EFFECT OF TEMPERATURE ON THE INDIRECT TENSILE STRENGTH TEST OF ASPHALT MIXTURES

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ABSTRACT

The indirect tensile test in diametral compression, also known as splitting test, is commonly used in Brazil to characterize asphalt mixtures, due to the rapid rate of conducting the test, and the ease of assembling the apparatus. The test method was initially proposed by Carneiro for estimating the tensile strength of cement-based materials. The tensile strength at failure is calculated using the theory of elasticity and neglecting the effect of multiaxial state of stress. Although the asphalt mixtures present elastic behavior only at extremely low temperatures, the Brazilian standard method to estimate the tensile strength of asphalt mixtures establishes the test temperature as 25C. This paper presents the tensile strenght results of different asphalt mixtures (HMA, SMA, Gap Graded and Porous Friction Course with neat and modified asphalt binders) determined at four test temperatures: 5C, 15C, 25C and 35C. The paper also evaluates the energy dissipated along the test, in an attempt to provide a better assessment of the asphalt mixture behavior, still in the mix design phase.

Keywords: asphalt mixtures, indirect tensile strenght test, dissipated energy

1. INTRODUCTION

The importance of asphalt pavements in the Brazilian scenario is notorious. Roads are the main mean of transportation for goods in the country, and most of them are paved with some type of asphalt surfacing. The quality of paving is a constant concern for highway operators, especially in terms of resistance and durability. The development of high performance highway surfacing solutions with more resistant materials not only provide for greater durability of the asphalt pavement, but also lead to lower operational costs and greater safety for users.

The maintenance cost of the pavements is directly associated with environmental factors such as: (i) the use of natural resources (aggregates), and (ii) fuel consumption and gas emissions during the asphalt mixture production. In this way, the use of more durable materials is a key factor in the prevention or reduction of these maintenance costs. The investment in prevention and mitigation of environmental impacts in road construction are just as important as providing highways with adequate comfort and safety conditions.

Thermal environmental conditions, to which pavements are exposed, significantly impact pavement stability and long-term performance. If the selected asphalt was too soft, it would result in lower structural capacity at high temperatures and experience rutting. On the other hand, if the selected asphalt was too hard, it would be brittle at low temperatures, cracking under loading. The better assessment of the impact of pavement temperature variations on asphalt mixes is important in determining its behavior under different environmental conditions. Another important factor about asphalt mixtures is its dependence on stress state, moisture, temperature, strain rate, and damage, making their characterization complex. To state a performance requirement for asphalt mixture selection is not a simple matter due to economic considerations and due to the lack of universal agreement as to what constitutes the maximum allowable loss of structural integrity in flexible pavement.

This study presents the results of the indirect tensile (IDT) strength test, ASTM D6931 [1], for twelve asphalt mixtures tested at four different temperatures (5, 15, 25, and 35°C) in an attempt to provide a better assessment of the asphalt mixture behavior, still in the mix design phase. In the following items the reader will find meaningful information about the test, some of its limitations, and additional data that can be obtained using the IDT test configuration. The additional information, related to the energy dissipated along the test, can be helpful in guiding the choice of which asphalt mixture is more appropriate to use, depending on the climate conditions of the region it will be placed. The study was developed for the *Autopista Régis Bittencourt*, a highway under federal concession in Brazil, under the funding of the National Agency of Overland Transport, ANTT (*Agência Nacional de Transportes Terrestres*). In Brazil, the concessionaries together accouns for about 7% of the approximately 15000 kilometers of paved roads in the national network [2].

2. INDIRECT TENSILE STRENGHT TEST

The indirect method to determine tensile strength is attributed to Carneiro and Barcellos [3]. According to the theory of elasticity, this loading configuration produces a nearly constant stress along approximately 75 percent of the diameter. The indirect tensile (IDT) test, also known as split cylinder test, is frequently used in civil engineering because of its simplicity over direct tension testing. In the mid-1990´s, and IDT protocol was developed for evaluating strength and creep properties of asphalt concrete mixtures, as specified by the American Association of State Highway Transportation Officials (AASHTO), in AASHTO T322.

