Acta Scientiarum

http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v45i1.60212

CIVIL ENGINEERING

Study of the mechanical behavior of asphalt mixtures in terms of creep and Superpave compaction parameters

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ABSTRACT. This was a study on the mechanical behavior of hot asphalt mixtures with regard to permanent deformation, considering static creep tests and the parameters derived from the Superpave compaction curve. For the asphalt mixture production, mineral aggregates and two types of asphalt binder (CAP 50/70 and AMP 60/85) were used. These mixtures were designed using the Superpave methodology and compacted in the content and number of gyrations according to the design. For the design condition, asphalt mixtures using the conventional CAP 50/70 asphalt binder showed better workability and lower deformation than asphalt mixtures with the AMP 60/85 polymer binder. Furthermore, the influence of asphalt binder content on the behavior of asphalt mixtures in relation to permanent deformation and compaction indices was studied, considering the maximum number of gyrations in the design. Regarding this investigation, asphalt mixtures with higher asphalt binder content tend to show higher permanent deformation and better workability. Complementarily, the compaction curve indices (Construction Densification Index, CDI; modified Traffic Densification Index, TDIm and Locking Point, LP) were correlated with parameters obtained from static creep tests (total deformation after the recovery period, Dt; creep modulus, CM and curve inclination, Icurve) through curves obtained by the correlation between these indices. Based on this analysis, a good correlation was found between the results of static creep tests and compaction indices, showing the potential of these indices for predicting the mechanical behavior of the analyzed mixtures in relation to the development of permanent deformations.

Keywords: permanent deformation; static creep test; gyratory compactor; densification indices.

Received on July 21, 2021.
Accepted on April 29, 2022.

Introduction

Permanent deformation is one of the main deterioration mechanisms in asphalt pavements. This type of structural pathology has a significant impact on pavement performance over its service life (Sousa, Craus, & Monismith, 1991; Xu & Huang, 2012). Permanent deformation in asphalt pavements is one of the major concerns in roadway engineering, especially in high temperature regions since this pathology can affect the pavement performance over time and reduce the user safety. The grooving formation derived from the permanent deformation of asphalt mixtures is mainly caused by a series a factor combined such as the mixture densification over time and the shear strain derived from the traffic load (Lu et al., 2021). Therefore, the asphalt binder plays a fundamental role in the asphalt mixture resistance to the development of permanent deformations, since it is associated to aggregate lubrication during compaction, and its consequent hardening (Zhang et al., 2019). However, the performance of asphalt binders is related to its viscoelastic behavior, which has different mechanical responses according to factors, such as stress levels and temperature (Bahia & Anderson, 1995).

An approach to infer about the asphalt binder viscoelastic behavior consists of evaluating its susceptibility to developing permanent deformations by the static Creep test, by means of the Creep Modulus (CM) (Little, Button, & Youssef, 1993). Saboo and Kumar (2015) utilized this test and showed that conventional binders are more sensitive to creep, as temperature and stress levels change indicating that conventional binders have lower performance (higher permanent deformations) compared to polymer modified binders with respect to the recovery rate.

The development of permanent deformation is also related to compaction (densification) of asphalt mixtures (Dessouky, Pothuganti, Walubita, & Rand, 2013). In this context, it is essential to establish a relationship between site and laboratory compaction. The compaction method conventionally used for design of asphalt mixtures is the Marshall mix design method, based on impact compaction, which does not reliably simulate the in-site compaction process. In order to mitigate the drawbacks of the Marshall method, the Strategic Highway Research Program (SHRP) proposed the Superpave mix design method, which better simulates the pavement conditions during construction by incorporating to the mixture design, parameters related to material and to traffic load (Khosla & Ayyala, 2013), as well as promoting compaction by 'kneading' through the Superpave gyratory compactor (SGC) (Liu, Cao, Li, Li, & Sun, 2018).

Faheem, Bahia, and Ajideh (2005) proposed a method for interpreting the volumetric data from the Superpave compaction curve to extract two indices for predicting the mechanical behavior of the pavement in-site. This method consists of dividing the compaction process into two steps: the first simulating the behavior of asphalt mixtures during compaction, represented by the Construction Densification Index (CDI); and the second, related to pavement performance under traffic conditions, based on the Traffic Densification Index (TDI).

The CDI index is the energy required to compact asphalt mixtures between eight gyrations and 92% Maximum Specific Mass of the mixture (Gmm), simulating the behavior of compacted asphalt mixtures in the field. As these are related to the construction process (Faheem et al., 2005), lower CDI values are desirable to result in better workability of the mixture and less effort required during compaction in the field (Ribas & Thieves, 2019). The TDI index reflects the mixture performance under traffic loading and its consequent densification during the service life of the pavement. This index is obtained through the energy required to compact asphalt mixtures between 92 and 98% Gmm (Faheem et al., 2005). In practice, higher TDI values indicates a greater ability of the mixture to withstand the load without developing significant deformation, since densification and shear flow of asphalt mixtures under external loads are the main reasons for irreversible permanent deformation. of the asphalt pavement (Lu et al., 2021; Dan et al. 2021).

