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Evaluating the Role of Aggregate Gradation on Cracking Performance of Asphalt Concrete for Thin Overlays

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Abstract: Thin asphalt concrete overlays are a maintenance technique that mainly restore the functional properties of pavements. One of the main issues in thin overlays is reflective cracking that can cause early deterioration and reduce their service life. For this reason, the purpose of this investigation is to evaluate the effect of material selection on cracking performance of asphalt concrete mixtures for thin overlays. In particular, this paper evaluates the role of aggregate skeleton gradation. The study of the effect of aggregate gradation was divided into two stages: (1) fine fraction content and (2) maximum nominal aggregate size. Based on this, up to seven asphalt mixture gradations were designed and evaluated through the Fénix test at different test temperatures. The results showed a significant correlation between the fine fraction content, and maximum nominal aggregate size, and the cracking performance of the asphalt concrete mixtures. Mixtures manufactured with a low content of fine aggregates, as well as small nominal maximum size, experienced a further improvement of their toughness. These results reflected the importance of considering not only the effect of asphalt binder and environmental conditions but also aggregate gradation in the design of asphalt concrete mixtures in order to achieve a desirable cracking performance.

Keywords: aggregate gradation; fine aggregates; maximum aggregate size; cracking; Fénix test

1. Introduction

As our road infrastructure ages, infrastructure managers are looking for cost-effective solutions to preserve and extend pavement service life [1]. Selecting the right pavement maintenance strategy is crucial for the authorities because it leads to significant cost savings and also reduces traffic interruptions. Well-constructed full-depth or deep-depth asphalt pavement structures only need functional improvements instead of structural enhancement [2]. In this sense, Infrastructure managers are exploring new maintenance techniques that improve the functionality and provide an extended period of service life of the existing structurally sound pavements. These techniques include, among others, thin asphalt concrete overlays, chip seals, and ultrathin overlays.

Thin asphalt concrete overlays can meet functional requirements and correct surface deficiencies. They can restore skid resistance and ride comfort, improve water resistance, reduce noise, etc. Indeed, asphalt concrete overlays not only provide a new surface for the pavement but they are also the only preservation technique that improves the structural value of the pavement as well as extending its service life [3,4]. However, the bonding between the overlay and the existing pavement is crucial to prevent early distresses and secure a future performance [5]. Thin overlays have advantages over other rehabilitation techniques such as low life cycle cost, rapid opening to traffic, improved smoothness, very little dust generation during construction, low tire-pavement noise generation, are easily maintained or recyclable [3].

Depending on users' needs, asphalt concrete mixtures for thin overlays range from dense graded mixtures to stone matrix asphalt, open-graded friction course, permeable friction course, or ultra-thin bonded wearing courses [6].

Since thin asphalt concrete overlay mixtures are used for the wearing course, their mix design is very similar to the employed practices for standard wearing mixtures. One of the main differences is their nominal maximum aggregate size (NMAS) due to the reduced layer thickness, ranging from 15 mm to 50 mm [7]. In order to ensure adequate compaction, the NMAS should not be longer than about one-third the compacted layer thickness. For thin layers, an NMAS between 12.5 mm and 4.75 mm is typically used [8]. Since fine aggregates make up the majority of aggregate used in thin asphalt concrete mixtures and the smaller NMAS, higher asphalt content is needed to properly coat and bind the aggregate. Asphalt grade must be selected according to climate and traffic level.

The performance of thin asphalt concrete overlays will depend upon a number of factors including mix design approach and materials, underlying pavement type, surface preparation, traffic, climate and the construction quality. Based on the long-term pavement performance (LTPP) database, which is managed by the Federal Highway Administration, numerous studies have been conducted to evaluate the performance of different maintenance techniques, including thin overlays [9–11]. Indeed, there is a Specific Pavement Studies Experiment 5 (SPS-5) in the LTPP program that studies the effects of overlay thickness, overlay material, and pre-overlay treatment on the performance of asphalt overlay [12].

One of the main issues in thin asphalt concrete overlays is reflective cracking [13]. Reflective cracking occurs due to the propagation of discontinuities and cracks from the existing underlying pavement surface to the new overlay due to the vertical and horizontal movements of the overlay caused by temperature/seasonal variations and traffic loads. Reflective cracks can cause early deterioration and reduce the service life of asphalt concrete overlays. Researchers' efforts have been focused on enhancing cracking resistance of asphalt concrete overlays through increasing overlay thickness, density, employing polymer modified binders, geosynthetic interlayers or cut and seal techniques [13–18]. Some authors studied the effect of using reclaimed asphalt pavement on the cracking resistance of asphalt concrete overlays [19]. But extensive laboratory studies that examine the effects of material selection on cracking performance of asphalt mixtures for thin overlays have not been conducted. Since thin asphalt concrete overlays can address functional and safety issues and last over 10 years, the proper selection of materials, the mix design approach, and the proper conditioning of the underlying pavement are crucial to develop well-performing and long-lasting pavements.

The purpose of this study is to gain insight on how a key mix design variable such as aggregate skeleton gradation affects the cracking performance of asphalt concrete mixtures used for thin overlays. Because aggregate gradation can strongly influence aggregate interlock and mortar performance, there is a need for an in-depth study of the relationship between aggregate gradation and cracking response of mixtures.

