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Monotonic Torsional Loading (MTL) test on asphalt binders and correlation with fracture properties of corresponding mixtures

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ABSTRACT

The experimental work described in this paper investigates the relationship between the failure properties of asphalt binders, determined using the Monotonic Torsional Loading (MTL) test, and the fracture characteristics of corresponding asphalt mixtures, determined by means of the Semi-Circular Bending (SCB) test. The MTL test, following a procedure developed in a previous study based on the use Dynamic Shear Rheometer (DSR) equipped with 4 mm parallel plates, was applied on a set of selected binders, both of the neat and polymer-modified types. The asphalt mixtures containing different binders were prepared in the laboratory by adopting the same job-mix formula, in order to highlight the sole role of binder and to exclude other spurious effects. The results obtained from the investigation indicated a strong correlation between the brittleness index (I_B) and critical cracking temperature (T_{cr}) obtained from MTL testing on binders, and the fracture parameters (G_f and CRI) obtained from SCB testing on mixtures. This outcome provides evidence of the effectiveness of MTL method in assessing asphalt binder potential in terms of thermal cracking performance.

1. Introduction

Thermal cracking is one of the main types of distress affecting asphalt pavements in cold regions [1]. Low-temperature conditions to which the asphalt mixtures are exposed may cause the formation of transverse cracks that undermine the functional and structural integrity of the pavement [2,3]. Such transverse cracks also compromise the ability of the asphalt pavement to prevent water intrusion, causing moisture damage in the lower layers with consequent long-lasting and costly effects [4,5].

Resistance to thermal cracking of asphalt mixture is mostly governed by asphalt binder due to its viscoelastic and temperature-dependant properties. Thus, the selection of asphalt binders with adequate low-temperature performance is crucial in preventing the occurrence of thermal cracking phenomena [6–8]. To this purpose, the use of suitable experimental methods and specification criteria is of prominent importance for a reliable evaluation of asphalt binders in terms of their actual thermal cracking potential.

The most diffused standardized method for the characterization of low-temperature characteristics of asphalt binders is that based on the Bending Beam Rheometer (BBR) test [9]. It consists in a flexural creep test that entails the measurement of stiffness and elasticity of prismatic beam subjected to a constant bending load. During the test, the material is kept in the linear viscoelastic region, thereby preventing any direct assessment of the tensile strength and cracking resistance of the material. The BBR is used to determine the low-limiting temperature of binder Performance Grade (PG) according to Superpave classification system [10]. However, several studies have indicated that BBR test is not optimal for the performance characterization of binders. It has been observed that materials can exhibit remarkable differences in their actual performance in the field despite having the same PG low temperature [2,11,12]. Moon et al. [13] compared BBR test results on asphalt binders and data carried out from the Indirect Tensile Test (IDT) on asphalt mixtures [14]. Due to significant discrepancies between the results obtained from two tests, they argued that the BBR was inadequate for predicting thermal stresses in mixtures.

Alternative approaches to BBR have been proposed in recent years for the rheological characterization of asphalt binders at low temperatures. These involve the use of the Dynamic Shear Rheometer (DSR) equipped with 4-mm diameter parallel plates [15–18]; in fact, 4-mm

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geometry has expanded the capability of the DSR to include low-temperature measurements by overcoming instrument limitations and machine compliance issues.

In this context, Baglieri et al. [19] developed a new method called Monotonic Torsional Loading (MTL) test that uses the 4-mm DSR to evaluate failure properties of asphalt binders at low temperatures. The test method consists in the application of constant shear strain rates to binder cylindrical specimens at various temperatures until rupture. Test data are modelled by means of the elastic viscoelastic correspondence principle to eliminate time dependant-effect of the material. Based on MTL test results, the two parameters Brittleness Index (I_B) and Critical Brittleness Temperature (T_{cr}) are determined to evaluate and rank materials response. The MTL test was proven to be effective in discriminating the low-temperature failure properties of asphalt binders [20, 21]. In particular, the proposed methodology seemed to be able to emphasize and capture the contribution of SBS polymer modification in enhancing binder's thermal cracking performance [22].

To corroborate previous findings, data obtained from binder testing need to be compared with the performance of corresponding mixtures. The research study described in this paper aims to fulfil this need by correlating the failure properties of a set of asphalt binders determined by means of MTL tests with the fracture characteristics of corresponding mixtures determined by means of Semi-Circular Bending (SCB) tests.