In order to establish compaction indices of asphalt mixtures associated with workability, compactability and susceptibility to permanent deformation, Dessouky et al. (2013) demonstrated a significant correlation between the compactability index, and the results of the tests performed in their study (Hamburg wheel tracking, static Creep and dynamic modulus), highlighting the potential of the compactability index to predict the mixture stability based on its resistance to permanent deformation. Although there are some studies in the technical literature related to this subject, such as those developed by Dessouky et al. (2013) and Zhang et al. (2019), there is a lack of recent studies compatible with analysis carried out in the present study.

This study aimed to study the creep mechanical behavior of two compacted asphalt mixtures using the Superpave gyratory compactor. This analysis was based on the parameters obtained in the compaction test (CDI, TDIm and LP) and the results obtained through the static Creep test, which were used to predict the behavior of asphalt mixtures in site regarding the development of permanent deformation, as well as to evaluate the influence of the binder type (conventional and polymer modified) used in asphalt mixing on this process. It was also verified whether static creep test data can be used to predict the behavior of asphalt mixtures in site. Studying asphalt mixture creep behavior and its susceptibility to developing permanent deformations is essential for the proper specification of the constituent materials of the asphalt mixture, as well as to ensuring the proper compaction of the material during construction, ensuring pavement performance and its serviceability throughout its life service.

Material and methods

All the laboratory tests to characterize the materials were performed at the Asphalt Materials and Mixtures Laboratory, *Universidade Federal de Viçosa* (UFV), and the Pavement Laboratory, *Universidade Federal de Juiz de Fora* (UFJF). All tests performed followed the technical standards and recommendation in technical literature regarding the repeatability and procedures of tests. It was presented the methodologies applied to materials characterizations, mechanical characterization of specimens by the static creep test, and the characterization of the behavior of asphalt mixtures in relation to compaction through the parameters from the compression curve. Figure 1 illustrates a flowchart describing the methodology applied in this study.

Table 1 lists the laboratory tests and their respective standards used for characterization of the fine (stone dust) and coarse (gravel 0 and gravel 1) gneiss mineral aggregates used in this study. The asphalt binders employed were: (i) CAP 50/70 petroleum asphalt cement and (ii) asphalt cement modified with SBS elastomeric polymers (AMP 60/85). Table 2 shows the results of the characterization tests performed on asphalt binders' samples, and the respective standards consulted.

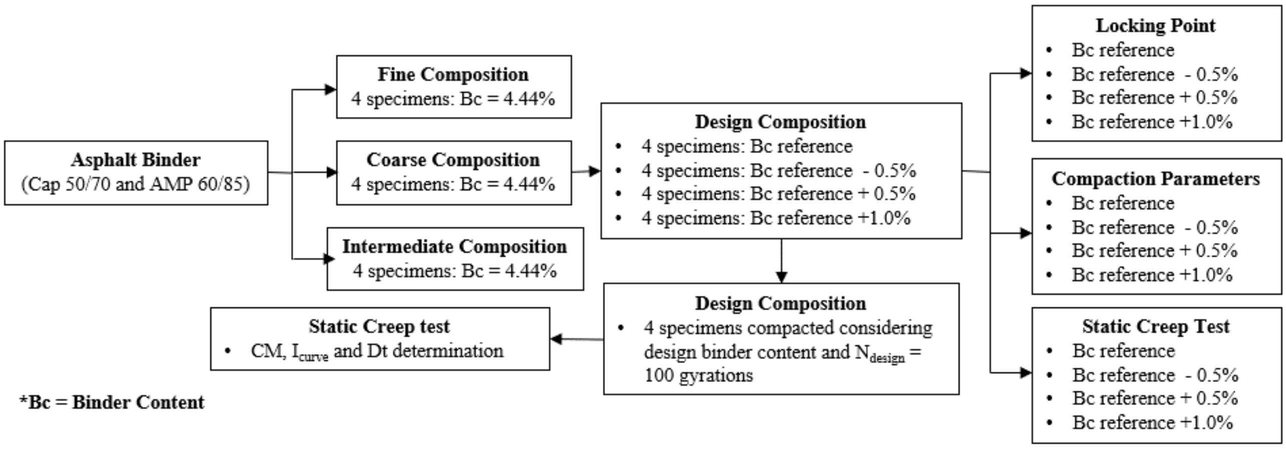


Figure 1. Flowchart describing the methodology of this study.

Table 1. Characteristics of the coarse and fine aggregates used in the study.