There are numerous test methods available to understand cracking performance of asphalt concrete mixtures and among all these tests, the Fénix test, which belongs to the category of Semi-Circular Single-Edge Notched Tension Test, is performed directly on the cylindrical asphalt concrete specimens to effectively evaluate cracking resistance of mixtures in a short duration of time [20,21]. This test was developed by the Technical University of Catalonia and evaluates the cracking process in asphalt mixtures through the calculation of the dissipated energy [22].

Since the NMAS is a differential factor in thin asphalt concrete overlays, the aim of this research is to evaluate the influence of NMAS on cracking performance of asphalt concrete mixtures, as well as the effect of fine aggregate content. In order to accomplish this objective, three different gradations were designed to evaluate the influence of fine particles content, while four other different aggregate gradations were designed to evaluate the effect of the NMAS. All the gradations were studied using two different asphalt binders, a conventional binder and a polymer modified binder, in a temperature range between −5 and 20 °C.

2. Materials and Methods

The aim of this study is to evaluate the role of the aggregate skeleton gradation on the cracking resistance of asphalt concrete mixtures for thin overlays. For this purpose, the experimental work of this research was performed and discussed according to two main stages: (1) evaluation of the influence of the fine fraction content and (2) assessment of the NMAS. Additionally, the mix design included two different types of asphalt binder.

In order to evaluate the effect of the fine fraction content, three aggregate gradations were designed, (see Table 1 below). All gradations were designed with a NMAS of 8 mm. As observed in Figure 1, the designed gradations cover from continuously graded mixes to gap-graded mixes. The same filler content and nature (calcium carbonate) was used in all mixes to reduce variables in this study.

Table 1. Passing percentage for the designed aggregate gradations for stage 1.

% Passing	Sieve Size (mm)					
	10	8	4	2	0.5	0.063
Gradation 1 (F1)	100	91	70	50	22	5
Gradation 2 (F2)	100	82	40	29	15	5
Gradation 3 (F3)	100	78	20	16	10	5

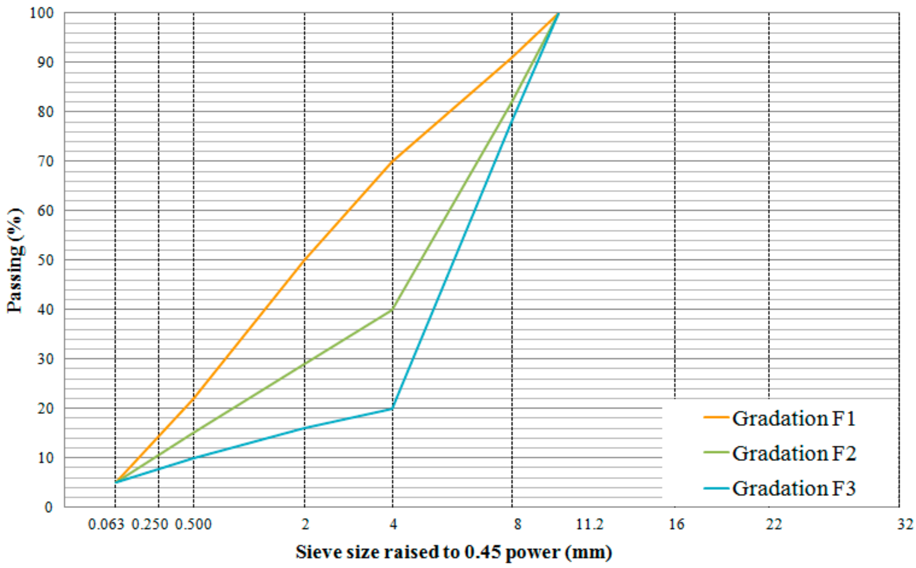

Figure 1. Aggregate gradation for stage 1.

In the case of the NMAS assessment four different aggregate gradations were designed as shown in Table 2. Mixture specimens with four different NMAS, ranging from 11.2 mm to 4 mm, and the same fine fraction content were fabricated, Figure 2. Again, the same filler content was used in all mixes.

The used coarse aggregates consisted of porfidic aggregates (specific gravity of 2.841 kg/m^3) while fine aggregates had a calcareous nature (specific gravity of 2.697 kg/m^3). All aggregates were collected from a local quarry and are being used for paving constructions in many locations.

As mentioned, two different types of asphalt binders were selected to manufacture all mixtures: a conventional binder, B35/50, and a polymer modified binder, PMB 45/80-65. Asphalt binder specifications are shown in Table 3. Both asphalt binders are frequently used in the manufacture of mixtures. In the case of study of the fine fraction effect, the bitumen content was 5.0% of the total mixture weight for both types of asphalt binders, while for the NMAS study the bitumen content was 5.5% of the total mixture weight, (see Table 4 below).

Table 2. Passing percentage for the designed aggregate gradations for stage 2.