The standard test method for the indirect tensile strength has proved to be a useful experimental method to evaluate the tensile strength of concrete and mortar. Because of its simplicity, the rapid rate of conducting the test, and the ease of assembling the apparatus, its use has been extended to other materials such as rocks, ceramics, and bituminous materials. Breen and Stephens [4] stated that this test is applicable to materials that have an ultimate compressive strength greater than three times their ultimate tensile strength, and suggested also that at low temperatures an asphaltic concrete meets this condition.

Castro-Monteiro et al. [5] mentioned that the state of stress in the test is not uniaxial, due to significant compressive stress in the transverse direction, and that there is redistribution of stress due to the nonlinearity of materials. The study developed by Bynum et al [6] presents the comparison of split cylinder test with uniaxial tension test. The authors found that the split cylinder test underestimated the ultimate tensile stress by about one-half an order of magnitude for all values of strain rate that would be used in highway work. Some authors suggested the use of an ultimate, or critical, strain instead of stress [6] [7].

Another concern is related to the size effect on the indirect tensile strength. The test results of Hondrus [8] show that the splitting strength increases with the diameter. By contrast, other studies [9] [10] [11] show that the splitting tensile strength decreases. There are also some studies that revealed a more complicated trend [12] [13]. For small diameters, the strength decreases as the diameter increases, but after a certain diameter is exceeded, the trend seemed to reverse.

The indirect tensile (IDT) strength of bituminous mixture is conducted by loading a cylindrical specimen across its vertical diametral plane at a specified rate of deformation (50mm/min) and test temperature (25°C). The peak load at failure is recorded and used to calculate the IDT strength of the specimen. The tensile strength at failure is calculated using the theory of elasticity and ignoring the effect of multiaxial state of stress. The values of IDT strength can be used to evaluate the relative quality of bituminous mixtures in conjunction with laboratory mix design testing. The results can also be used to determine the potential to moisture damage when results are obtained on both moisture-conditioned and unconditioned specimens.

At elevated temperatures, the viscosity of the asphalt binder is low enough to permit relaxation of the tensile stresses by accompanying flow. In contrast, at low temperatures the asphalt within the mix will have low ductility and the tensile stress will build up until the tensile strength is reached and fracture results. A question to be addressed regarding the use of the IDT strength to asphalt mixtures is if the temperature 25°C used in the specifications is appropriate for the tensile strength measurement. It is recognized that the results of the IDT, or split, test on viscoelastic material can be influenced by indentation of the loading edge into the specimen [7].

The width of the bearing strips affects not only the tensile strength in absolute terms, but also its dependence on specimen size [14]. Rocco et al. [15] studied experimentally the fracture mechanism of mortar and granite discs in the splitting test. The authors gave special attention to the influence of the width of the bearing strips and the results confirmed the existence of two fracture mechanisms: one associated with development of central cracks and the other with a secondary crack system on both sides of the bearing strips. Castro-Monteiro et al. [5] evaluated cementitious material and concluded that the wedge formation in the test constitutes a secondary failure mode and it occurs after a single crack has propagated through the diameter of the specimen and after a significant loss of load has taken place.

With the increased use of fine aggregate gradations and polymer asphalt binders in asphalt mixtures, the validity of IDT strength results can be questioned in instances where significant crushing occurs under the narrow loading heads. Dave et al [16] proposed a flattened IDT configuration compatible with asphalt concrete mixtures consisting of small aggregate structures and soft binders, in order to reduce the amount of crushing under the loading heads (all strength testing were performed at -10°C). The indirect tensile strength at first failure increased as the amount of flatness also increased. The amount of flatness was defined by an interior angle, α, where a higher value indicates a wider flat face. Wang and Xing [17] demonstrated that there is a minimum value for the interior angle in order to satisfy the precondition that the crack should initiate at the disc center during loading and then propagate along the diameter.

3. MATERIALS AND METHODS

Four asphalt binders and five aggregate gradations were combined to produce twelve asphalt mixtures (Figure 1). The mixtures were named by letters and numbers to facilitate the results presentation. The following sections describe briefly the aggregates and asphalt binders characteristics, the asphalt mixtures designs, and the analysis method used in this study.