SCB tests involve breaking a semi-circular specimen using a three-point bending system under a vertical load in displacement-controlled conditions. Li and Marasteanu [23] developed a standardized SCB procedure specifically conceived to quantify fracture resistance of asphalt mixtures at low temperatures. They found that the SCB test exhibited extremely low variability in assessing the fracture toughness of asphalt specimens at low temperatures, making it a reliable method. In addition, SCB tests present other advantages, including short duration and ease of sample preparation in the laboratory. Several parameters derived from the SCB test have been analysed in various experimental studies to understand the behaviour of asphalt mixtures at low temperatures. Fracture energy (G_f) and Flexibility Index (FI) have been often used to predict fracture toughness [24]. Majidifard et al. [25] proposed the Balanced Cracking Index (BCI), calculated as the product between G_f and the displacement at 75 % of the maximum load, indicated as L_{75}. Such a parameter accounts for the influence of the post-peak zone on the ductile-to-brittle behaviour of the asphalt sample. Another parameter measured in the SCB test is fracture toughness (K_{ic}). Malek et al. [26] investigated the effects of temperature, air voids, and loading rate on K_{ic}. They found that K_{ic} increases as the test temperature decreases, due to the rise in Young's modulus of the mixture with decreasing temperature. In another study, Xiongzhou et al. [27] evaluated K_{ic} by varying specimen thickness. According to the study, K_{ic} is not highly sensitive to the thickness of the SCB specimen. However, the authors recommend using 50 mm thick samples. Ashani et al. [28] proposed a method to identify a "mixture-based" performance grade by correlating G_f obtained from the SCB test and rheological results obtained from the BBR test. This mixture-based PG can be determined by reporting the temperature at which the G_f reaches a minimum established threshold value. Moreover, Kaseer et al. [29] introduced the Cracking Resistance Index (CRI), calculated as G_f divided by the peak load. Such a parameter was demonstrated to capture the differences in behaviour between different mixtures exhibiting same G_f but different peak loads. CRI also showed high repeatability and reliability in identifying brittle properties of the material.

1.1. Objective

The experimental study described in this paper aimed to correlate low-temperature failure properties of asphalt binders and those of corresponding mixtures. I_B and T_{cr} parameters derived from MTL tests were selected to assess low-temperature performance of binders and compared to G_f and CRI parameters calculated from SCB tests on asphalt mixtures. The analysis of results was conducted with the specific goal of assessing the coherence in ranking order of binders with that of corresponding mixtures, to corroborate the effectiveness of MTL test method for the evaluation of binders' thermal-cracking potential.

2. Materials

The set of asphalt binders employed in the experimental investigation included two neat binders (referred to as A and B) and two SBS polymer-modified binders (referred to as C and D). Binders A and B belonged to 50/70 penetration grade according to EN 12591 [30]; binders C and D were classified as PMB 45/80–70 according to EN 14023 [31]. The materials were subjected to a preliminary characterization including rheological tests carried out according to AASHTO T 313–12 [9] and AASHTO T 315–22 [32]. They were also subjected to short- and long-term aging treatments, using the Rolling Thin Film Oven Test (RTFOT) [33] and Pressure Aging Vessel (PAV) [34], respectively. Based on test results, the binders were classified according to AASHTO M 320–23 [35]. A description of asphalt binders used in the experimental investigation is given in Table 1.

The four unaged asphalt binders were used to produce four asphalt mixtures. In order to discriminate the sole effect of binder phase, the mixtures were characterized by the same composition in terms of aggregate, sieve-sized distribution and binder content. They were named Mix A, Mix B, Mix C, and Mix D depending on the binder used in each.

The aggregates employed for mixing were of siliceous origin and were supplied by a local quarry in five different particle sizes (Fine sand 0/4, Coarse sand 2/6.3, Crushed stone 6.3/12.5, Crushed stone 10/20, Filler). The five classes were properly combined to obtain a target gradation curve corresponding to a standard dense-graded mixture with maximum nominal aggregate size of 16 mm (AC16). The asphalt binder content was set equal to 4.5 % by weight of total mixture, based on a volumetric mix design conducted according to Italian technical specifications [36]. Composition of mixtures (in terms of relative proportions of aggregate fractions and asphalt binder) and design gradation curve are reported in Table 2 and Fig. 1, respectively.

3. Methods

3.1. MTL test and data modelling

The MTL tests were carried out following a procedure similar to that adopted in previous works [19–22]. Measurements were conducted by means of an Anton Paar MCR302 DSR on cylindrical specimens of 4 mm in diameter and 5 mm in height. The adopted procedure consists of three main phases: I) thermal conditioning of the specimen, II) fingerprint test, and III) failure test. During the phase I, two different thermal gradients are applied to the specimen until the target test temperature is reached; afterwards, the specimen is conditioned for 10 minutes. In the phase II, the specimen is subjected to a frequency sweep test conducted in the linear viscoelastic (LVE) domain at the test temperature across a frequency range between 1 and 100 rad/s. The phase III of the procedure entails applying a monotonic torsional load until failure at a fixed strain rate.

Temperatures used in MTL testing ranged between −3 to −18°C for neat binders (A and B) and between −6 to −24°C for SBS polymer

Table 1
Asphalt binders used in the experimental investigation.

Asphalt binder code	Description	Class	Performance Grade
A	Neat	50/70	PG 64–22
B	Neat	50/70	PG 70–16
C	Modified with SBS	45/80–70	PG 76–22
D	Modified with SBS	45/80–70	PG 82–16

Table 2
Composition of asphalt mixtures.

