile loading head for production control has received specific attention. Bennert et al. [14, 15] documented its adoption by a state department of transportation in the United States as a performance indicator during quality control, highlighting the speed of the test and the low capital investment required, and verified its repeatability through a round robin study conducted with asphalt plant quality control laboratories as participants. Monotonic procedures using the same loading head have since been standardised for both ends of the problem: the CT index for cracking [10] and the RT index for permanent deformation, by means of the IDEAL rutting test at high temperature [16]. The approach developed in the present work follows the same logic, with the distinction that the admissible range is not established from direct performance indices but from the stiffness modulus, a property for which calibrated requirements already exist in Ecuador, and that it is applied to the 101.6 mm Marshall specimen routinely produced by Ecuadorian laboratories.

In recent years a great deal of research has employed the IT test, most of it focused on mixtures with polymer- and crumb-rubber-modified binders [17, 18], mixtures with fillers [19, 20] and mixtures recycled

from reclaimed asphalt pavement [21, 22]. Attempts to relate tests that use indirect tensile loading heads under static and dynamic procedures have been less frequent. Static procedures are used to determine the ITS and dynamic ones essentially to evaluate resilient moduli, either under ASTM D7369-20 [23] or under EN 12697-26 [24], although the latter are referred to as stiffness moduli.

Cerni et al. [25] analysed the correlation between asphalt concrete stiffness measurements obtained from dynamic and static IT tests according to the European standards. For the static tests, data were processed either by applying Hondros theory or graphically from the stress–strain curve. The results showed that very good correlations can be established between the dynamic and the static modulus. In Indonesia, a study investigated the relationship between ITS and resilient modulus in foamed bitumen asphalt mixtures [26], obtaining a power relationship with a coefficient of determination of 0.75. The results indicate that the resilient modulus measured under repeated loading and the ITS can be quantitatively linked.

Along the same lines, Kumar et al. [27] developed predictive models of ITS in bituminous mixtures considering different variables, and proposed that the resulting ITS may also be used as a predictor of the resilient modulus following the IRC 37 criterion [28]. In this Indian standard, the relationship between resilient modulus and ITS, for tests on 150 mm diameter specimens at 35°C and a deformation rate of 50 mm/min, in non-polymer-modified DBM mixtures – dense mixtures with a large maximum aggregate size for binder or base courses – is expressed as:

$$MR \text{ (MPa)} = 11.088 \times ITS \text{ (kPa)} - 3,015.80 \text{ (} R^2 = 0.68 \text{)} \text{ (2)}$$

A key input for the present work comes from earlier research in which performance requirements for asphalt mixtures in Ecuador were proposed on the basis of tests using the Nottingham Asphalt Tester (NAT) [29]. That study covered mixtures from 15 production plants and 9 flexible pavements located in different regions of the country. For the stiffness modulus, determined according to EN 12697-26 Annex C [24], the performance rating of the mixtures as a function of the modulus at 20°C and a 0.12 s load time is as follows:

- Satisfactory mixtures: 3,000 to 4,000 MPa
- Tolerable mixtures: 2,500 to 3,000 MPa and 4,000 to 5,000 MPa
- Inadequate mixtures: below 2,500 MPa or above 5,000 MPa

Values below 2,500 MPa correspond to mixtures prone to permanent deformation and values above 5,000 MPa to mixtures prone to fatigue cracking.

Since stiffness moduli are determined through non-routine dynamic tests that require expensive equipment and that, in the procedure adopted, use an indirect tensile loading head, the objective of this work was defined as determining and assessing the relationship between dynamic ITSM values and ITS values in a monotonic test, both at 20°C, obtained experimentally on Marshall specimens prepared from dense mixtures produced by several plants, so that this relationship, combined with the requirements

already developed for ITSM, allows recommendations to be proposed for improving the routine quality control of this material using the indirect tensile test.

2 Experimental work

A total of 292 Marshall specimens (101.6 mm in diameter) were tested, corresponding to dense asphalt mixtures commonly used in Ecuador with a maximum aggregate size of 12 mm [30]. Binder contents by weight fall mostly between 5.5% and 6.5%, with air void contents in the laboratory-compacted mixture very close to 4%. The mixtures came from 5 hot-mix plants located around the city of Guayaquil, using aggregates from different quarries, including basalts, diabases and limestones, together with unmodified asphalt cement from the Esmeraldas Refinery. This asphalt cement exhibits premature ageing problems: across 128 samples taken between 2015 and 2023, the residue of the rolling thin film oven test averaged a viscosity of 1,060 Pa·s against the maximum of 800 Pa·s required by the Ecuadorian standard [31], and a ductility of 38 cm against the minimum of 50 cm [32]. In this same binder, the RTFOT residue alone has been shown to correspond to approximately 1.1 years of field ageing in the Coastal region and 1.7 years in the Andean region [33]. All mixtures were designed by the Marshall method and are approved by the municipal road authority.