	NEAT ASPHALT	POLYMER MODIFIED (SBS)	ASPHALT RUBBER	ELVALOY
HMA12,5mm	A1	A2	A3	A4
SMA8S	B1	B2	-	-
SMA11S	C1	C2	-	-
GAP12,5mm	D1	D2	-	-
PFC 12,5mm	E1	E2	-	-

Figure 1: Summary of the asphalt mixtures evaluated (combinations of aggregate gradations and asphalt binder type)

3.1. Aggregates

Three aggregates, from the same source, were used to prepare the asphalt mixtures in five different gradations. Table 1 presents some of its physical characteristics.

Table 1: Aggregates characterization

	Sieves	Agg 1	Agg 2	Agg 3
Aggregate Gradation (% Passing)	1”	100,0	100,0	100,0
	3/4”	83,2	100,0	100,0
	1/2”	16,0	99,8	100,0
	3/8”	1,2	75,6	100,0
	N° 4	1,0	1,5	91,0
	N° 10	1,0	1,3	56,5
	N° 40	1,0	1,3	22,5
	N° 80	0,9	1,3	14,5
	N° 200	0,8	1,1	9,9
Los Angeles Abrasion (%)		11,7	11,7	-
% Particles with ratio > 1:3		24,5	32,4	-
% Particles with ratio > 1:5		1,5	3,4	-
Sand Equivalent Test (%)		-	-	60,4
Apparent Density (g/cm^3)		2,791	2,790	2,803
Bulk Density (g/cm^3)		2,771	2,764	2,794
Water Absorption (%)		0,3	0,3	0,1

3.2. Asphalt Binder

Four types of asphalt binders were used to prepare the asphalt mixtures, one neat and three modified (by SBS, rubber and Elvaloy). Table 2 presents some of the asphalt binders’ characteristics, according to the requirements of the Brazilian specification.

Table 2: Asphalt binders characterization

Characteristics / Properties	**Neat Asphalt**	**Polymer Modified (SBS)**	**Asphalt Rubber**	**Elvaloy**
Penetration (0,1mm)	32	35	46	40
Softening Point (°C)	55	80	61	58
Brookfield Viscosity at 135°C (cP)	515	1055	2110	1005
Brookfield Viscosity at 150°C (cP)	241	498	1102	453
Brookfield Viscosity at 177°C (cP)	83	190	385	144
Specific Gravity	1,023	1,014	1,032	1,015
Flash Point (°C)	240	293	245	263
Mixing Temperature (°C) –Viscosity between 150 and 190cP	156 a 162	176 a 183*	198 a 206**	170 a 176
Compaction Temperature (°C) – Viscosity between 250 and 310cP	145 a 150	163 a 169*	183 a 190**	160 a 164

* According to the producer´s recommendation, the mixing temperature was fixed between 165-170°C and the compaction temperature between 155-160°C.

** According to the producer´s recommendation, the mixing temperature was fixed between 173-178°C and the compaction temperature between 162-167°C

3.3. Asphalt Mixtures Design

Five aggregate gradations were investigated in this study: one HMA, two SMAs, one Gap Graded, and one PFC (Figure 2). The HMA and SMAs were designed for 4,0% air voids, the Gap Graded for 5,0%, and the PFC for 18,0%. The Marshall compaction was used for the samples preparation (HMA and Gap Graded – 75 blows per face; SMA and PFC – 50 blows per face). All mixtures were short-term aged for two hours at compaction temperature before compaction. The asphalt mixture designs are summarized in Table 3.