Base components	Relative content (by weight of mixture) %
Fine sand 0–4	41.3
Coarse sand 2–6.3	13.5
Crushed stone 6.3–12.5	15.3
Crushed stone 10–20	19.8
Filler	5.7
Asphalt binder	4.5

modified binders (C and D), with a single shear strain rate equal to 0.001 s^{-1}. All tests were performed on PAV-aged binders, as such condition is considered the most relevant for low-temperature characterization.

All measurements were run in five replicates and average data were used for the analysis.

To accurately determine the behaviour of the asphalt binders at failure, stress-strain data generated from MTL tests need to be processed in order to eliminate spurious time-dependent effects due to the viscoelastic nature of materials. For this purpose, the elastic-viscoelastic principle introduced by Schapery [37] is used to convert measured strains into pseudo-strain (γ^R), as defined in Eq. 1:

$$\gamma^R(t) = \tau(t)/G^R \tag{1}$$

where $\tau(t)$ is the shear stress and G^R is a reference modulus, set equal to 1. $\tau(t)$ can be computed using the convolution integral expressed by Eq. 2:

$$\tau(t) = \int_0^{t_R} G(t_R - \xi)\frac{d\gamma}{d\xi}d\xi \tag{2}$$

where γ is the physical shear strain, G is the relaxation function, t_R is the reduced time, and ξ is the time variable of integration. Substituting Eq. 1 in Eq. 2, γ^R is obtained as follows:

$$\gamma^R(t) = \int_0^{t_R} G(t_R - \xi)\frac{d\gamma}{d\xi}d\xi \tag{3}$$

The solution of Eq. 3 requires the analytical determination of the relaxation functions of the material under consideration. In this study, the generalized Maxwell model expressed in the form of a Prony series is used, as shown in Eq. 4:

$$G(t) = G_\infty + \sum_{m=1}^{M} G_m \bullet e^{-t_R/\rho_m} \tag{4}$$

where G_∞ is the long-term relaxation modulus (assumed equal to zero for asphalt binders) whereas G_m and ρ_m are the Prony's coefficient (with m representing the number of elements in the Prony series). Substituting the value of the relaxation modulus into the pseudo-strain equation gives Eq. 5:

$$\gamma^R(t) = \int_0^{t_R} \left(\sum_{m=1}^{M} G_m \bullet e^{-t_R/\rho_m}\right)\frac{d\gamma}{d\xi}d\xi \tag{5}$$

The two components of the complex modulus G* , named G' (storage modulus) and G'' (loss modulus), can also be expressed in Prony's series terms:

$$G'(\omega_R) = \sum_{m=1}^{M} \frac{G_m \omega_R^2 \rho_m}{\omega_R^2 \rho_m^2 + 1} \tag{7}$$

$$G''(\omega_R) = \sum_{m=1}^{M} \frac{G_m \omega_R \rho_m}{\omega_R^2 \rho_m^2 + 1} \tag{8}$$

Coefficients ρ_m and G_m are determined by using the collocation method: values of ρ_m are chosen to have two values per decade, while angular frequency values are set equal to ω_i. Values of G_m are determined by means of the cross product between the inverse of the relaxation matrix $[B_m]$ and the shifted storage modulus array $\{G'\}$:

$$G_m = [B_m]^{-1} x \{G'\} \tag{9}$$

where terms of the B_m matrix are given by following expression:

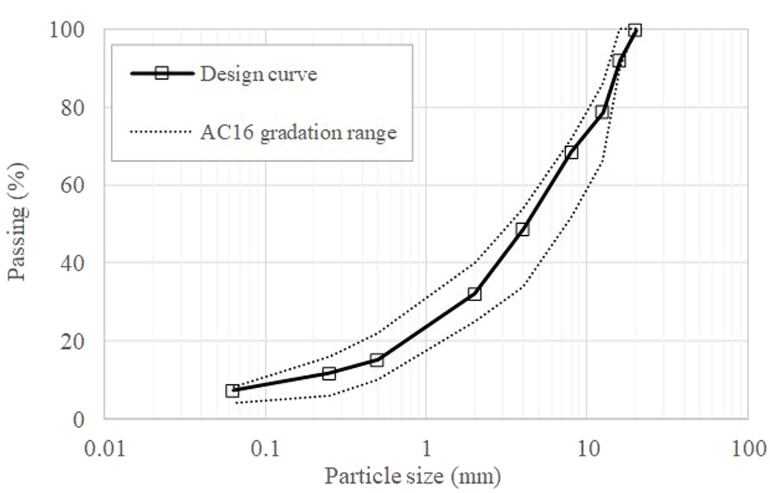
$$B_{mi} = \frac{\omega_i^2 \rho_{mi}^2}{\omega_i^2 \rho_{mi}^2 + 1} \tag{10}$$

Once the Prony terms are determined, the convolution integral of the pseudo-strain is solved using a numerical technique based on the state variable method. This method allows for the determination of the viscoelastic strain at a given time $t + \Delta t$ by knowing viscoelastic stress and strain at time t, using Eq. 11:

$$\psi_m^{n+1} = e^{-\frac{\Delta t_R}{\rho_m}} \bullet \psi_m^n + G_m \bullet \rho_m \left(\frac{\gamma^{n+1} - \gamma^n}{\Delta t_R}\right) \bullet \left(1 - e^{-\frac{\Delta t_R}{\rho_m}}\right) \tag{11}$$

where Ψ_m^n and Ψ_m^{n+1} are the values of the associated state variable of the m-th Prony coefficient at step n and n + 1, while γ^n and γ^{n+1} are the strain values at step n and n + 1, respectively.