The specimens used were received at the laboratory for stiffness modulus testing, which the municipal government requires from construction companies as part of the mandatory quality controls. Specimens tested for ITSM undergo no appreciable structural alteration, since the test is performed within the linear viscoelastic regime with controlled deformations in the order of micrometres; the ITS was therefore determined on the same specimens within a maximum period of one week. During that interval the specimens were stored at laboratory ambient temperature and protected from solar radiation. The ITSM was determined with a NAT device following the same procedure as in that earlier research [29] (EN 12697-26 Annex C [24]), applying the load along two mutually perpendicular diameters. See Fig. 3.

The ITS was likewise determined on the specimens at 20°C in a Marshall press at a deformation rate of 50 mm/min, according to ASTM D6931-17 [3]. The data to be processed were assembled in this way. Figure 4 presents the results obtained together with the fitted model discussed below.

3 Statistical processing

Data processing was carried out with a commercial statistical package, supplemented by the analytical computation of the intervals associated with the model. The results are presented below.

3.1 Determination of the model

The relationship between the two properties was modelled by simple linear regression, taking ITS as the independent variable (X) and ITSM as the dependent variable (Y). This assignment follows from the applied purpose of the study: ITS is the property that the site laboratory can measure routinely, and ITSM the one to be inferred from it. The model fitted by ordinary least squares to the 292 pairs of values is:

$$\text{ITSM (MPa)} = -2,329.40 + 5.15986 \times \text{ITS (kPa)} \quad (3)$$

The parameters obtained are shown in Table 1 and the corresponding analysis of variance in Table 2.

Table 1
Estimators of the linear model

Parameter	Estimate	Standard error	t statistic	p-value	95% CI
Intercept, <i>a</i>	-2,329.40	208.95	-11.15	< 0.001	-2,740.7 to -1,918.1
Slope, <i>b</i>	5.15986	0.18586	27.76	< 0.001	4.794 to 5.526

Table 2
Analysis of variance of the model

Source	Sum of squares	d.f.	Mean square	F ratio	p-value
Model	1.92×10^8	1	1.92×10^8	770.76	< 0.001
Residual	7.24×10^7	290	249,506		
Total (corr.)	2.65×10^8	291			

The slope is highly significant ($t = 27.76$; $p < 0.001$) and its 95% confidence interval, from 4.794 to 5.526 MPa per kPa, excludes zero by a wide margin. The Pearson correlation coefficient is $r = 0.850$ and the coefficient of determination $R^2 = 72.66\%$, so that ITS explains slightly less than three quarters of the observed variability in stiffness modulus. The standard error of the estimate, $S_{y,x} = 499.51$ MPa, and the mean absolute error, 400.42 MPa, quantify the residual scatter and govern the uncertainty discussed in the following sections.

A second-degree polynomial model was also evaluated, raising the coefficient of determination to 73.04%. The F test of the additional term is marginally significant ($F_{1,289} = 4.07$; $p = 0.045$), but the explanatory gain is only four tenths of a percentage point and the predictions of the two models differ negligibly within the working range. For reasons of field applicability — where the criterion must be verifiable with a two-parameter expression — the linear model was adopted.

3.2 Verification of the model assumptions

The studentised residuals (Fig. 5) express the deviation of each observation from the model in units of standard deviation. Table 3 lists the observations whose studentised residual exceeds an absolute value of 2.

Table 3
Outlying observations. X values in kPa; Y values, predictions and residuals in MPa

Row	X (ITS)	Y (ITSM)	Predicted Y	Residual	Studentised residual
3	1,182	2,689	3,770	-1,081	-2.18
7	1,335	3,550	4,559	-1,009	-2.04
12	1,504	4,418	5,431	-1,013	-2.06
34	1,125	2,474	3,475	-1,001	-2.02
38	1,012	1,871	2,892	-1,021	-2.06
46	1,016	1,839	2,913	-1,074	-2.17
58	1,191	2,813	3,816	-1,003	-2.02
80	1,398	6,143	4,884	1,259	2.56
89	1,203	5,010	3,878	1,132	2.29
104	1,327	3,451	4,518	-1,067	-2.16
122	1,046	4,078	3,068	1,010	2.04
240	1,472	6,266	5,266	1,000	2.03
279	929	3,559	2,464	1,095	2.22
281	1,110	4,462	3,398	1,064	2.15
284	1,220	5,169	3,966	1,203	2.44

Fifteen of the 292 observations (5.1%) exceed an absolute value of 2, a proportion virtually identical to the 4.6% expected under the normality assumption, and none reaches the value of 3 that conventionally identifies aberrant observations. The largest residual in absolute value is 2.56. This behaviour provides no evidence of contamination of the sample, and no observation was therefore discarded. The great majority of the points lie within the ± 1.5 band.

The Durbin–Watson statistic takes a value of 1.2322. Its scope should be made precise: this test detects correlation associated with the order in which the data were recorded, and its usual interpretation as temporal autocorrelation does not apply here, since the tests were performed on specimens received in a non-sequential manner. The plot of residuals against run order revealed no systematic pattern. Nevertheless, a value appreciably below 2 admits a second reading, which is considered more pertinent: the 292 specimens are not strictly independent observations, but are clustered by plant of origin and by production lot, and specimens from the same lot share mix design, aggregates and mixing conditions. This hierarchical structure does not bias the estimate of the slope, but it may lead to underestimation of its standard errors, so that the intervals computed in the following section should be regarded as a lower bound on the true uncertainty.