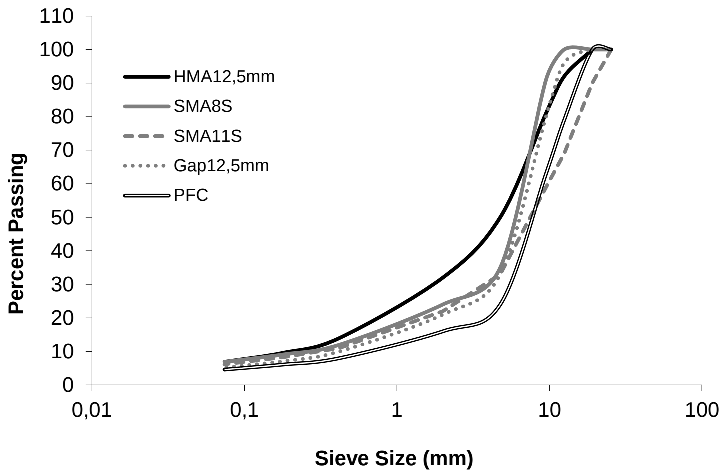


Figure 2: Aggregate gradations evaluated

Table 3: Optimum asphalt binder content (percent by mass)

Gradation / Asphalt Binder	Neat Asphalt	Polymer Modified (SBS)	Asphalt Rubber	Elvaloy
HMA 12,5mm	4,7	5,0	6,1	5,0
SMA 8S	6,9	7,3	-	-
SMA 11S	6,2	6,5	-	-
GAP 12,5mm	5,6	6,0	-	-
PFC 12,5mm	4,9	5,0	-	-

3.4. The Indirect Tension Test and the Analysis Method

For all tests, monotonic loading was applied to Marshall size samples at a rate of 50mm/min until the load was close to zero, unloading portion of the test (Figure 3). Three parameters were determined through the indirect tensile test: (i) indirect tensile strength (maximum tensile stress applied to the sample during the test), (ii) energy dissipated up to the point of maximum load ($Energy_{Pmax}$), and (iii) total energy dissipated ($Energy_{total}$), characterized by the sum of the $Energy_{Pmax}$ and $Energy_{post}$. The tests were performed at four temperatures, 5°C, 15°C, 25°C, and 35°C.

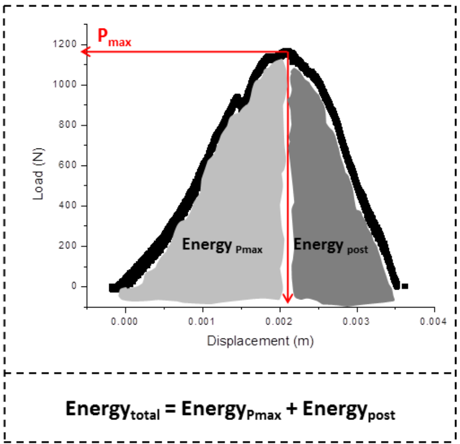


Figure 3: Illustration of the energy dissipated along the indirect tensile strength test

The fracture energy of a medium, defined by the area under the load-displacement curve in the loading portion, is the sum of the strain energy and the dissipated energy due to structural changes (i.e., microcracking). One assumes that the load increases until P_{max} is reached, corresponding to the critical displacement d_{Pmax}. At this time, visible cracks start appearing and begin expanding. Lee et al. [18] mention that the resistance of asphalt concrete to fatigue cracking can be quantified through resistance to structural deformation with strain energy and damage with dissipated energy. Thus, the resistance to fatigue cracking of an elastic material is greater as strain and dissipated energy increase, because most of the work is subject to deforming the material prior to fracture.

4. RESULTS AND DISCUSSION

In Brazil, the indirect tensile strength test is continuously replacing the Marshall stability test, especially if the asphalt mix will be placed in a high volume traffic road. Figure 4 illustrates the typical behaviour of the HMA subjected to the IDT strength test at different temperatures. The loading and unloading portions of the load x displacement curve were recorded during the test. The following subsections present the results of the: (i) indirect tensile strength, (ii) $Energy_{Pmax}$, and (iii) $Energy_{total}$.