Finally, pseudo-strains are calculated by summing all m state variables via Eq. 12:



Sieve size mm	Passing %
20	100
16	92
12.5	79
8	68
4	49
2	32
0.5	15
0.25	12
0.063	7

Fig. 1. Design gradation curve of AC16 mixtures and gradation limits.

$$\gamma^{R\quad n+1} = \sum_{m=1}^{N} \psi_m^{n+1} \tag{12}$$

This leads back to Hooke's law, adapted as follows:

$$\tau(t) = C \bullet \gamma^R(t) \tag{6}$$

where C is the so-called pseudo-stiffness. To account for specimen-to-specimen variation, the pseudo-stiffness C is corrected for each analysed specimen with a correction factor ranging between 0.9 and 1.1.

According to Eq.6, the constitutive law of a viscoelastic material is equivalent to the constitutive law of an elastic body expressed in the τ-γ^R space. It can be deduced that $\tau - \gamma^R$ curve obtained from the MTL test will be a straight line if the material exhibits a perfect LVE behaviour. Any deviation from the straight line indicates the presence of non-linear effects due to a combination of intrinsic material non-linearity and/or damage.

A parameter that can be used in the characterization of failure properties of the material is the energy density, representing the ability to absorb energy before rupture. Two energy density values can be derived from the stress–pseudostrain diagrams: the effective pseudo-strain energy density (w^R) and the potential pseudo-strain energy density (w^R_{LVE}). w^R is given by the area under the stress-pseudo-strain curve until failure, calculated according to the integral expressed by Eq. 13:

$$w^R = \int \tau(t) \quad d\gamma^R \tag{13}$$

w^R_{LVE} is given by the area under the LVE line in the same stress-pseudo-strain diagram, calculated according to Eq. 14:

$$w^R_{LVE} = \int \tau_{LVE}(t) \quad d\gamma^R \tag{14}$$

If the binder does not exhibit any non-linearity during the loading process, the two curves completely overlap with w^R and w^R_{LVE} values being the same: this condition is associated to a perfect brittle behaviour until failure. The brittleness of asphalt binder can be then quantified by means of the brittleness index I_B, calculated as the ratio between effective and potential pseudo-strain energy densities:

$$I_B = \frac{w^R}{w^{LVE}} \tag{15}$$

By definition, I_B may range between 0 and 1 with tendency to reach the unit value (corresponding to an ideally perfect brittle failure) as temperature decreases and/or strain rate increases. In general, it is possible to identify three main regions characterized by different material behaviour, denoted as ductile, brittle-ductile, and brittle regions. By associating different I_B thresholds, these regions can be appropriately discretized. For I_B values below 0.75, the material behaves in a ductile manner, whereas values above 0.95 indicate a brittle response; the intermediate brittle-ductile region is associated to I_B values between 0.75 and 0.95. As observed in previous studies [19–22], within the intermediate region the data points plotted in terms of I_B versus temperature follow an almost straight line with an abrupt change in slope above the 0.95 threshold. Based on such evidence, temperature corresponding to an I_B index of 0.95 was assumed as critical temperature (T_{cr}) to be used to evaluate and compare low temperature failure performance of asphalt binders.

3.2. SCB test and fracture parameters

SCB tests were performed on notched semi-circular specimens by subjecting them to increasing bending load until failure. Test specimens were obtained from larger cylindrical samples of 140 mm in height and 150 mm in diameter with target air voids equal to 5.0 % ± 0.2 % for all samples, manufactured by means of a gyratory shear compactor in height control mode. Loose mixtures were conditioned in oven at 135 °C for 4 hours before compaction following the ageing procedure described in AASHTO R30 [38].

Two smaller cylindrical specimens (50 mm in height) were then extracted from the top and the bottom of each gyratory sample and halved to yield two SCB specimens each. A notch of 10 mm in length and less than 1 mm in width was made for each specimen. This process allowed to obtain four semi-circular specimens (50 mm in height, 75 mm in radius) for any large gyratory cylindrical sample (Fig. 2). SCB specimens were tested at four different temperatures (Table 3) after being conditioned for period of 4 hours at the test temperature. Measurements were conducted with an UTM device by applying a vertical load in displacement-controlled condition at a rate of 5 millimetres per minute, according to EN 12697–44 [39]. Three replicates were run for each test condition.

G_f and CRI parameters used in the analysis of mixture response were determined from load-displacement curves derived from SCB test data.