Properties	Material		
	Gravel 1	Gravel 2	Stone dust
Los Angeles Abrasion (%) (DNER ME 035)	45	45	-
Absorption (%) (DNER ME 195)	1.14	1.14	-
Adhesiveness to CAP 50/70 and AMP 60/85 binder (DNER ME 078)	Satisfactory	Satisfactory	-
Shape Index (DNER ME 086)	0.68	0.68	-
Specific mass (g cm^{-3}) (ABNT NBR NM 52)	2.794	2.794	2.794
Sand equivalent (%) (DNER ME 054)	-	-	59
Angularity (ASTM C 1252)	-	-	Sub rounded
Apparent specific mass (g cm^{-3}) (ABNT NBR NM 52)	2.705	2.705	-
Elongated and flat particles (ASTM - D 4791)	Semi Elongated - Semicircular	Semi Elongated - Semicircular	-

Table 2. Characteristics of asphalt binders used in the study.

Properties	Unit	Results	
		CAP 50/70	AMP 60/85
Penetration (DNIT 155 ME)	0.1 mm	55	57
Softening point (DNIT 131 ME)	°C	49.8	75
Brookfield viscosity 135GC-SP21 - 20RPM (ABNT NBR 15184)	cP	318	1120
Brookfield viscosity 150GC-SP21 (ABNT NBR 15184)	cP	162	620
Brookfield viscosity 177GC-SP21 (ABNT NBR 15184)	cP	61	235
RTFOT Retained penetration (DNIT ME 155)	%	67	73.5
RTFOT – Increased softening point (DNIT ME 131)	°C	3.8	0.5
RTFOT – Ductility at 25°C (DNIT ME 130)	%	> 150	93.0
RTFOT – Mass change % (ABNT NBR 15235)	%	-0.003	0.89
Ductility at 25°C, 20 cm, min. (ASTM D 113)	%	> 150	99.8
Flash point, min. Flash Point, min. (ABNT NBR 11341)	°C	356	220

The particle-size distribution curve corresponding to grading zone C, proposed by DNIT 031 ES, was considered for the asphalt mixture preparation. For this grading zone, the aggregate gradation and the asphalt mixture design were determined according to the Superpave design method, considering medium to high traffic. Superpave Level 1 analysis was conducted in accordance with the AASHTO PP2 specification (Asphalt Institute, 2001). The main premise of the Level 1 Superpave mix design method is that the binder content employed must be such that the asphalt mixture reaches exactly 96% Gmm or a void volume (Vv) of 4% on the number of design gyrations (Ndesign).

The respective design asphalt binder content corresponding to both asphalt binders used (CAP 50/70 and AMP 60/85) were defined for specimens cast on the Superpave Gyratory Compactor (SGC) at a number of gyrations (N) corresponding to the traffic condition in the design. Thus, samples were compacted for the number of gyrations in the design, established for the test, was Ndesign = 100, aiming to obtain samples with densities close to the road surface, for the pre-established traffic volume.

The static creep test was performed according to the methodology described in Report 465 (National Cooperative Highway Research Program [NCHRP], 2002). The asphalt mixtures designed using the Superpave method with CAP 50/70 and AMP 60/85 binders were designed in the respective design asphalt binder contents and compacted at the number of design gyrations (Ndesign = 100). Four samples in the design content for each type of asphalt mixture were compacted using the SGC, reaching the design number of gyrations. During the compaction procedure, the parameters developed based on the theories established by Hills (1973) were considered and calculated (Equation 1, 2 and 3).

$$Dt = \Delta h_{4,500}/h_0;(t = 4,500\ s) \quad (1)$$

$$CM = \sigma_0/Dt;(t = 4,500\ s) \quad (2)$$

$$I_{curve} =; \quad (3)$$

In Equation 1, h_0 corresponds to the initial sample height (mm) and Δh_{4500} corresponds to sample height variation after the recovery period of 4,500 s (mm). Parameters shown in equation 2 (Dt, CM and σ_0) corresponds, respectively, to the total specific deformation after the recovery period or permanent specific deformation (mm mm^{-1}), the creep modulus after 4,500 s test (MPa), and to the test stress applied (MPa). In Equation 3, the curve inclination I_{curve} is defined as function of deformation at 1,000 ($\varepsilon_{1,000}$) and 3,600 ($\varepsilon_{3,600}$) seconds of testing, being both expressed in mm mm^{-1}. Parameters derived from the Superpave compaction curve were used to evaluate the asphalt mixture behavior under compaction. From this compaction curve, the following parameters were obtained according to NCHRP (2002): Construction Densification Index (CDI), Modified TDI (TDIm) and Locking Point (LP).

The CDI parameter, as illustrated in Figure 2, is defined as the area between the compaction curve, the horizontal line crossing the compaction curve at the eighth gyration, and the vertical line intersecting the compaction curve at density equivalent to 92% from Gmm.