% Passing	Sieve Size (mm)							
	16	**11.2**	**8**	**5**	**4**	**2**	**0.5**	**0.063**
Gradation 1 (S1)	100	80	68	-	40	29	15	5
Gradation 2 (S2)		100	78	-	40	29	15	5
Gradation 3 (S3)			100	-	40	29	15	5
Gradation 4 (S4)				100	40	29	15	5

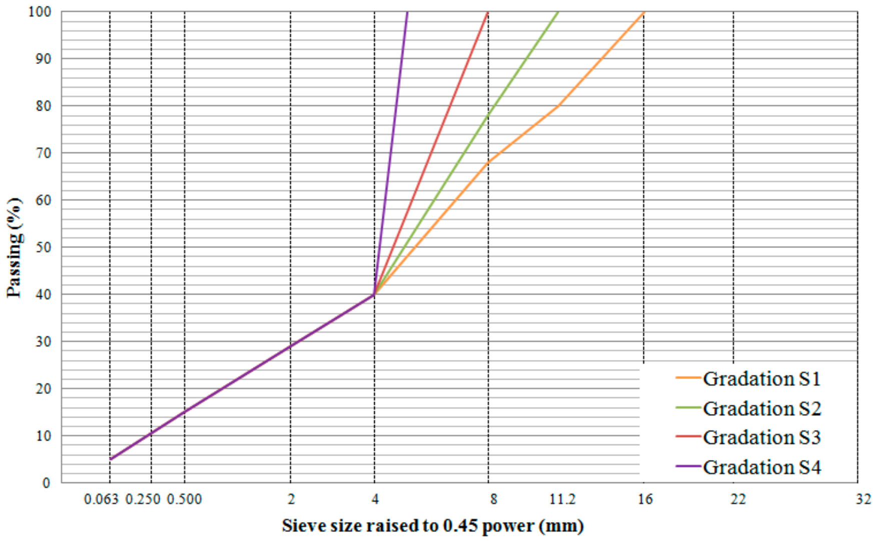

Figure 2. Aggregate gradation for stage 2.

Table 3. Properties of the evaluated asphalt binders.

Test	Unit	B35/50	PMB 45/80-65
Penetration at 25 °C	(0.1 mm)	39	57
Softening point R&B	(°C)	53.6	65.3
Penetration index	(°C)	−0.90	-
Elastic recovery at 13 °C	%	-	74

Table 4. Properties of asphalt concrete mixtures.

Gradation	Asphalt Binder	Binder Content (%)	Mean Density (kg/m^3)	Average Air Void Content (%)
F1	PMB45/80-65 B35/50	5.0 5.0	2.310 2.292	9.7 10.4
F2	PMB45/80-65 B35/50	5.0 5.0	2.249 2.261	11.5 11.0
F3	PMB45/80-65 B35/50	5.0 5.0	2.074 2.079	17.2 17.0
S1	PMB45/80-65 B35/50	5.5 5.5	2.347 2.346	7.9 7.9
S2	PMB45/80-65 B35/50	5.5 5.5	2.322 2.315	8.0 8.3
S3	PMB45/80-65 B35/50	5.5 5.5	2.259 2.265	11.0 10.8
S4	PMB45/80-65 B35/50	5.5 5.5	2.147 2.149	16.6 16.5

Marshall specimens were manufactured with 50 blows per side. In the following table the main properties of the asphalt concrete mixes are shown.

In order to evaluate the cracking resistance of these mixtures, the Fénix test was conducted. The test consists of applying a tensile stress at a constant rate of 1 mm/min on a half cylindrical Marshall specimen until the propagation of a previously induced 6-mm deep crack starts [22].

Stress and displacement data are recorded simultaneously until the displacement reaches 4×10^{-2} m, a value at which the test shall be considered terminated. Based on this load-displacement curve, the main parameters from the Fénix test are obtained:

- The Tensile Stiffness Index (TSI) measures the slope of the ascending part of the stress-displacement curve and it is related to the stiffness of the mixture
- Fracture energy (G_F) represents the work done during the cracking process divided by the fracture area
- The toughness index (TI) gives a notion of the undergone post-peak work once the specimen has failed
- The displacement at 50% post-peak load (d0.5PostFmax) is directly related to the ductility of the mixture [23] The equations used to obtain these parameters are shown in Figure 3.

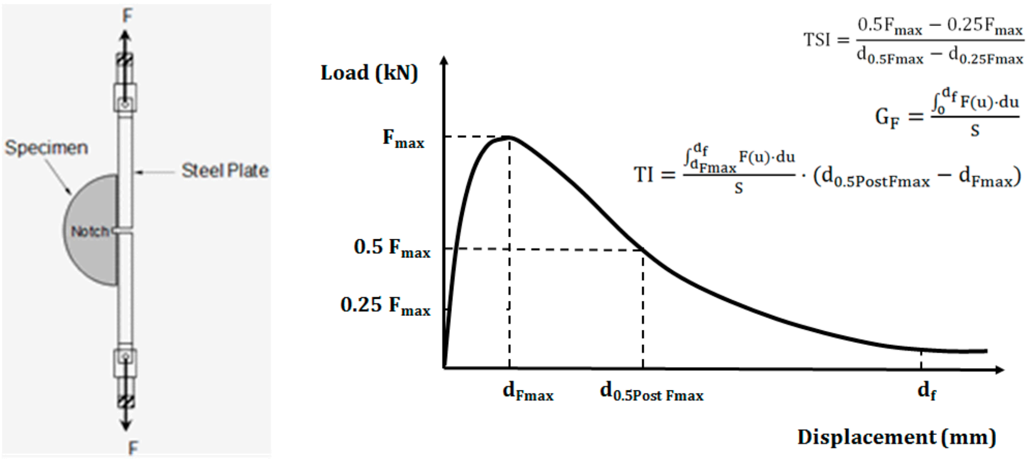

Figure 3. Fénix test set-up and stress-displacement output curve.