The fracture energy G_f (expressed in J/m^2) was determined according to AASHTO T 393–22 [24] with the following equation:

$$G_f = \frac{W_f}{A_{lig}} \tag{16}$$

where W_f is the work of fracture calculated as the area beneath the load-displacement curve and A_{lig} is calculated as the area of ligament. According to Eq. 16, G_f is proportional to the work of fracture; specifically, the higher the value of fracture energy, the stronger the specimen tested. G_f is affected by the test temperature with lower temperatures resulting in lower G_f values. In fact, asphalt materials tend to be more brittle at lower temperatures and this reflects in less energy required to fail.

The CRI index was calculated using Eq. 17:

$$CRI = \frac{G_f}{P_K} \tag{17}$$

where P_K is the peak load (expressed in kN). This parameter is associated to ductility properties of the mixtures; specifically, the higher the CRI value, the more ductile the specimen tested. CRI is also dependent upon temperature: as the temperature decreases, the CRI decreases reflecting the increased brittleness of the asphalt mixture.

4. Experimental results

Diagrams reported in Fig. 3 show the results of MTL tests carried out on the investigated asphalt binders expressed in the form of I_B plotted as a function of temperature. The error bands indicate the range between the minimum and maximum values obtained from the different replicates.

Coherently with expectations, for each binder the brittleness index increases with the decrease of temperature showing a progressive tendency to reach the unit value. Moreover, a clear distinction between neat and SBS polymer-modified binders is observed, with curves of binders C and D being shifted on the left-hand side of the diagram with respect to the ones of other two binders A and B. This indicates that for polymer-modified binders the brittle region is achieved at significantly lower temperatures as compared to neat binders, due to the presence of rubbery SBS networks within the materials. Such an outcome reflects on lower critical brittleness temperatures T_{cr}. This is demonstrated by the results reported in the following Table 4; for comparison purposes, Table 4 also reports the low limiting PG temperatures T_S and T_m obtained from BBR tests, corresponding to the limiting creep stiffness value S_{60}= 300 MPa and the limiting creep slope value m_{60}= 0.3, respectively. It is worth noting that binder A and binder C have the same low PG temperature, even though their T_{cr} values are significantly different. Analogous consideration can be made by comparing binders B and D to each other. It follows that the two systems led to different ranking of investigated materials.

Fig. 4 reports the values of G_f versus temperature obtained for

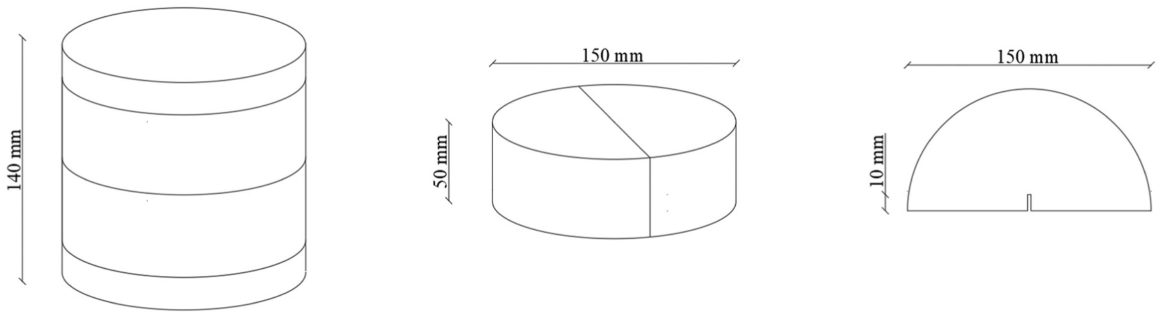


Fig. 2. Schematic representation of SCB specimen manufacturing.

Table 3
SCB test temperatures and replicates.

Test temperature °C	Mix A	Mix B	Mix C	Mix D
0	3	3	3	3
−6	3	3	-	-
−12	3	3	3	3
−18	3	3	3	3
−24	-	-	3	3

various asphalt mixtures subjected to SCB tests. As in the previous case, the error bands indicate the maximum and minimum values gathered from different replicates. All mixtures show a decreasing trend in fracture energy with decreasing test temperature. This result is also coherent with expectation since lower temperatures imply greater brittleness. The distinction between Mixes A and B (containing the unmodified binders) and Mixes C and D (containing SBS-modified binders) is readily apparent, with neat mixtures exhibiting poorer performance than modified mixtures. In fact, the fracture energy values of Mixes A and B are lower than those of Mixes C and D for any of the considered test temperature. It is also observed that both neat mixtures have a G_f value of approximately 680 J/m^2 at the temperature corresponding to critical brittleness temperature of corresponding binders; for both modified asphalt mixtures, the value of G_f is around 780 J/m^2. This confirms the

Table 4
Critical temperatures of asphalt binders determined from MTL and BBR tests.