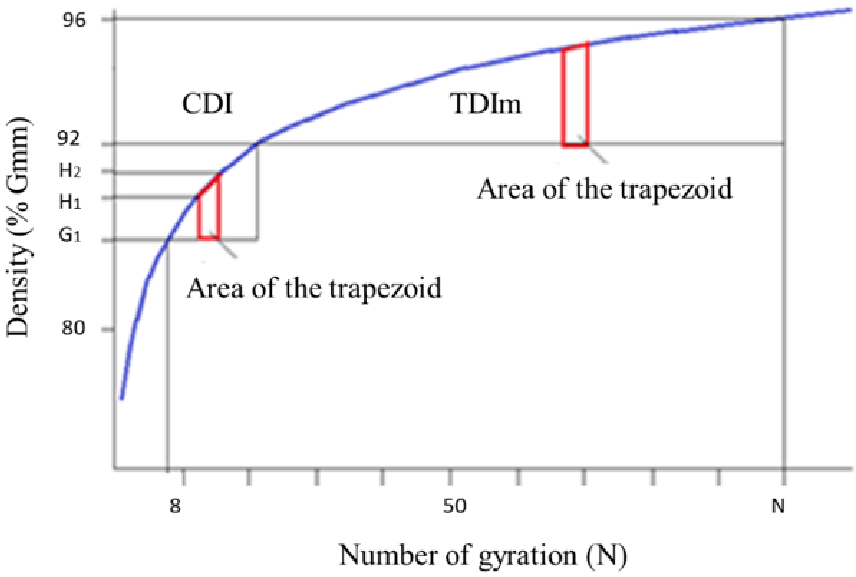


Figure 2. Graph showing the calculation of the CDI and TDIm indices.

This parameter was obtained by calculating the area of the trapezoid utilizing Equation 4 and 5. The TDI corresponds to the area between compaction curves, the horizontal line at which 92% Gmm is observed and the vertical line crossing the compaction curve when the apparent density is equivalent to 98% Gmm. Given that the compaction curve of asphalt mixtures in the study did not reach 98% Gmm, as the samples made were not compacted until the maximum number of gyrations of the test ($N_{maximum}$= 160), comprising 100 (one hundred) gyrations determined by the project, the TDIm parameter was determined by summing the trapezoid area shown in Figure 1 and utilizing Equation 6, considering the mixture reaching a maximum of 96% Gmm. Finally, the LP parameter was obtained by analyzing the height and number of gyrations of compacted samples. The LP will be the first gyration of a sequence of three gyrations of the same height, preceded by two pairs of gyrations of the same height, the first pair being 0.1 mm larger than the LP and the second 0.1 mm larger than the first.

$$Ai = \frac{(H1-G1)+(H2-G1)}{2} \times X_1 \quad (4)$$

$$CDI_{N=8gyrations}^{92\%Gmm} = \sum Ai \quad (5)$$

$$TDIm_{92\%Gmm}^{96\%Gmm} = \sum Ai \quad (6)$$

Parameters from the compaction curve (CDI, TDI or TDIm and LP) were analyzed to estimate workability in the compaction phase and the susceptibility of asphalt mixtures to stresses imposed by traffic in relation to deformations imposed.

Static creep tests were also performed, considering different asphalt binder content, which obtained the I_{curve}, Dt and CM parameters for the asphalt mixtures analyzed. These asphalt mixtures were compacted to the maximum number of gyrations ($N_{maximum}$ = 160). As compaction curves reached 98% Gmm, the TDI parameter could be calculated. If this statement was not confirmed, TDIm parameters could be obtained from compaction curves instead of the TDI index. Thus, four asphalt mixture specimens of the same aggregate gradation were compacted, with varying binder contents according to the Superpave mix design method.

To check whether the indices obtained from the compaction curve can be used to predict permanent deformation of asphalt mixtures, the compaction curve indices (CDI, TDIm and LP) were compared with the parameters obtained from the static uniaxial compression creep tests (CM, I_{curve} and Dt) to investigate the relationship between these parameters.

Results and discussion

Table 3 lists the properties obtained for design asphalt mixtures prepared using the CAP 50/70 and AMP 60/85 binders. For the CAP 50/70 asphalt mixture, the design binder content was 4.5%, and for the AMP 60/85 asphalt mixture, the design binder content was 4.00%. From this table, it is also important to notice that both asphalt mixtures meet the requirements stablished by Superpave methodology (Asphalt Institute, 2001).