Due to the thermal susceptibility and complex rheological behavior of asphalt binders, the performance of asphalt concrete mixtures may change with temperature and for this reason, the effect of temperature on the cracking resistance behavior was also considered. The test was conducted at three different temperatures: 20, 5 and −5 °C. Before starting the test specimens were kept in an environmental chamber at the test temperature for a minimum of 12 h.

Four replicates for each mix design were tested at each test temperature to ensure the repeatability of the results.

3. Results and Discussion

3.1. Effect of Fine Fraction Content on Cracking Resistance

Figure 4 plots the load undergone by a representative mixture sample against displacement at a test temperature of 5 °C. Based on the obtained curves, the influence of the fine fraction content on the cracking resistance has been evaluated through parameters obtained from the Fénix test.

Analyzing the shape of the curve, two characteristics of the cracking process can be distinguished: the initial slope of the curve provides a sense of the stiffness of the mixture and the post-peak curve gives a notion about the brittleness of the specimen. The initial increased slope and the sharp dropping post-peak curve observed in the B35/50 samples show a higher stiffness and brittleness compared to the same aggregate gradation manufactured with PMB 45/80-65 at a test temperature of 5 °C. It can also be observed that mixtures with the lowest fine fraction content exhibit a more ductile breaking behavior.

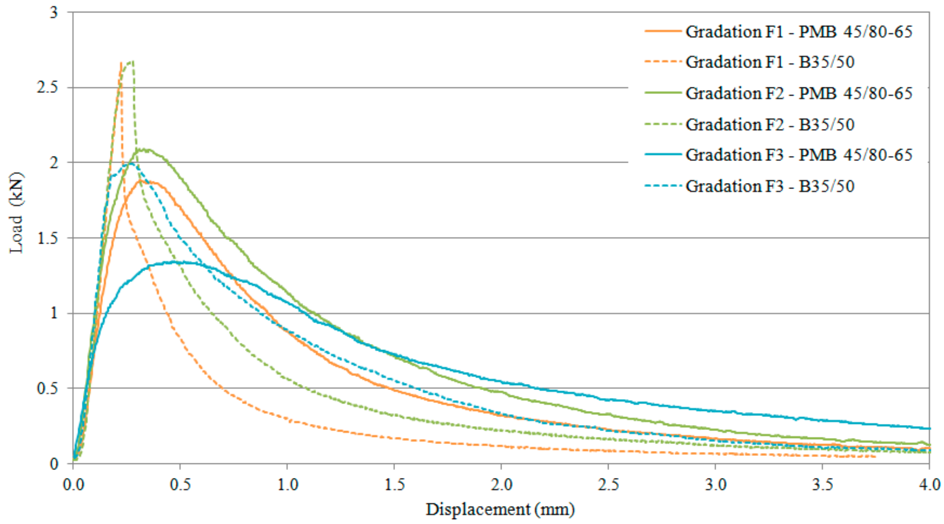

Figure 4. Stress-displacement curve at a test temperature of 5 °C.

Each one of the cracking parameters are analyzed below.

3.1.1. Tensile Stiffness Index (TSI)

The tensile stiffness index assesses the stiffness of the mixture. Figure 5 provides the average TSI values against temperature, obtained from the four replicates for each mix design.

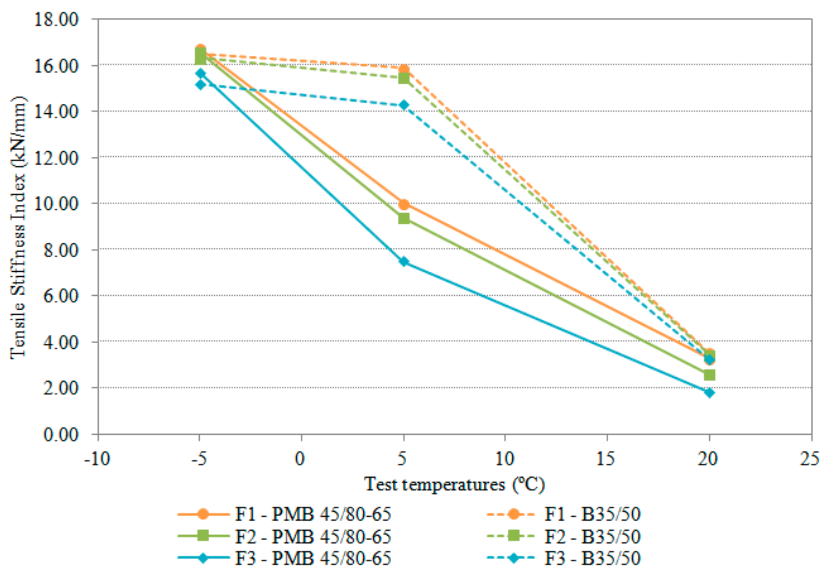

Figure 5. Tensile stiffness index versus temperature.