Asphalt binder code	T_{cr} °C	T_s °C	T_m °C
A	−12	−13.1	−14.0
B	−6	−14.1	−10.7
C	−18	−18.7	−17.7
D	−19	−9.4	−19

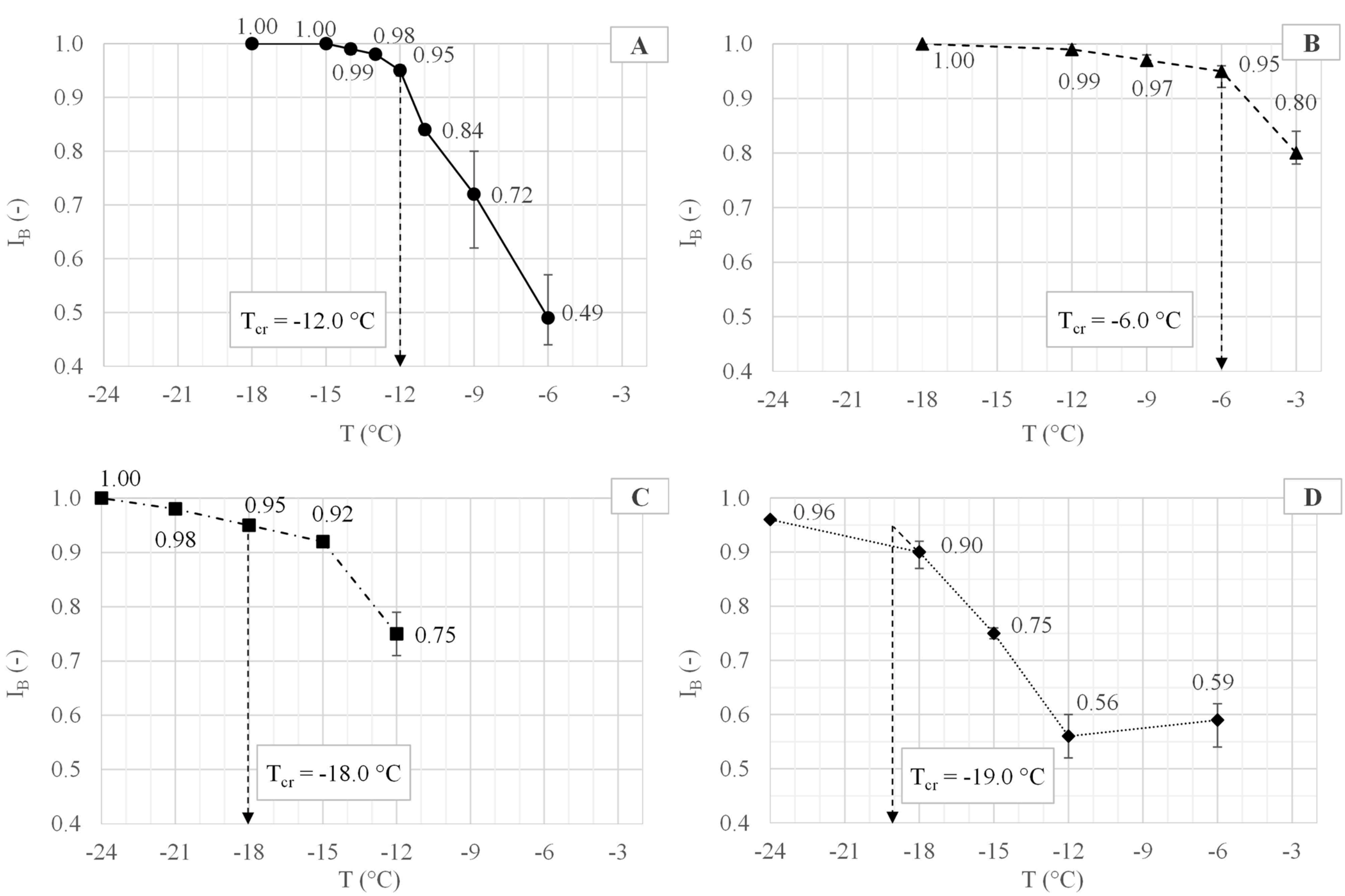


Fig. 3. I_B versus temperature plots for investigated binders.