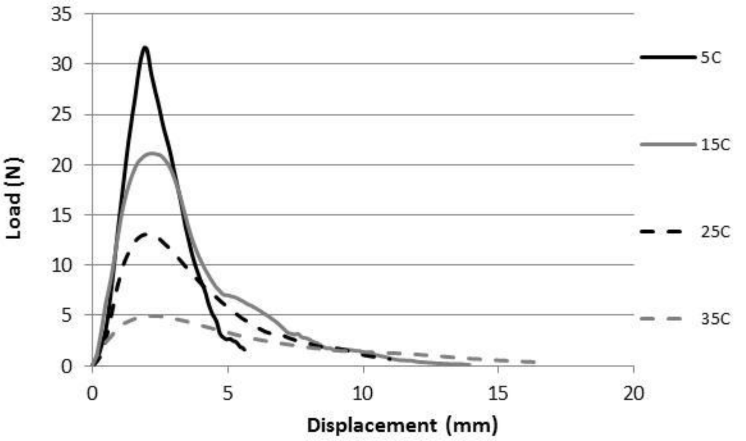
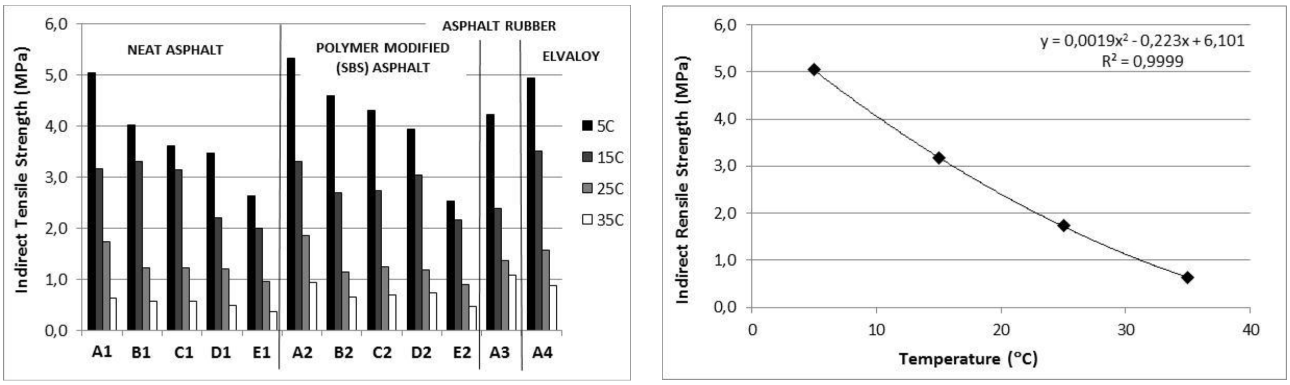


Figure 4: Illustration of the load-displacement curve for different temperatures

4.1. Indirect Tensile Strength

Figure 5(a) presents the results of IDT strength. In general, the mixtures prepared with polymer (SBS) modified asphalt presented the highest indirect tensile strength. The authors found that for some polymer systems, the indirect tensile strength increased considerably at 25°C. With respect to the aggregate gradations evaluated, the HMA showed the highest values, then the mixtures with discontinuous gradations (SMA and Gap Graded), while the PFC mix showed the lowest. The temperature had a close to linear influence on this parameter, as illustrated in Figure 5(b). This trend was similar to the other mixtures evaluated.



(a) (b)

Figure 5: (a) Indirect tensile strength results, (b) results for mixture A1

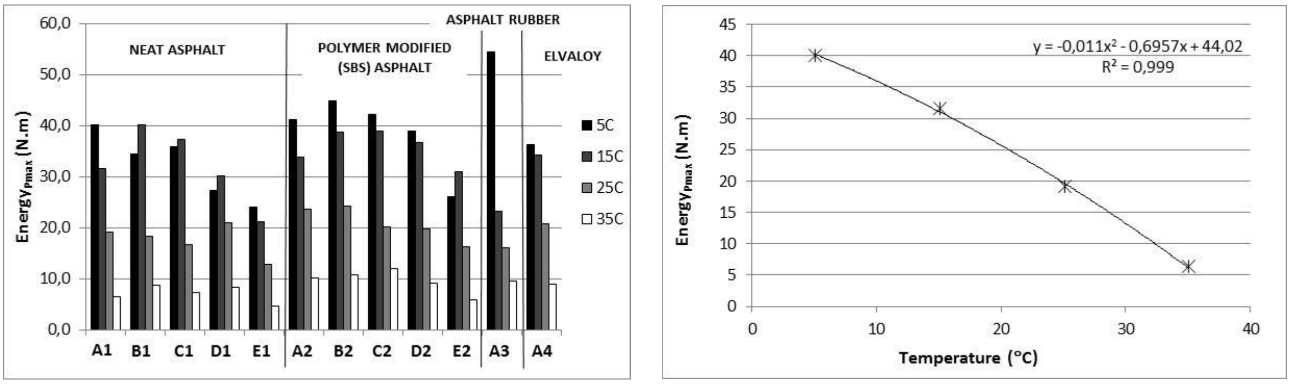
4.2. $Energy_{Pmax}$ and $Energy_{total}$