It should finally be noted that both ITS and ITSM are quantities measured with experimental error. Ordinary least squares regression assumes that the independent variable is free of error, and the violation of this assumption produces attenuation of the estimated slope. Since the purpose of the model is predictive rather than the estimation of a physical constant, this attenuation does not compromise its usefulness, but it should be borne in mind when comparing the slope obtained here with those reported in other studies.

3.3 Intervals associated with the model

Three different intervals derive from the same fit [34], and the choice between them determines the thresholds proposed in the following section. The confidence interval (Eq. 4) bounds the mean value of the population of mixtures for a given ITS value. The prediction interval (Eq. 5) bounds a future individual specimen and incorporates, in addition to the uncertainty of the model, the natural variability of the material about the line. The interval for the mean of m new observations (Eq. 6) bounds the mean of a lot, which is the decision actually taken on site.

$$\hat{Y} \pm t_{\alpha/2, n-2} \times S_{y,x} \times \sqrt{\frac{1}{n} + \frac{(X - \bar{X})^2}{S_{xx}}}$$

4

$$\hat{Y} \pm t_{\alpha/2, n-2} \times S_{y,x} \times \sqrt{1 + \frac{1}{n} + \frac{(X - \bar{X})^2}{S_{xx}}}$$

5

$$\hat{Y} \pm t_{\alpha/2, n-2} \times S_{y,x} \times \sqrt{\frac{1}{m} + \frac{1}{n} + \frac{(X - \bar{X})^2}{S_{xx}}}$$

6

where $\hat{Y}$ is the value computed from the regression equation, $n = 292$ the size of the calibration sample, $\bar{X} = 1,113.2$ kPa the mean of the independent variable, $S_{xx} = 7.223 \times 10^6$ kPa² the corrected sum of squares of ITS, and $t_{\alpha/2, n-2} = 1.968$ the value of Student's t distribution for 290 degrees of freedom and 95% confidence. Figure 6 shows the fitted model with its bands.

The practical difference between the three expressions is substantial. Table 4 quantifies it for ITS = 1,100 kPa, close to the mean of the data, where the point prediction is 3,346 MPa.

Table 4
Width of the 95% intervals for ITS = 1,100 kPa

Quantity estimated	Half-width (MPa)	Interval (MPa)
Population mean of ITSM (regression CI, Eq. 4)	± 58	3,288 to 3,404
Mean ITSM of 3 new specimens (Eq. 6, $m = 3$)	± 571	2,775 to 3,917
ITSM of an individual specimen (PI, Eq. 5)	± 985	2,361 to 4,331

The confidence interval of the regression is narrow because 292 observations determine the position of the line with great precision. That interval, however, does not describe the uncertainty of a particular mixture: for that purpose the two lower rows of Table 4 apply. Figure 4 makes this evident, since in the vicinity of ITS = 1,100 kPa measured moduli range from 2,000 to 4,600 MPa. This spread is a real property of the material and of the test methods, not a deficiency of the fit, and any acceptance criterion must be formulated in recognition of it.

3.4 Derivation of the ITS thresholds

The applied objective of this work reverses the natural direction of the model: the ITSM ranges associated with satisfactory, tolerable and inadequate behaviour are known [29], and the corresponding ITS range is sought. This is formally a calibration or inverse prediction problem, whose rigorous treatment requires Fieller's theorem [35], since the ratio of two estimators does not follow a normal distribution.

The ITS values obtained by direct inversion of the point equation are 936, 1,033, 1,227 and 1,421 kPa for moduli of 2,500, 3,000, 4,000 and 5,000 MPa respectively. Adopting a conservative criterion, the ITS value for which the limit of the confidence interval – rather than the point estimate – reaches each modulus threshold was determined instead: the lower limit for the lower bounds of the admissible range and the upper limit for the upper bounds. This procedure slightly narrows the bands and shifts the uncertainty of the model in favour of safety. The results are given in Table 5.

Table 5
ITS thresholds derived from the ITSM ranges

Target ITSM (MPa)	Bound	ITS by point inversion (kPa)	ITS by CI inversion (kPa)	Value adopted (kPa)
2,500	lower	936.0	951.9	950
3,000	lower	1,032.9	1,045.0	1,050
4,000	upper	1,226.7	1,213.4	1,200
5,000	upper	1,420.5	1,397.4	1,400

The resulting rating, based on the mean ITS of three specimens, is as follows:

- Satisfactory mixtures: ITS between 1,050 and 1,200 kPa
- Tolerable mixtures: ITS between 950 and 1,050 kPa, or between 1,200 and 1,400 kPa
- Inadequate mixtures: ITS below 950 kPa or above 1,400 kPa

Applying Fieller's theorem to the mean of three specimens, the set of ITS values compatible with an ITSM of 3,000 MPa at 95% confidence is 921 to 1,143 kPa, and the set compatible with 4,000 MPa is 1,116 to 1,338 kPa. The overlap of these bands expresses the uncertainty inherent in the inversion and confirms that the thresholds in Table 5 should be understood as screening criteria rather than as deterministic equivalences. The following section quantifies this limitation.