Regarding the asphalt mixtures prepared with CAP 50/70 and AMP 60/85, four specimens were compacted using Superpave Gyratory Compactor with 4.30% binder content and considering the coarse granulometric composition. In addition, four specimens prepared with each asphalt binder were compacted up to maximum gyration (Nmaximum = 160) varying the binder content (4.30 ± 0.5 and +1.0%) (04 speciemens for each binder content). Volumetric properties (Vv, VAM and RBV) were determined considering the design number of gyration (Ndesign = 100). This procedure allowed to plot the following charts: (i) Vv x Binder Content; (ii) RBV x Binder Content; (iii) VAM x Binder Content; (iv) %Gmm at Ninitial x Binder Content; and (v) %Gmm at Nmaximum x Binder Content. From the plots aforementioned, it was found that the asphalt mixture prepared with 4.50% CAP 50/70 in its composition met the criteria established by the Superpave protocol, as indicated in Table 3. Regarding the AMP 60/85 asphalt mixtures, the asphalt mixture prepared with 4.0% binder content (AMP 60/85) met the criteria established by the Superpave protocol, as also presented in Table 3.

The results of the static uniaxial compression creep (static creep) tests for the CAP 50/70 and AMP 60/85 asphalt mixtures (Figure 3 and 4, respectively) show the total deformation parameters after the recovery period (Dt), creep modulus (CM) and slope of the strain curve (Icurve). The results in those figures correspond to the mean value obtained from four tested specimens.

In Figure 3, the AMP 60/85 asphalt mixture showed a higher Dt value than the CAP 50/70 asphalt mixture. Considering that Dt value represents the capacity of the mixture to remain deformed after unloading, it can be inferred that the asphalt mixture with AMP 60/85 asphalt binder is more susceptible to accumulating permanent deformations, since it has greater Dt values compared to the asphalt mixture with CAP 50/70. The results are explained by analyzing the asphalt binder viscosity. According to Bahia et al. (2001), the more viscous the asphalt binder is, greater is the influence of this property on the development of permanent deformation.

Asphalt mixtures compacted to the N_{design} for the established traffic volume are known to produce mixtures with the same density as expected in the field (FHWA, 1995). Thus, based on the results, asphalt mixtures with CAP 50/70, designed using Superpave methodology, are less susceptible to permanent deformation in site. However, since both asphalt mixtures had lower Dt values, it can be assumed that both asphalt mixtures tend to develop acceptable values of permanent deformations in site.

Table 3. Properties of the design asphalt mixtures with CAP 50/70 and AMP 60/85.

Properties	CAP 50/70 Asphalt mixture		AMP 60/85 Asphalt mixture	
	Results	Criterion*	Results	Criterion *
Void volume	4.00%	4.00%	4.00%	4.00%
Voids in mineral aggregate	14.10%	13.00% min.	13.20%	13.0% min.
Voids filled with bitumen	73.00%	65 to 75%	71.00%	65 to 75%
Asphalt-dust ratio	1.04	0.6 a 1.2	1.04	0.6 a 1.2
%Gmm at $N_{initial}$	87.40%	< 89%	87.00%	< 89%
%Gmm at N_{design}	96.00%	96%	96.00%	96%
%Gmm at $N_{maximum}$	97.40%	< 98%	97.25%	< 98%
Binder content	4.50%	-	4.00%	-

*Asphalt Institute (2001). Superpave Mix Design. Superpave Series 2 (SP-2), Third Edition, USA.

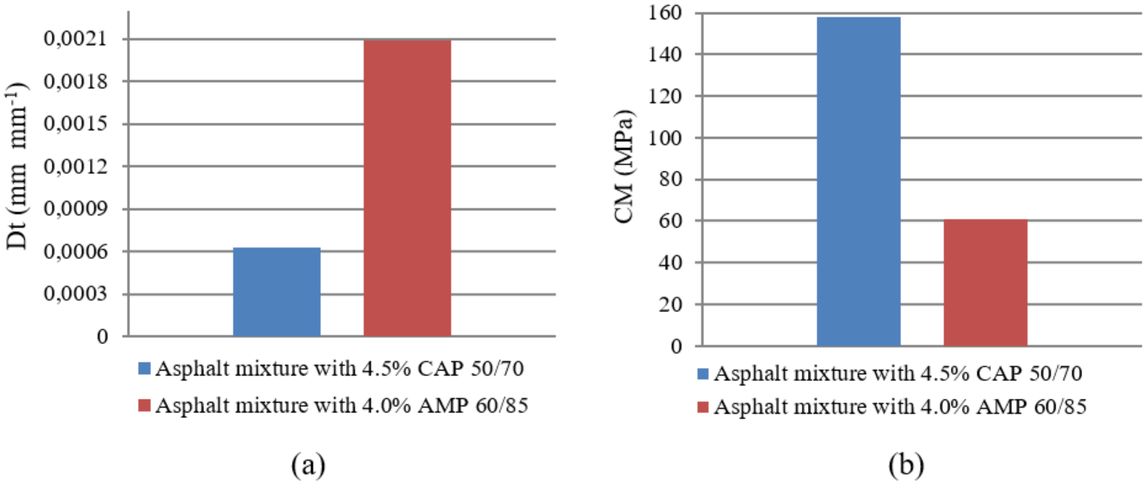


Figure 3. Total deformation after the recovery period (Dt) (a) and Creep modulus (CM) (b) of designed and compacted asphalt mixtures with their design asphalt binder contents.