Figure 6 presents the results of the area under of the loading portion of the load x displacement curve. The linear influence of temperature in the indirect tensile strength was not observed in the $Energy_{Pmax}$ parameter. Four of twelve mixtures presented higher values of $Energy_{Pmax}$ at 15°C, instead of 5°C as observed for the IDT strength of all the mixtures.

In some fracture tests of asphalt mixtures, the area under the load x displacement curve after the peak load is also considered. Some reasons found in the literature are:

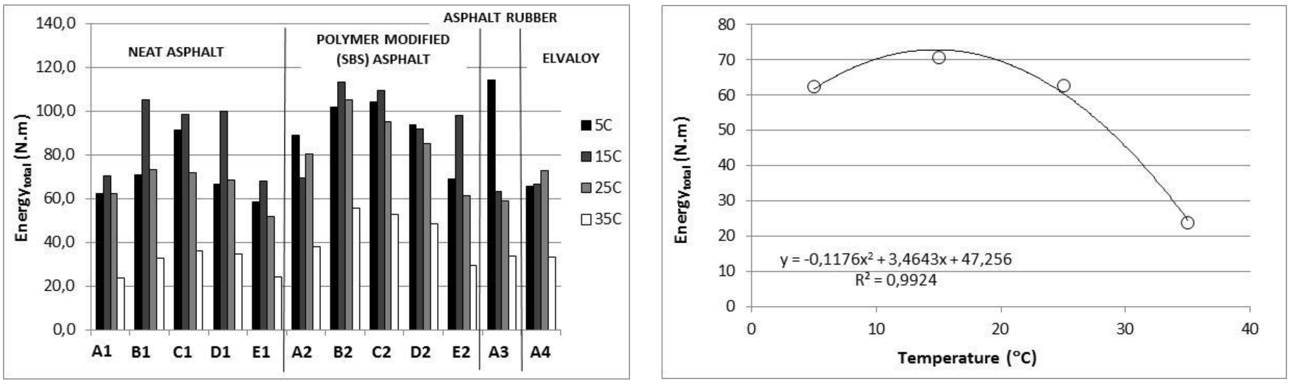
- An increase in the cohesive strength results in an increase of the peak load, an increase in the total area under the curve, and a slight increase in the severity (slope) of the post peak softening behavior [19].
- The pre-peak region represents the elastic part of the intrinsic cohesive law whereas the softening portion after the peak load accounts for various forms of damage occurring in the fracture process zone [20].
- Montestruque et al. [21] used the semi-circular bending (SCB) test to evaluate the fracture resistence of fine aggregate mixtures (the only variable among the mixtures was the type of asphalt binder). The authors found that the total energy dissipated along the SCB test better differentiate the mixtures

Figure 7(a) presents the results of total energy dissipated along the test (area under the loading and unloading portion of the curve). One can observe that this parameter rank the asphalt mixtures differently when compared to the rank determined from the indirect tensile strength and the energy dissipated up to the maximum load (for the same temperature). The total energy parameter (especially at higher temperatures) accounts not only for the crack(s) initiation and propagation along the test, but also for the deformation the sample can resist. One can observe from Figure 7(a) that different asphalt mixtures presented higher values of the total energy parameter at different temperatures. It may be an indicative that the best mechanical behavior happens at different temperatures depending on the asphalt mixture tested.