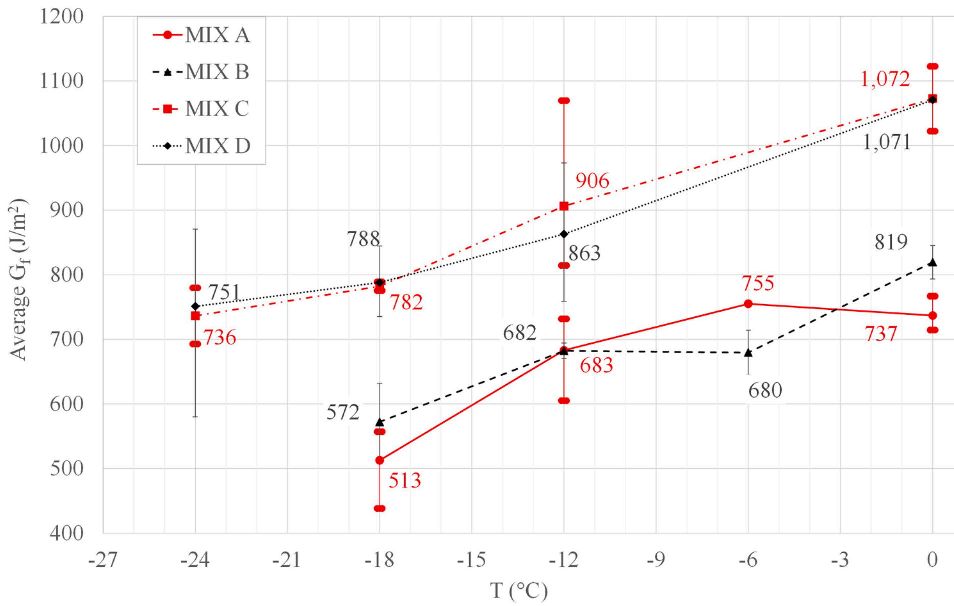


Fig. 4. Fracture energy G_f as a function of temperature T for investigated asphalt mixtures.

inconsistencies between performance of mixtures and the performance grade of the corresponding asphalt binders: in fact, mixtures containing binders having the same low limiting PG temperature showed completely different behaviours.

Additional considerations on fracture properties of mixtures can be drawn from diagrams depicted in Fig. 5, that shows the values of Cracking Resistance Index versus temperature. As already highlighted, CRI parameter normalizes the fracture energy G_f by dividing its value by the peak load achieved during the SCB test: higher CRI values correspond to better-performing samples. Similarly to G_f, the CRI decreases with the decrease of temperature. Two factors contribute to this outcome: first, the fracture energy in the numerator decreases as the temperature decreases; second, the peak load in the denominator generally increases as the temperature decreases.

Looking at Fig. 5.**A**, CRI curves of mixtures reflect the results obtained from MTL tests. In fact, Mix B exhibits a more rapid decline in CRI values than Mix A, indicating a more brittle behaviour consistently with the higher T_{cr}. Mixes C and D show very similar trends all over the temperature range considered for testing, in full coherence with the very similar T_{cr} values obtained for corresponding binders.

Fig. 5.**B** plotted CRI values of each asphalt blend as a function of $\Delta T = T\text{-}T_{cr}$, i.e. the difference between the temperature of SCB test on mixture and the critical brittleness temperature derived from MTL test on binder. This "shift" allows the data to be directly compared at the same ΔT, representing the same distance from the critical conditions. The line corresponding to ΔT equal to zero identifies the values of CRI at T_{cr}. Surprisingly, all the mixtures at $\Delta T = 0$ show very similar CRI values, ranging between 68.2 and 69.6. Moreover, below the zero value, all plots seem to follow an almost horizontal trend with very small variations and differences in data points. This indicates that for the data set considered, it has been possible to establish a single critical CRI value of around 69.0 corresponding to T_{cr}, regardless of the type of asphalt binder used for mixing.

Such an outcome suggests the existence of a mix-related low-temperature threshold associated to a critical level of fracture energy and crack resistance. In other words, the T_{cr} value determined from MTL tests seems to be able to capture a critical state of the asphalt binder reflecting on critical conditions of corresponding mixtures. From this perspective, T_{cr} parameter could be a reliable indicator of asphalt binder in terms of its thermal cracking potential.

5. Summary and conclusions

The experimental study described in this paper aimed to correlate low-temperature performance of asphalt binders and those of corresponding mixtures. Asphalt binders were evaluated by means of MTL test to determine their thermal cracking potential expressed in terms of critical brittleness temperature. Asphalt mixtures were evaluated by means of SCB tests to determine their fracture characteristics expressed in terms of fracture energy and crack resistance. The experimentation was conducted on a set of asphalt binders of several types and origins; the corresponding mixtures were prepared by adopting the same job-mix formula in order to highlight the sole role of binders and to exclude other possible concurrent effects.

The results obtained from the investigation indicated a strong correlation between the critical temperature determined from MTL testing on binders and the fracture parameters obtained from SCB testing on mixtures, thus corroborating the effectiveness of MTL method in assessing low temperature properties and thermal cracking potential of asphalt binders.

Specific conclusions of the study can be summarized as follows:

- Neat binders exhibited significantly lower T_{cr} values as compared to SBS polymer-modified binders. The last ones exhibited very similar critical temperatures (-18 for binder C and −19 °C for binder D) despite having different low-limiting PG temperatures (-22 and −16 °C, respectively).
- Asphalt mixtures containing binders characterized by lower I_B values showed higher fracture energies at considered temperatures. Furthermore, G_f values highlighted significant difference in fracture properties between neat and SBS polymer-modified asphalt mixtures.
- T_{cr} and CRI were proved to be interdependent. Asphalt mixtures containing neat binders, which are characterized by higher T_{cr} values, exhibited a sudden decrease in CRI as a function of temperatures indicative of a higher sensitiveness to premature cracking. Conversely, mixtures containing SBS-modified binders exhibited an almost overlapping trend of CRI curves, consistently with their similar T_{cr} values derived from MTL testing.
- Analysis of data in the CRI-ΔT space revealed that all asphalt mixtures exhibited approximatively the same CRI value (around 69.0) at temperature equal to the T_{cr} of their corresponding binder. Such an