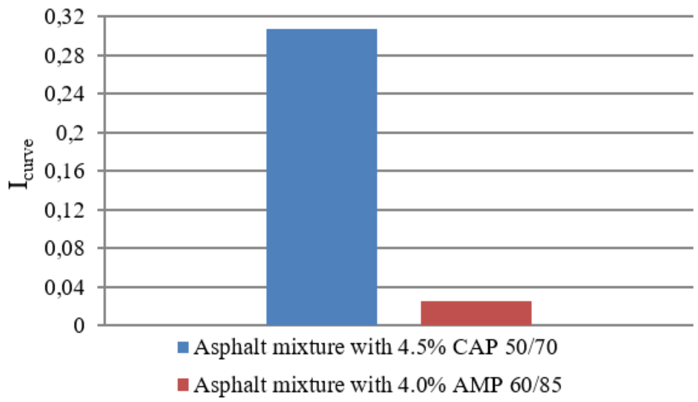


Figure 4. I_{curve} of compacted asphalt mixtures and its respective asphalt binder contents.

Since the creep modulus CM represents the relationship between applied stress and the total deformation of the specimen after the recovery period, this parameter can be used to determine the ability of an asphalt mixture to resist permanent deformation. Therefore, it can be seen in Figure 3 that the mixture with the CAP 50/70 asphalt binder has higher CM value compared to the mixture prepared with AMP 60/85, confirming that, in the context of this study, mixtures made with conventional binder have a higher ability to withstand permanent deformation in relation to mixtures with AMP 60/85.

Regarding the I_{curve} parameter (Figure 4), the asphalt mixture with binder CAP 50/70 had higher I_{curve} than the asphalt mixture with AMP 60/85. Assuming that the I_{curve} expresses the rate of permanent deformation of the asphalt mixture, high deformation rates can be correlated to a faster development of permanent deformations. Therefore, it can be inferred that the asphalt mixture with AMP 60/85 by having lower deformation rates is less affected by permanent deformation for the same loading period when compared to CAP 50/70 mixtures.

Figure 5a and b show, respectively, the CDI and TDIm results obtained from compaction tests performed with the design asphalt mixtures with CAP 50/70 and AMP 60/85. The results in Figure 4 correspond to the mean value calculated from four tested specimens. Presuming that CDI index simulates the stress applied during mixture compaction to achieve design density, asphalt mixtures with lower CDI values are desirable because they require less energy during compaction. As shown in Figure 5a, the asphalt mixture prepared with CAP 50/70 had a lower CDI value compared to the mixture with AMP 60/85, enabling to infer, therefore, that it is more workable than the mixture with the modified binder, making it more technically viable for *in situ* application.

Lower workability of mixtures with AMP 60/85 (higher CDI values) is presumed to be related to the fact that modified binders tend to have higher viscosity values compared to conventional binders. Higher binder viscosity is associated with lower lubrication of the aggregate contacts, resulting in a higher energy required for compacting the asphalt mixture to the design density (Li, Li, Su, Xue, & Rao, 2019). Moreover, the CDI values can be explained from the perspective of the design binder content required by each asphalt mixture, in a way that an asphalt mixture with lower binder content tends to present poorer workability and will be more difficult to compact. Thus, the values found in this study for the CDI parameter can be explained by the higher binder content used in the design asphalt mix with CAP 50/70.

From the analysis of Figure 5b, the CAP 50/70 mixture had a higher TDIm value than the AMP 60/85 mixture. High TDIm values indicates the expectation of mixtures more resistant to stress imposed by traffic during their service life (Li et al., 2019). Therefore, as the mixture with CAP 50/70 showed a higher value for this index than the mixture with AMP 60/85, it is believed that the asphalt mixture should have greater resistance to the densification process caused by vehicle traffic demand.

Figure 6 illustrates the mean LP index calculated from four tested specimens designed with each asphalt binder considered in this study. In this Figure 6, it is noticed that the mixture with CAP 50/70 had a lower value compared to the mixture with AMP 60/85, evidencing the greater difficulty of the asphalt mixture with modified binder in locking the solid skeleton in the compaction phase. Considering that more viscous asphalt binders tend to have less workability in the compaction phase, this type of mixtures tends to face more difficulty in particle arrangement. As a result, asphalt mixtures designed with CAP 50/70 are expected to have better workability in the field and, consequently, less energy spent in the compaction phase, which could save on compaction equipment.