As a practical experimental control criterion, the three specimens to be tested must have previously determined bulk specific gravities (G_{mb}) with a coefficient of variation not exceeding 1%. This condition does not alter the statistical uncertainty of the model, but it ensures that the specimens are representative of a single compaction condition and prevents the scatter in ITS from reflecting differences in densification rather than mixture properties.

3.5 Risk of misclassification

An acceptance criterion based on a relationship with residual scatter necessarily entails a risk of misclassifying a mixture. Quantifying this risk allows both the client and the producer to know the exposure associated with using ITS as a surrogate for the dynamic test. Assuming normal residuals with standard deviation $S_{y,x}$, the probability that the true modulus of a mixture classified as satisfactory falls outside the range of 3,000 to 4,000 MPa follows directly from Eqs. 5 and 6. The results are shown in Table 6.

Table 6

Probability that the actual ITSM falls outside the satisfactory range, for mixtures classified as satisfactory according to ITS

ITS (kPa)	Predicted ITSM (MPa)	$P(\text{ITSM} < 3,000)$	$P(\text{ITSM} > 4,000)$	$P(\text{outside range})$
An individual specimen				
1,050	3,088	43.0%	3.4%	46.4%
1,100	3,346	24.4%	9.6%	34.0%
1,150	3,604	11.4%	21.5%	32.8%
1,200	3,862	4.2%	39.2%	43.4%
Mean of three specimens				
1,050	3,088	38.0%	0.1%	38.1%
1,100	3,346	11.6%	1.2%	12.8%
1,150	3,604	1.9%	8.6%	10.5%
1,200	3,862	0.1%	31.8%	31.9%

Two operational conclusions follow from Table 6. The first is that testing three specimens instead of one appreciably reduces the risk in the centre of the range, from 34.0% to 12.8% for ITS = 1,100 kPa, which quantitatively justifies that recommendation. Contrary to what a superficial reading might suggest, the mean of three specimens does modify the applicable interval, through the $1/m$ term of Eq. 6, and it is that reduction which underpins the criterion. The second is that the risk remains high in the vicinity of the boundaries, where a difference of a few tens of kPa changes the rating. It is therefore recommended that ITS values lying within 50 kPa of a threshold be treated as an indeterminate zone and prompt verification by dynamic testing, where available, or repetition of the sampling.

3.6 Verification of the proposed ranges

In order to assess the criteria and recommendations developed, fifteen specimens from five plants in the same province were tested. Three of them (samples 1, 2 and 5) come from plants not included in the calibration stage and two (samples 3 and 4) from a plant that did form part of it. On each specimen the stiffness modulus was first determined with the NAT device, following the same procedure as in the calibration stage, and the indirect tensile strength was subsequently measured. Independent measured pairs are thus available, allowing the prediction of the model to be contrasted against the actual value rather than merely applying the equation. Results per specimen are given in Table 7 and the summary per sample in Table 8.

Table 7
Verification results per specimen

Sample	Specimen	ITS (kPa)	Measured ITSM (MPa)	Predicted ITSM (MPa)	Residual (MPa)	Within 95% PI?
1	1	1,451	4,696	5,158	-462	Yes
1	2	1,197	4,443	3,847	+ 596	Yes
1	3	1,512	4,787	5,472	-685	Yes
2	4	958	3,283	2,614	+ 669	Yes
2	5	957	2,513	2,609	-96	Yes
2	6	950	2,678	2,572	+ 106	Yes
3	7	1,069	3,316	3,186	+ 130	Yes
3	8	1,051	3,373	3,094	+ 279	Yes
3	9	1,142	4,190	3,563	+ 627	Yes
4	10	1,087	3,636	3,279	+ 357	Yes
4	11	1,147	4,113	3,589	+ 524	Yes
4	12	1,064	3,673	3,161	+ 512	Yes
5	13	1,014	2,596	2,903	-307	Yes
5	14	1,068	2,813	3,181	-368	Yes
5	15	955	2,763	2,598	+ 165	Yes

Table 8
Summary per sample. Coefficients of variation in parentheses

Sample	Mean ITS (kPa)	Measured ITSM (MPa)	Predicted ITSM (MPa)	95% CI mean of 3 (MPa)	Rating by ITS / by ITSM
1	1,387 (12.05%)	4,642 (3.84%)	4,826	4,246 to 5,405	Tolerable / Tolerable
2	955 (0.46%)	2,825 (14.35%)	2,598	2,025 to 3,172	Tolerable / Tolerable
3	1,087 (4.43%)	3,626 (13.48%)	3,281	2,710 to 3,852	Satisfactory / Satisfactory
4	1,099 (3.90%)	3,807 (6.97%)	3,343	2,772 to 3,914	Satisfactory / Satisfactory
5	1,012 (5.58%)	2,724 (4.17%)	2,894	2,322 to 3,466	Tolerable / Tolerable

Nature of the aggregates: sample 1, tuffaceous shales ($G_{sb} = 2.232$; water absorption 5.7%); sample 2, river gravel and sand ($G_{sb} = 2.709$; absorption 1.4%); samples 3 and 4, basalts ($G_{sb} = 2.804$; absorption 0.9%); sample 5, limestones ($G_{sb} = 2.528$; absorption 2.1%).