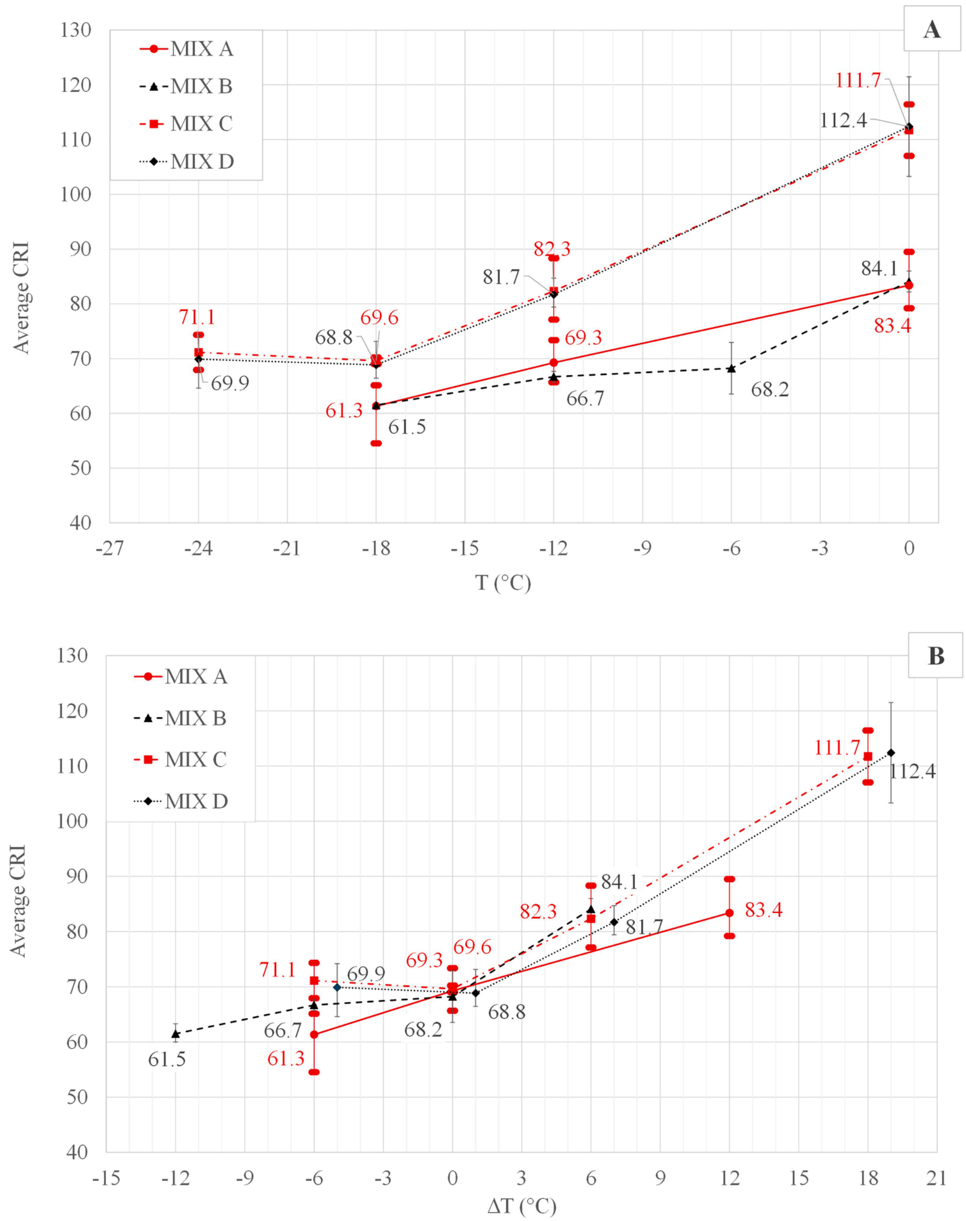


Fig. 5. CRI vs T (A) and CRI vs ΔT (B) plots for asphalt mixtures.

outcome suggests the existence of a critical level of fracture energy and crack resistance index of the mixture associated with the critical brittleness temperature of asphalt binder.

The positive results yielded by the research study need to be supported by more experimental data. Further research is warranted to correlate MTL testing on binders with low-temperature properties of mixtures by considering a wider array of materials, including mixtures characterized by different aggregate size distributions. The research should also be extended to other methods for the evaluation of low-temperature properties of asphalt mixtures, including the Thermal Stress Restrained Specimen Test (TSRST).

CRediT authorship contribution statement

La Macchia Joseph Nicolas: Writing – original draft, Methodology, Investigation, Data curation. **Memoli Mario:** Writing – original draft, Investigation, Formal analysis, Data curation. **Santagata Ezio:** Writing – review & editing, Supervision, Resources. **Dalmazzo Davide:** Writing – original draft, Data curation, Conceptualization. **Baglieri Orazio:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Data availability

Data will be made available on request.

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