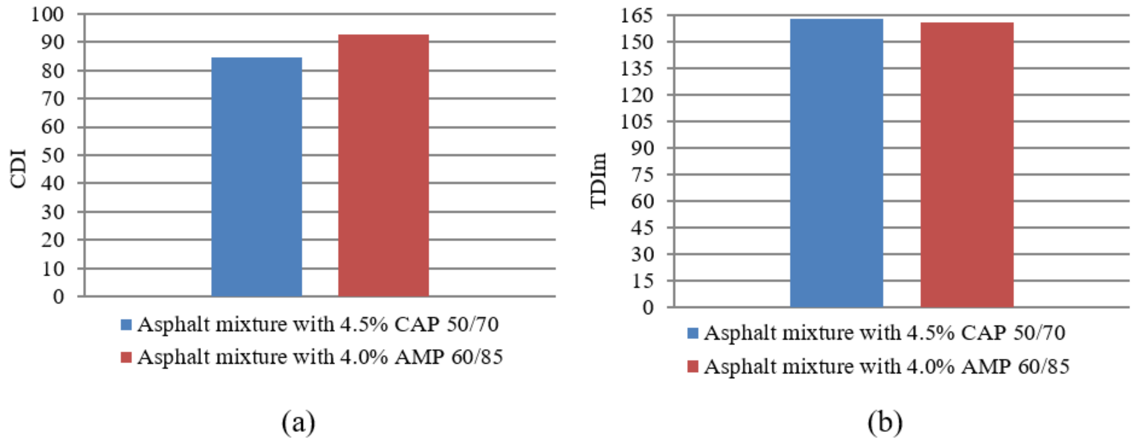


Figure 5. CDI values (a) and TDIm (b) values of compacted design asphalt mixtures.

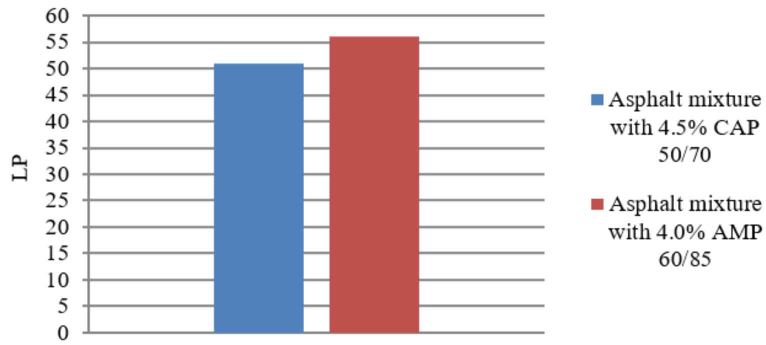


Figure 6. LP values for the compacted design asphalt mixtures.

Importantly, the results of the CDI and LP parameters indicated that the asphalt mixture designed with CAP 50/70 tends to have better workability in the field than that designed with AMP 60/85, while the TDIm parameter indicates that the mixture with CAP 50/70 is more resistant to stresses imposed by traffic during the pavement service life when compared to the mixture with BETUBLEX 60/85.

Figure 6a and b show the correlation of the static creep parameters, obtained by the static creep test, for the different asphalt binder contents (3.8, 4.3, 4.8 and 5.3%), observing the tendency of mechanical creep behavior variation in relation to content and type of binder used. Results in this figure correspond to the mean value obtained from four tested specimens considering the coefficient of variation of 10% between the results. In Figure 6, it is also possible to observe a good correlation between static creep and binder content data from the R^2 values obtained from the statistical analysis.

For creep parameters (Dt, CM) in Figure 7a and b, the results showed an opposite tendency to that identified in the design compaction condition (N_{design} = 100) for the asphalt mixtures investigated, as mixtures with CAP 50/70 were more susceptible to permanent deformation than those with AMP 60/85 under similar conditions of aggregate gradation and binder content.

The reduced CM value and the consequent increase in total deformation are related to the increase in compaction energy ($N_{maximum}$ = 160) and the increase in binder content studied in this step. The CM tendency observed from the test results converges to what was observed by Sousa, Craus, and Monismith (1991), which also highlight that increasing binder content also increases the aggregate lubrification, enabling structure rearrangement, making it less rigid and less resistant to permanent deformation.