As observed in Figure 5, two main groups can be differentiated: mixtures manufactured with the polymer modified binder, PMB 45/80-65, and those manufactured with the conventional binder, B35/50. These results are consistent with those obtained in previous studies that stated the importance of selecting the optimal asphalt binder based on the environmental conditions to increase the cracking resistance of asphalt concrete [24].

Results show that the values of the tensile stiffness index increase with the decrease of temperature in all the evaluated mixtures. At a temperature of 20 °C all the mixtures present a similar behavior but as the temperature decreases clear differences can be observed. Mixtures manufactured with B35/50 increase stiffness more sharply than those manufactured with PMB 45/80-65, showing the greatest disparity at a temperature of 5 °C. Below this temperature, the trend is reversed and PMB 45/80-65 mixtures present the fastest growth in stiffness. However, B35/50 mixtures present the highest values over the whole temperature range, which is consistent with the properties of this binder, which has a greater stiffness compared with the polymer modified binder.

Regarding the fine fraction content, the results show slight differences depending on the fine content leading to a higher tensile stiffness index as the content of fine aggregates increases.

Statistical techniques have also been used to strengthen the conclusions drawn from the graphical interpretation. A multi-linear regression analysis has been used to fit the data and establish correlations between the tensile stiffness index and the predictors. R software (The R foundation©) was used for model estimation.

$$y = \beta_0 + \beta_1 \times x_1 + \beta_2 \times x_2 + \ldots + \beta_i \times x_i + \varepsilon \quad (1)$$

where β_i = partial regression coefficients or estimates of the regression parameters and ε = random error term.

It should be noted that only two types of asphalt binder were studied in this experimental work. So, in order to generalize these correlations other asphalt binders must be evaluated. The aim of these multi-linear relationships was to establish the weight of each studied factor and compare relevance between relevant properties.

In this case, a multi-linear relationship between the tensile stiffness index and the temperature (T), the bitumen penetration at 25 °C (BG) and the fine fraction content (F) has been obtained.

$$TSI = 19.269 - 0.531 \times T - 0.137 \times BG + 0.049 \times F$$
$$R^2 = 0.897 \quad (2)$$

The negative estimated regression coefficient for temperature implies that a temperature decrease would lead to an increase of the tensile stiffness index. Mixtures with higher fine fraction content presented higher values of stiffness, indicated by the positive coefficient.

3.1.2. Toughness Index (TI)

The toughness index gives a measure of the ability of the asphalt concrete to resist cracking fracture after reaching maximum resistance, (see Figure 6 below).

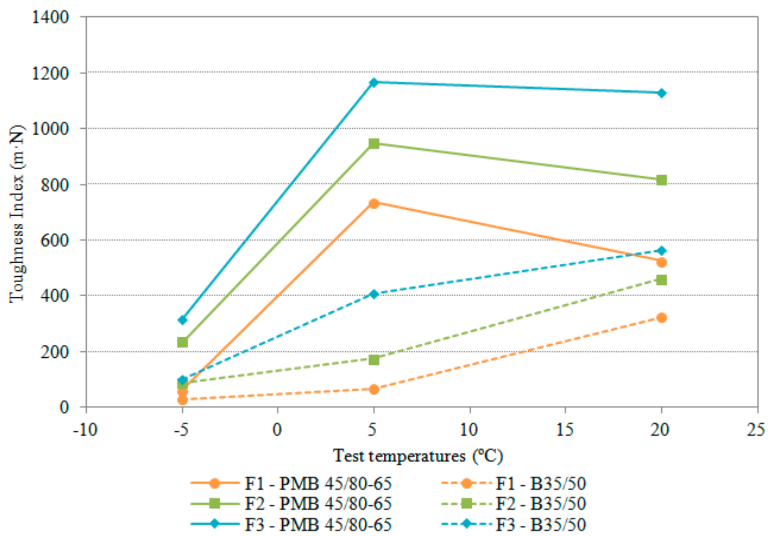

Figure 6. Toughness index versus temperature.

The toughness index gives a notion of the post-peak behavior of the mixture. At 20 °C differences in asphalt binder type and fine fraction content are more pronounced than at lower temperatures. Two trends are observed based on the nature of the asphalt binder; PMB 45/80-65 mixtures present higher values due to the greater deformation ability provided by this type of asphalt binder.

However in terms of gradation, significant variations are also shown. Asphalt concrete manufactured with the lower content of fine aggregates present more ductile breaking behavior.

The multi-linear relationship between the toughness index and the bitumen penetration at 25 °C (BG), test temperature (T) and the fine fraction content (F) can be obtained from Equation (3).

$$TI = -468.297 + 22.828 \times BG + 18.829 \times T - 9.457 \times F$$
$$R^2 = 0.614 \quad (3)$$

The statistical results are consistent with the graphical interpretation and a correlation could be established with a goodness of fit (R^2) of 0.614. As the fine fraction content increases the mixture presents a more brittle cracking response. This is consistent with the tensile stiffness index results.