Agreement of the rating. The rating assigned on the basis of ITS agreed with the one derived from the measured ITSM in all five samples, including the two that lie close to a boundary. This is the most relevant practical result, since the decision that the criterion must support on site is precisely that of classifying a mixture.

Accuracy of the prediction. The mean bias is + 137 MPa, equivalent to 4.1% of the mean observed modulus, and does not differ significantly from zero (one-sample t test on the 15 residuals: $t = 1.22$; 14 d.f.; $p = 0.243$): the model shows no systematic tendency to overestimate or underestimate. The root mean square error is 300 MPa at sample level and 441 MPa at individual specimen level. The standard deviation of the verification residuals, 434 MPa, agrees closely with the standard error of the estimate from the calibration stage ($S_{y,x} = 499.51$ MPa), indicating that the scatter of the model is reproduced in independent material and that no overfitting is present. Considering only the three samples from plants outside the calibration set, the bias falls to – 43 MPa and the root mean square error to 195 MPa.

Coverage of the intervals. All fifteen specimens fell within their 95% prediction interval computed from Eq. 5, and the five sample means within the interval of Eq. 6 for $m = 3$. This is the most direct check that the uncertainty declared by the model is calibrated. It should be emphasised that none of the five measured means falls within the confidence interval of the regression (Eq. 4), which empirically confirms that this interval is not the one applicable to a decision on a lot.

Scatter of the dynamic test. The coefficients of variation of ITS within a single sample reach 14.35% and 13.48%, well above those obtained for ITS. Sample 2 is illustrative: three specimens with ITS values of 958, 957 and 950 kPa – a range of 8 kPa – exhibited moduli of 3,283, 2,513 and 2,678 MPa, a range of 770 MPa. The intrinsic variability of the stiffness test accounts for an appreciable fraction of the residual scatter of the model and by itself justifies the width of the intervals employed.

Comments on individual samples. Sample 1 has the highest mean ITS, 1,387 kPa, very close to the upper limit of the tolerable range, and two of its specimens exceed it. It comes from a plant working with high-absorption aggregates (5.7%), which tends to stiffen the mixture and make it more brittle, and it shows the highest coefficient of variation of ITS in the set (12.05%). Although the resulting rating is tolerable and agrees with that of the measured modulus, the magnitude of the scatter suggests that the origin of the high values should be verified. Sample 2 lies at the opposite extreme, at 955 kPa, very close to the boundary with inadequate values; low ITS values also imply low ITSM values, which may indicate a possible tendency to permanent deformation that should be confirmed by a specific test at high temperature. This mixture is made of crushed river gravel and river sand, which require strict control during crushing because of potential problems with fractured faces. Samples 3 and 4, produced by the same plant with the same mix design on different days, yielded ITS values of 1,087 and 1,099 kPa and moduli of 3,626 and 3,807 MPa, evidence of stable production quality and of the reproducibility of the

criterion across lots. Sample 5, at 1,012 kPa, does not reach the satisfactory range but does reach the tolerable one, a rating that agrees with that of its measured modulus.

4 Conclusions and recommendations

The statistical analysis of the ITSM and ITS values obtained on each of the 292 specimens prepared from plant-produced dense asphalt mixtures established the existence of a significant linear relationship between the two properties, with a p -value below 0.001 in the analysis of variance. The relationship is strong, as shown by a Pearson correlation coefficient of 0.850 and a coefficient of determination of 72.66%, a value that approaches or exceeds those reported for similar relationships in other countries. The estimated slope is 5.15986 MPa per kPa, with a 95% confidence interval of 4.794 to 5.526. The relationship determined at 20°C must be interpreted taking into account the quality of the Ecuadorian asphalt, unmodified by polymers and sourced from the Esmeraldas Refinery.

Inversion of the interval equations yielded the ITS ranges linked to the satisfactory and tolerable behaviour ranges of ITSM. The satisfactory range, corresponding to moduli between 3,000 and 4,000 MPa, lies between 1,050 and 1,200 kPa, whereas the tolerable range, corresponding to moduli between 2,500 and 5,000 MPa, extends from 950 to 1,050 kPa and from 1,200 to 1,400 kPa. ITS values below 950 kPa or above 1,400 kPa are considered representative of inadequate mixtures, which should be subjected to corrective measures or to more detailed study. These thresholds must be applied to the mean of three specimens and understood as screening criteria rather than as deterministic equivalences.

The verification carried out on fifteen independent specimens from five plants, on which the stiffness modulus was also measured, supported the proposed criterion. The rating derived from ITS agreed with that derived from the measured modulus in all five samples; the mean prediction bias, + 137 MPa, was not statistically significant ($p = 0.243$); the verification root mean square error, 441 MPa per specimen, is consistent with the standard error of the estimate from calibration, which rules out overfitting; and every specimen fell within its 95% prediction interval. For the three samples from plants outside the calibration set, the bias falls to - 43 MPa and the root mean square error to 195 MPa.