(a) (b)

Figure 6: (a) Energy dissipated up to maximum load - indirect tensile strength test, (b) results for mixture A1



(a) (b)

Figure 7: (a) Total energy dissipated - indirect tensile strength test, (b) results for mixture A1

5. CONCLUSIONS AND RECOMMENDATIONS

The indirect tensile strength is an important and widely used parameter used in Brazil to characterize asphalt mixtures. The Brazilian and ASTM specifications request the test to be run at 25°C under monotonic loading at the deformation rate of 50mm/min. Some studies, however, indicate that at this temperature the state of stresses in the cylinder asphalt mixture sample is not the one considered in the equations derived for the tensile strength calculation. In an attempt to better use the information of the IDT splitting test, this paper presented the results of load x displacement curves of twelve asphalt mixtures at four temperatures. The following parameters were calculated base on these curves: (i) indirect tensile strength, (ii) energy dissipated up to the point of maximum load ($Energy_{Pmax}$), and (iii) total energy dissipated ($Energy_{total}$). Following are some of the conclusions from this study.

- The load-displacement characteristic of the asphalt mixture is an important factor and should receive more attention during the asphalt mixture design.
- It is also important to consider the range of temperatures in which the asphalt mix(es) will be subjected along the year in the field, in order to better select the materials.
- The total energy parameter ($Energy_{total}$) is highly influenced by the type and amount of asphalt binder in the mixture, and should be considered during the design of the asphalt mixtures
- It was noted that even though the crack tempts to go around the aggregate particles at 25 and 35°C, it did go through the aggregates in some of the cross sections at 15°C, and most of the cross sections at 5°C. Similar observations were mentioned in the study conducted by Soares et al. [22] for 25°C and 10°C.
- The energy dissipated after the peak load increases and is more pronounced as the temperature increases (Figure 8). Based on that, one can conclude that the information up to the point of maximum load (indirect tensile strength and $Energy_{Pmax}$) is more valuable for lower temperature, while at higher temperature (where the

asphalt binder has more influence), it is suggested the use of $Energy_{total}$ to better characterize the asphalt mixture.

It is under investigation by this research group, the sensibility of the IDT strength, $Energy_{Pmax}$, and $Energy_{total}$ to the following parameters: (i) asphalt binder content, and (ii) air voids.

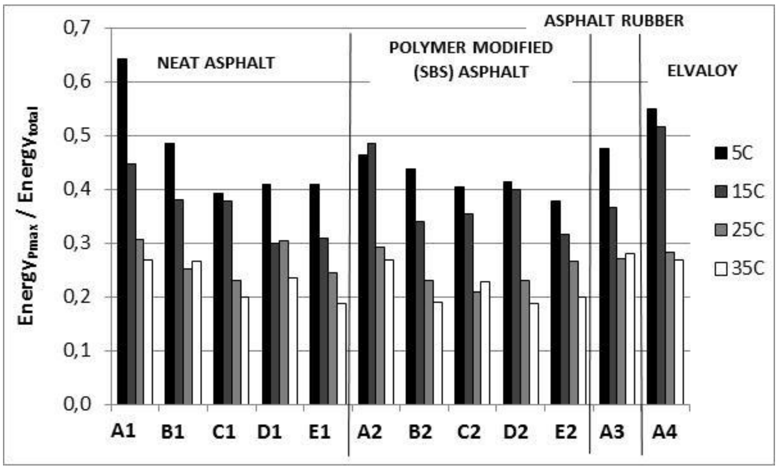


Figure 8: Percentage of the area up to the maximum load with respect to the total area

REFERENCES

[1] ASTM, *D6931 - Standard Test Method for Indirect Tensile Strength of Bituminous Materials*. 2007, ASTM International.

[2] ABCR, *Annual Report 2009*. 2009, Associação Brasileira de Concessionárias de Rodovias, ABCR.

[3] Carneiro, F.L. and A. Barcellos, *Tensile Strength of Concrete.* RILEM Bulletin No 3, International Association of Testing and Research Laboratories for Materials and Structures, 1953: p. 97-123.

[4] Breen, J.J. and J.E. Stephens, *Split Cylinder Test Applied to Bituminous Mixtures at Low Temperature.* Journal of Materials, 1966. **1**(1): p. 66-76.