3.1.3. Displacement at 50% of Post-Peak Load ($d_{0.5PostFmax}$)

As mentioned in Section 2, the displacement at 50% of post-peak load is directly related to the mixture ductility. As it can be observed in Figure 7, the results are consistent with the toughness results because they are both influenced by the ductility of the mixture.

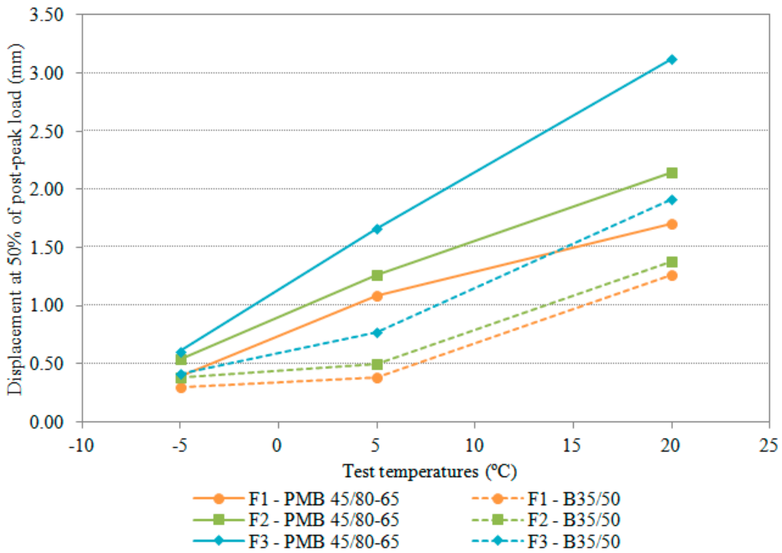

Figure 7. Displacement at 50% of post-peak load versus temperature.

At a temperature of 20 °C, clear differences can be observed. Again, two main groups can be distinguished depending on the binder type. Mixtures manufactured with the polymer modified asphalt binder present higher ductility values due to the higher deformation ability of this binder. As the temperature drops, the curves tend to come together, especially at low temperatures where smaller differences between all the mixtures are observed due to the hardening process that asphalt binders suffer.

Regarding the aggregate gradation, it is again noted that a lower content of fine aggregates leads to greater values, which indicate that the ductility of the mixture is strongly influenced by fine aggregate content.

Equation (4) presents the relationship between the displacement at 50% of post-peak load, the temperature (T), the asphalt binder penetration at 25 °C (BG) and the fine fraction content (F).

$$d_{0.5PostFmax} = -0.369 + 0.060 \times T + 0.033 \times BG - 0.015 \times F$$
$$R^2 = 0.854 \quad (4)$$

The statistical results are consistent with the graphical interpretation and a correlation could be established with a coefficient of determination of 0.854. So it can be concluded that there is a correlation between this cracking parameter and fine fraction content.

3.1.4. Fracture Energy (G_F)

The evolution of fracture energy, which is shown in Figure 8, measures the work required for crack initiation and propagation. As expected, PMB 45/80-65 mixtures present an improved cracking response.

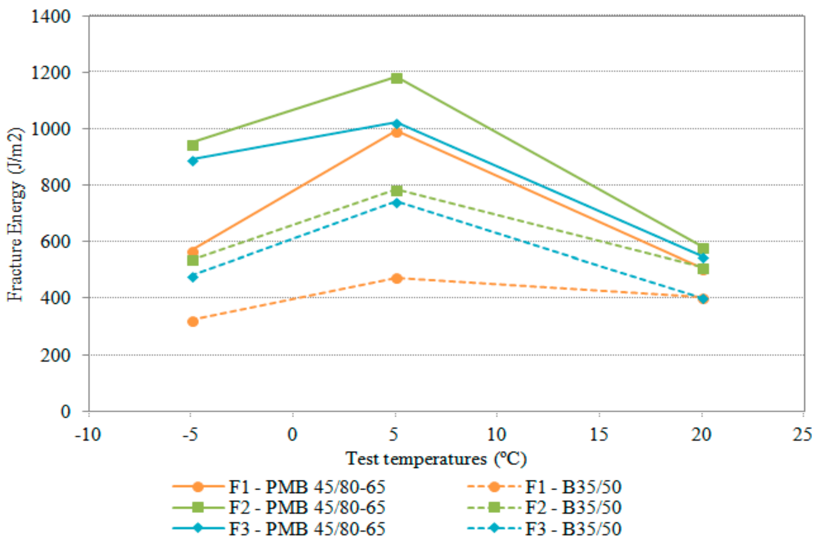

Figure 8. Fracture energy versus temperature.

However, in terms of fine fraction content, the results differ from those obtained in the above-mentioned cracking parameters. As can be observed F2 gradation requires the higher energy amount to achieve cracking followed by F3 and F1 gradation, in this order. Evaluating the statistical results, the coefficient of determination (R2) for the data set obtained is less than 0.500, showing a poor correlation between the fracture energy and the input parameters.

$$G_F = 58.855 + 16.743 \times BG - 5.890 \times T - 4.931 \times F$$
$$R^2 = 0.403 \quad (5)$$

This may be explained by the fact that the fracture energy parameter is influenced by the maximum load as well as the post-peak curve. As the fine fraction content increases, the maximum load tends to increase but at the same time, the toughness tends to diminish. For this reason, the fine fraction content that represents a balanced combination between the maximum load and maximum toughness will result in a peak value of the fracture energy.