These ITS ranges are proposed as a support tool for the routine quality control of dense asphalt mixtures in Ecuador, given their connection both with cracking, since very high ITS values correspond to very stiff mixtures that may be brittle, and with permanent deformation, since very low ITS values may signal insufficiently stiff mixtures. In addition, ITS is determined with a loading head and a Marshall press commonly available in most laboratories in the country, which are low-cost items compared with dynamic testing equipment. The test therefore satisfies the criteria of simplicity, efficiency, low equipment cost and repeatability established under NCHRP Project 9–57 for cracking tests intended for routine use in mix design and quality control [8]; the coefficients of variation obtained in the verification stage, at most 12.05% for ITS and 14.35% for ITSM, lie well below the 25% threshold proposed there.

The criterion has limitations that should be stated. First, the inference regarding permanent deformation from a low ITS measured at 20°C constitutes an indication rather than evidence, since rutting is a phenomenon associated with high temperatures; its confirmation requires specific testing at elevated temperature, such as the IDEAL rutting test [16] or the high-temperature indirect tensile strength test, both of which are performed with the same loading head used in this study. It should be noted, however, that ASTM D8360-22 is not applicable to specimens of a diameter other than 150 ± 2 mm, so that its adoption would require abandoning the Marshall specimen. Second, the relationship was established on Marshall specimens 101.6 mm in diameter. This does not preclude comparison with the IDEAL cracking test, which admits cylindrical specimens of either 100 or 150 mm diameter, the larger size having been proposed merely for consistency with the Hamburg wheel tracking test [8]; it does, however, call for caution when comparing with the IRC 37 relationship [28], which is based on 150 mm specimens at 35°C. Third, verification sample 1, prepared with aggregates of 5.7% absorption, exhibited the greatest scatter in the set, suggesting that in mixtures with high-absorption aggregates the relationship between strength and stiffness may depart from the general pattern. Finally, the clustering structure of the specimens by plant and lot was not incorporated into the model, so that the computed intervals represent a lower bound on the true uncertainty.

Further work along this line is recommended, incorporating air void content and binder content as additional explanatory variables. The priority of the former is supported by the ruggedness analysis reported for indirect tensile testing [8], in which air void content was the only statistically significant variable ($p = 0.013$) among specimen thickness, loading rate, test temperature and air voids. It is likewise recommended to fit a model that explicitly recognises the hierarchical structure of the data, and to extend the verification to mixtures with high-absorption aggregates and to specimens 150 mm in diameter.

Declarations

Author Contribution

Conceptualization: Rolando Vila Romaní. Methodology: Rolando Vila Romaní. Investigation and data curation: María Fernanda Márquez Cueva, Rolando Vila Romaní. Formal analysis: all authors. Writing – original draft: Rolando Vila Romaní. Writing – review and editing: all authors. Supervision: Rolando Vila Romaní. All authors read and approved the final manuscript.

Data Availability

The research works corresponding to this study were deposited in the "Repositorio Digital: DSPACE" of the Universidad Católica de Santiago de Guayaquil (UCSG) and are available at the following URL: <http://repositorio.ucsg.edu.ec/handle/3317/26615>.

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Figures



(a)



(b)

Figure 1

Indirect tensile test: (a) initial load application; (b) failure by splitting

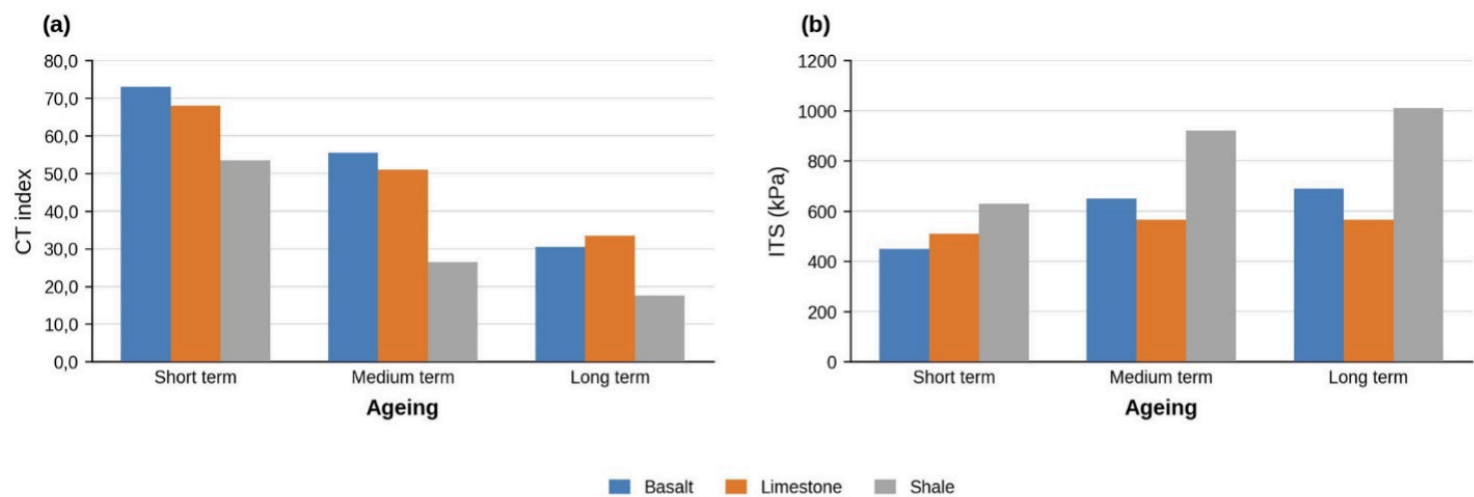


Figure 2

CT index (a) and ITS (b) of dense mixtures with three aggregate types at three ageing levels. Adapted from [9]