[5] Castro-Montero, A., Z. Jia, and S.P. Shah, *Evaluation of Damage in Brazilian Test Using Holographic Interferometry.* Materials Journal, 1995. **92**(3): p. 268-275.

[6] Bynum, D., R. Agarwal, and H. Fleisher, *Constitutive relations for split cylinder tests on bituminous concrete.* Materials and Structures, 1971. **4**(3): p. 163-169.

[7] Falcão, M.F.B. and J.B. Soares. *Considerações sobre o Ensaio de Compressão Diametral no Estudo de Materiais de Pavimentação*. in *Congresso Nacional de Pesquisa e Ensino em Transportes, ANPET*. 2002. Natal.

[8] Hondros, G., *Evaluation of Poisson Ration and the Modulus of Materials of Low Tensile Resistance by the Brazilian (Indirect Tensile) Test with Particular References to Concrete.* Australian Journal of Applied Science, 1959. **10**(3): p. 243-268.

[9] Sabnis, G.M. and S.M. Mirze, *Size Effects in Model Concrete?* Journal of the Structural Division, ASCE, 1979. **106 ST6**: p. 1007-1020.

[10] Chen, W.F. and R.L. Yuan, *Tensile Strength of Concrete: Double-Punch Test.* Journal of the Structural Division, ASCE, 1980. **106 ST8**: p. 1673-1693.

[11] Ross, C.A., P.Y. Thompson, and J.W. Tedesco, *Split-Hopkinson Pressure-Bar Tests on Concrete and Mortar in Tension and Compression.* ACI Materials Journal, 1989. **86**(5): p. 475-481.

[12] Lundborg, N., *Strength-Size Relation of Granite.* International Journal of Rock Mechanics and Mining Sciences, 1967. **4**: p. 269-272.

[13] Bazant, Z.P., M.T. Hasegawa, and J. Mazars, *Size Effect in Brazilian Slip-Cylinder Tests: Measurement and Fracture Analysis.* Materials Journal, 1991. **88**(3): p. 325-332.

[14] Rocco, C., et al., *Size effect and boundary conditions in the Brazilian test: Experimental verification.* Materials and Structures, 1999. **32**(3): p. 210-217.

[15] Rocco, C., et al., *Mechanism of Rupture in Splitting Test.* Materials Journal, 1999. **96**(1): p. 52-60.

[16] Dave, E., et al., *Development of a Flattened Indirect Tension Test for Asphalt Concrete.* Journal of Testing and Evaluation, ASTM, 2011. **39**(3).

[17] Wang, Q.-Z. and L. Xing, *Determination of fracture toughness KIC by using the flattened Brazilian disk specimen for rocks.* Engineering Fracture Mechanics, 1999. **64**(2): p. 193-201.

[18] Lee, S.J., et al., *Fatigue Cracking Resistance of Fiber-Reinforced Asphalt Concrete.* Textile Research Journal, 2005. **75**(2): p. 123-128.

[19] Kim, H., M.P. Wagoner, and W.G. Buttlar, *Simulation of Fracture Behavior in Asphalt Concrete Using a Heterogeneous Cohesive Zone Discrete Element Model.* Journal of Materials in Civil Engineering, 2008. **20**(8): p. 552-563.

[20] Song, S.H., G.H. Paulino, and W.G. Buttlar, *A bilinear cohesive zone model tailored for fracture of asphalt concrete considering viscoelastic bulk material.* Engineering Fracture Mechanics, 2006. **73**(18): p. 2829-2848.
[21] Montestruque, G., K.L. Vasconcelos, and L.L.B. Bernucci. *Ensaio de Flexão em Amostra Semi-Circular com Fenda e Análise de Imagens para Caracterização da Resistência à Fratura de Misturas Tipo AAUQ*. in *XXIV Congresso de Pesquisa e Ensino em Transportes*. 2010. Salvador, Brazil.
[22] Soares, J.B., F.A.C. Freitas, and D.H. Allen, *Considering Material Heterogeneity in Crack Modeling of Asphaltic Mixtures* Transportation Research Record: Journal of the Transportation Research Board, 2003. **1832**: p. 113-120.