3.2. Effect of the Nominal Maximum Aggregate Size on the Cracking Resistance

The following subsection evaluates the effect of the NMAS on the designed mixtures. In this case, four different aggregate gradations have been designed and manufactured with two different asphalt binders. Figure 9 shows the obtained curves for all the mixtures at 5 °C.

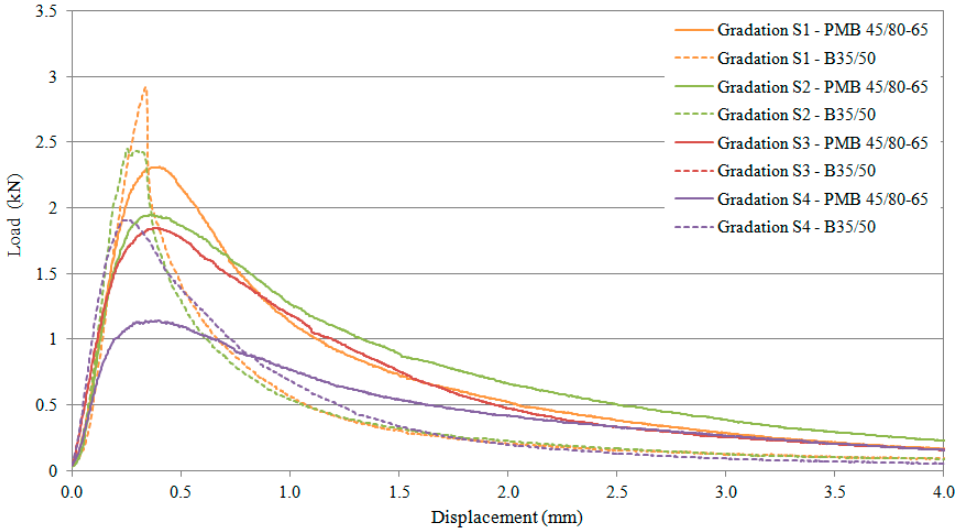

Figure 9. Stress-displacement curve at a test temperature of 20 °C.

As the NMAS decreases, peak load and initial slope also decrease, and a smoother drop of the post peak curve is observed. Such phenomena are indicators of a greater ductility, and are particularly pronounced in the case of PMB 45/80-65 mixtures.

3.2.1. Tensile Stiffness Index (TSI)

Figure 10 illustrates the fact that the tensile stiffness index increases with decreasing temperature for all mixtures due to the hardening process that asphalt binders suffer when temperature drops.

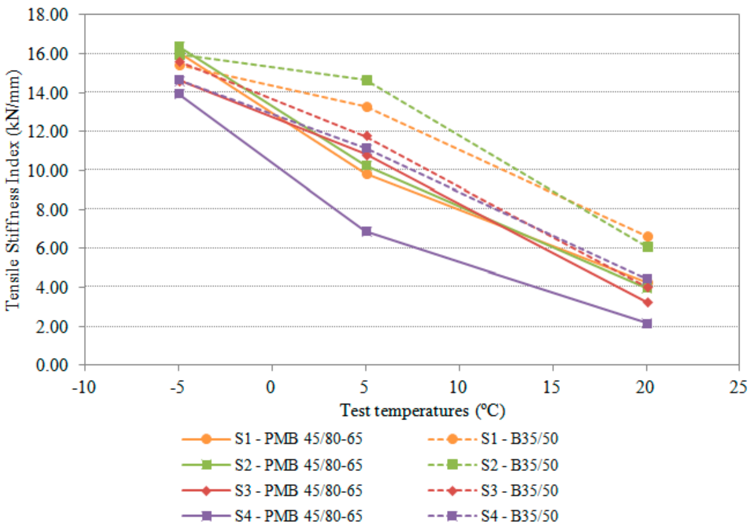

Figure 10. Tensile stiffness index versus temperature.

It can be stated that B35/50 mixtures present higher values of stiffness compared to PMB 45/80-65 mixtures, which is explained by the nature of this asphalt binder. However dissimilarities between the NMAS are not significant enough to draw conclusions visually. For this reason statistical techniques, regression analysis, have been used to establish correlations between variables. From the multi-linear regression analysis it can be concluded that the tensile stiffness index depends on the test temperature (T), the NMAS and the asphalt binder type (BG), Equation (6).

$$TSI = 15.939 - 0.441 \times T + 0.177 \times NMAS - 0.094 \times BG \quad (6)$$
$$R^2 = 0.888$$

As temperature drops, the tensile stiffness index increases and the NMAS raises.

3.2.2. Displacement at 50% of Post-Peak Load ($d_{0.5PostFmax}$)

Figure 11 provides a notion of the mixtures' ductility, which decreases as temperature drops. As expected, PMB 45/80-65 mixtures present the highest values due to greater ductility that such binder provides to the mixtures.