Figure 3

Stiffness modulus test on the Nottingham Asphalt Tester

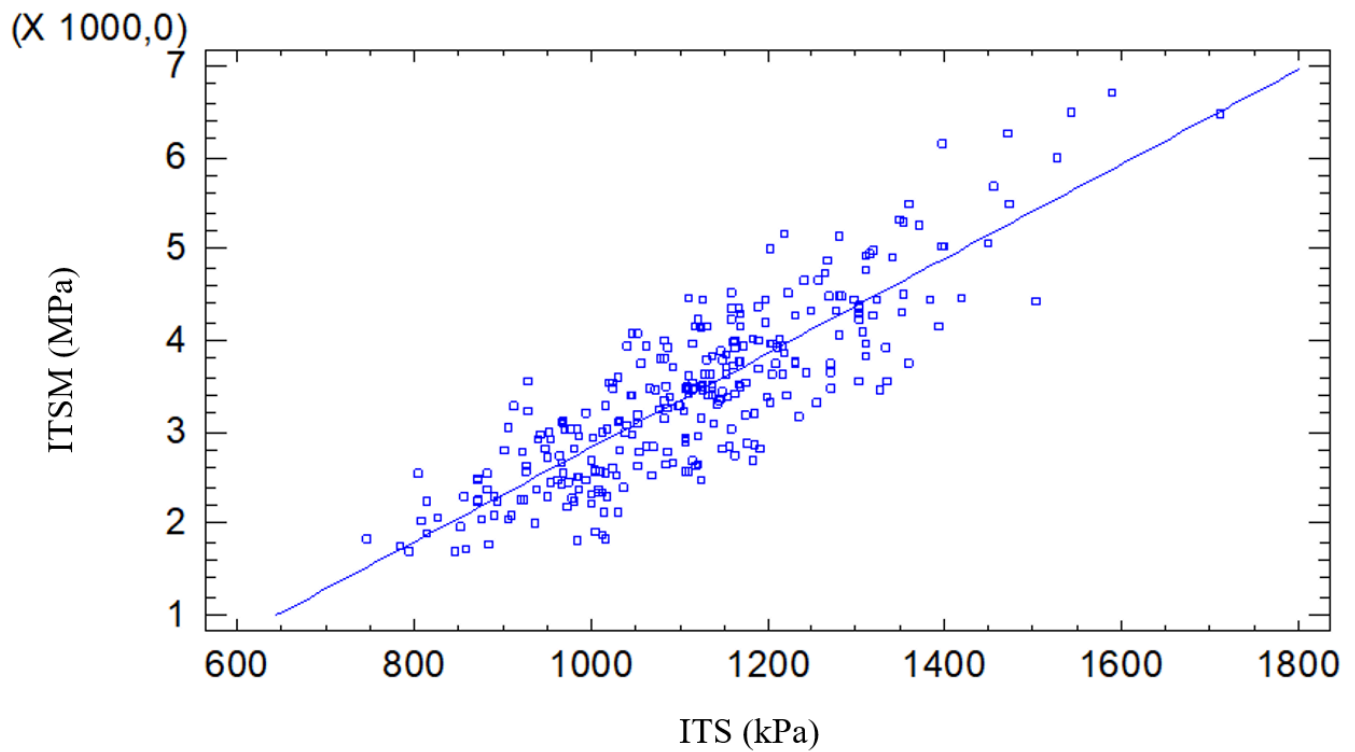


Figure 4

Measured ITSM against ITS for the 292 specimens, with the fitted linear model