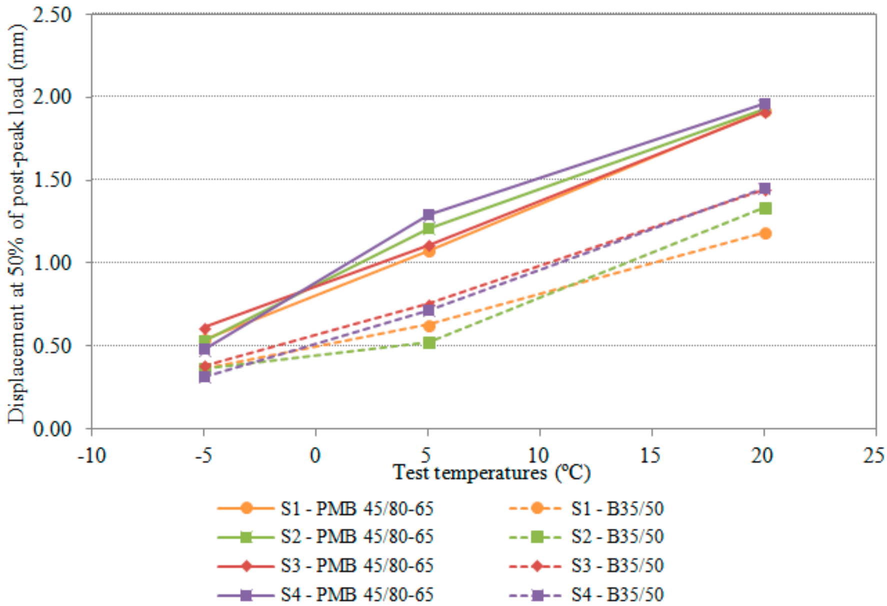

Figure 11. Displacement at 50% of post-peak load versus temperature.

Analyzing the obtained multi-linear regression equation, it can be observed that the displacement at 50% of post-peak load is strongly correlated to the test temperature (T) asphalt binder type (BG) and NMAS, Equation (7).

$$d_{0.5PostFmax} = -0.363 + 0.047 \times T + 0.023 \times BG - 0.008 \times NMAS \quad (7)$$
$$R^2 = 0.911$$

Based on the obtained results and comparing the resulting equations for fine fraction study, Equation (4), and NMAS study, Equation (7), it can be concluded that the fine fraction content exerts a stronger influence on the ductility of the mixture than the NMAS. This can be explained by the higher correlation coefficient of the fine content compared to the NMAS.

4. Conclusions

This study aimed to evaluate the influence of the aggregate skeleton gradation on the cracking resistance of asphalt concrete mixtures, especially those used in thin overlays. To investigate the effect of aggregate skeleton gradation, it was considered that aggregate gradation can be divided into two main factors: (1) fine fraction content and (2) nominal maximum aggregate size (NMAS). For each stage, different gradations were designed and manufactured with two different types of asphalt binders, a conventional binder, B35/50, and a polymer modified binder, PMB 45/80-65, and Fénix tested in a temperature range between −5 and 20 °C. Based on the findings, the following conclusions can be drawn:

- The Fénix test showed enough sensitivity to compare cracking performance between the designed gradations. This test allowed the performance of all the mixtures to be evaluated under different test temperatures and relatively quickly.

- The correlation between the aggregate skeleton gradation and the cracking performance of asphalt concrete mixtures was established. Not only temperature and asphalt binder nature have a strong influence on the cracking resistance of asphalt mixtures, but also aggregate skeleton gradation.
- Asphalt concrete manufactured with PMB 45/80-65 presented an enhanced performance due to its greater ductility but as temperature drops, the performance of all the mixtures tends to converge due to the hardening process that asphalt binders suffer.
- Regarding the fine particles content, the results show a significant correlation between the fine fraction content and the measured cracking parameters. For the same asphalt binder content, asphalt mixtures manufactured with a lower content of fines aggregates resulted in a further improvement of the toughness of the mixture. Accordingly, it can be stated that the asphalt mastic and the fine fraction content have a considerable influence on the cracking resistance of asphalt concrete for thin layers.
- Regarding the influence of the NMAS, a correlation between the NMAS and cracking response of asphalt concrete has also been obtained. Indeed, as the NMAS increases so does the stiffness of the mixtures.
- It should be noted that the established correlations shall not be used to describe the cracking behavior of asphalt concrete mixtures, but to compare the relevance between the studied properties. Based on the obtained equations for the displacement at 50% of post-peak load and comparing the regression coefficients of each equation, it can be concluded the fine fraction content exerts a stronger influence on the ductility of the mixture compared to the NMAS.

The obtained results reflect the importance of considering not only the effect of the asphalt binder nature and the environmental conditions but also the aggregate skeleton gradation in the design of asphalt concrete mixtures, especially those used in thin overlays, to achieve a desirable cracking performance. In particular, special attention should be paid to the fine fraction content when designing an asphalt concrete mixture. According to the results, mixtures designed with a reduced NMAS and a low content of fine aggregated experienced a further improvement of their toughness.

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