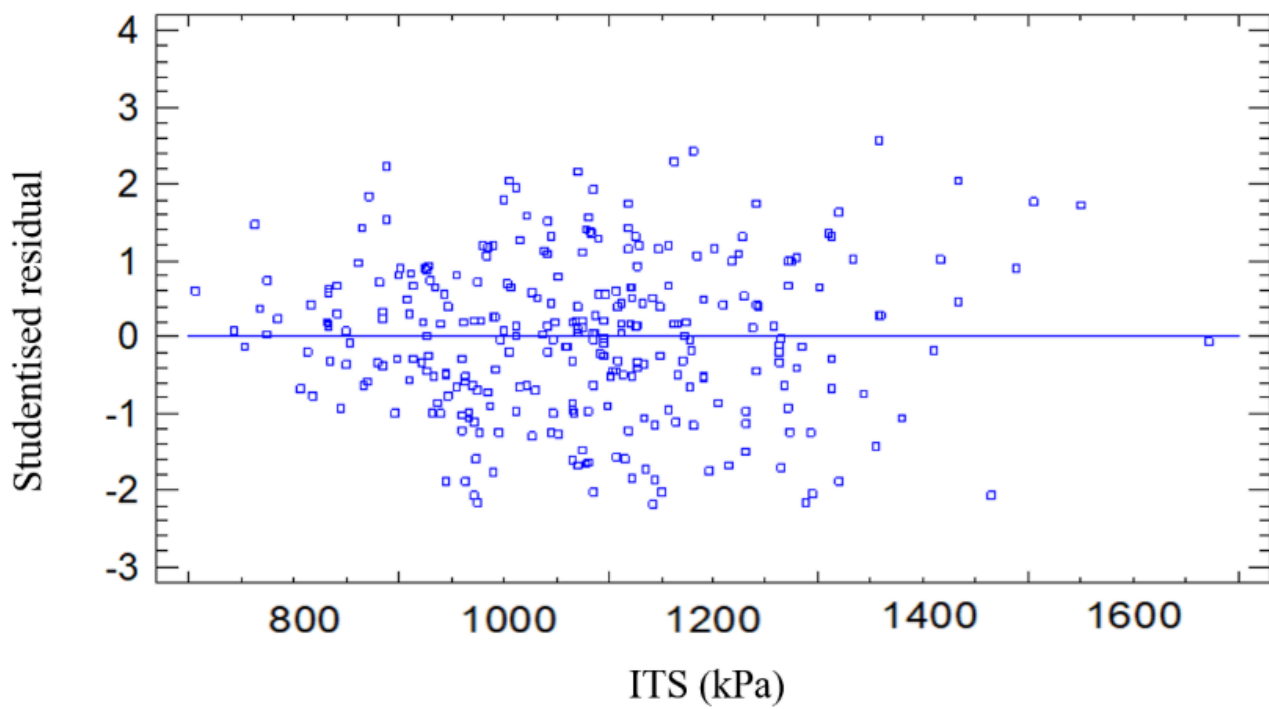


Figure 5

Studentised residuals of the linear model against ITS

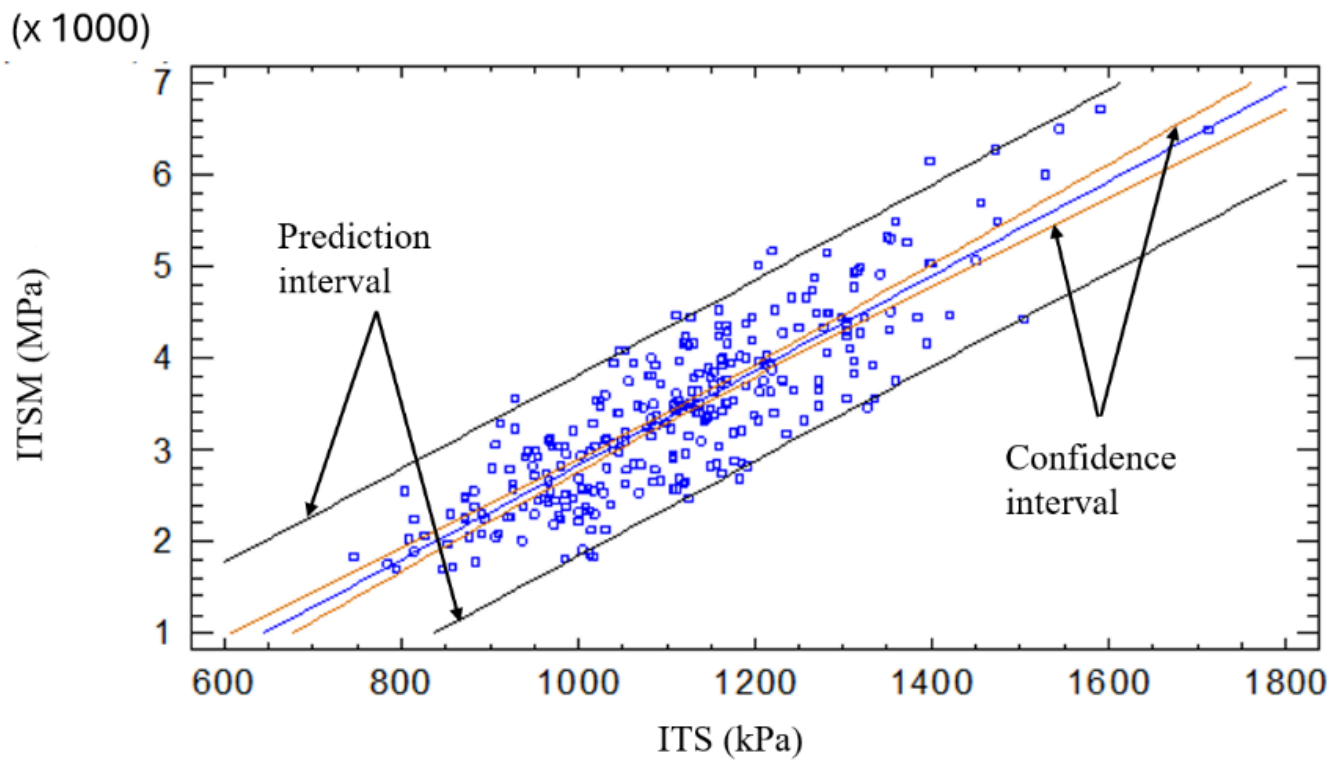


Figure 6

Fitted model with its 95% confidence and prediction bands