The reduction in CM encouraged by the increase in binder content also tends to increase I_{curve} values, as can be seen Figure 8. Analysis of the I_{curve} parameter of compacted mixtures with the maximum compaction energy ($N_{maximum}$ = 160) showed a higher deformation speed in mixtures with AMP 60/85 compared to mixtures with CAP 50/70. This is the opposite to that observed for N_{design} = 100 compacted mixtures, in which higher deformation velocities were found in mixtures with CAP 50/70. Given the analysis of the parameters obtained by static creep tests, it is assumed that, for the compaction energy corresponding to N_{design} = 100, the particles of asphalt mixtures designed with AMP 60/85 have not yet reached the necessary bonding to confer the compacted mixture with greater ability to resist permanent deformation compared to mixtures with CAP 50/70. However, when compacted at $N_{maximum}$ = 160, such mixtures appear to have achieved the bonding necessary to be less susceptible to permanent deformation than mixtures using conventional asphalt binder, justifying such a reversal of behavior. In practice, this indicates that the constraints imposed by the higher viscosity of a binder to rearrangement of the asphalt mixture particles under a given compaction energy may be offset by the increase in that energy, aiming at the densification required for the asphalt mixture to perform better regarding its susceptibility to permanent deformation.

Considering the above, adjustments in compaction energy relative to the reference energy (in the case of Superpave compaction, the reference energy is equivalent to N_{design}) should be technically considered in scenarios that include the use of more viscous asphalt binders. However, it is important to note that these adjustments do not result in excess densification of the asphalt mixture that can make it excessively rigid and, consequently, more susceptible to absorption of stress resulting from the action of traffic.

Figure 9, 10a and b show the correlation between compaction parameters of asphalt mixtures for the different asphalt binder contents analyzed. Thus, the behavioral trends of asphalt mixtures studied were found in relation to workability in the compaction phase, according to the CDI and LP indices, and their susceptibility to stresses imposed by the traffic, through the TDIm index.

By analyzing the correlation between the CDI index and the binder content (Figure 9), it can be verified that both mixtures had close CDI values for the same asphalt binder content. Note also the decrease in CDI values with increasing asphalt binder content of the mixtures. This is expected since the CDI index corresponds to the energy required to compact asphalt mixtures from $N_{initial}$ to N_{design}. The tendency of CDI to reduce with increasing binder content was also reported by Li et al. (2019), who attributed this behavior to the fact that the higher the asphalt binder content, the greater the lubrication of the contact between aggregates, making them move more simply, reducing the energy required for densification of the mixture.

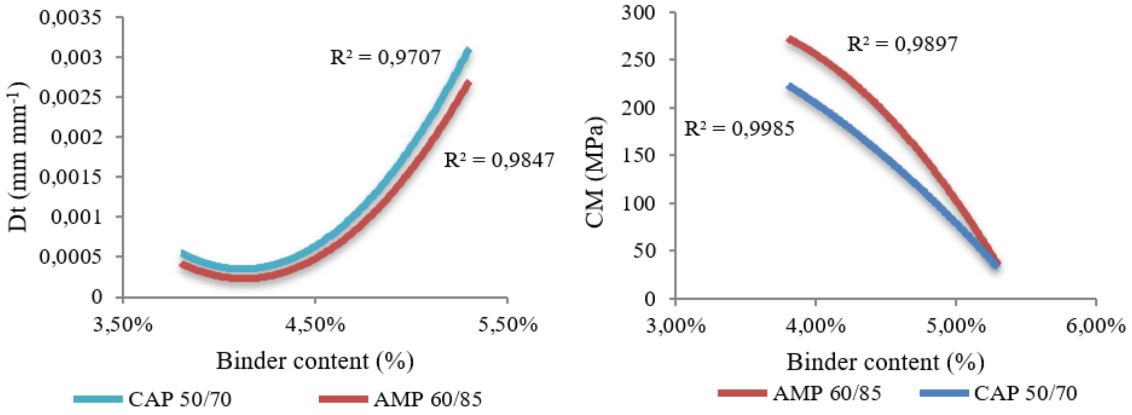


Figure 7. (a) Correlation between total deformation after the recovery period (Dt) and binder content for asphalt mixtures compacted at $N_{maximum}$ and (b) Correlation between creep modulus (CM) and binder content for asphalt mixtures compacted at $N_{maximum}$.

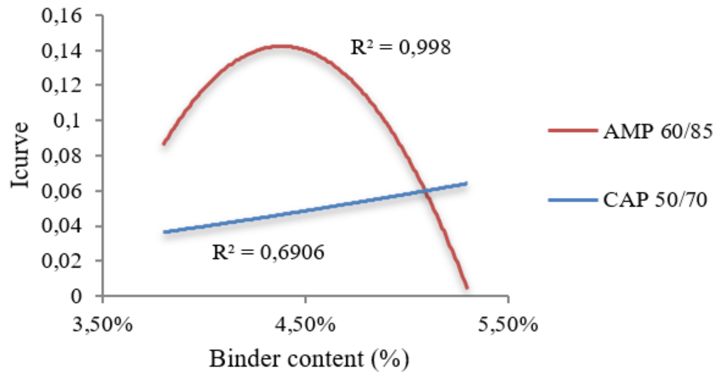


Figure 8. Correlation between the curve slope (I_{curve}) and binder content for asphalt mixtures compacted at $N_{maximum}$.

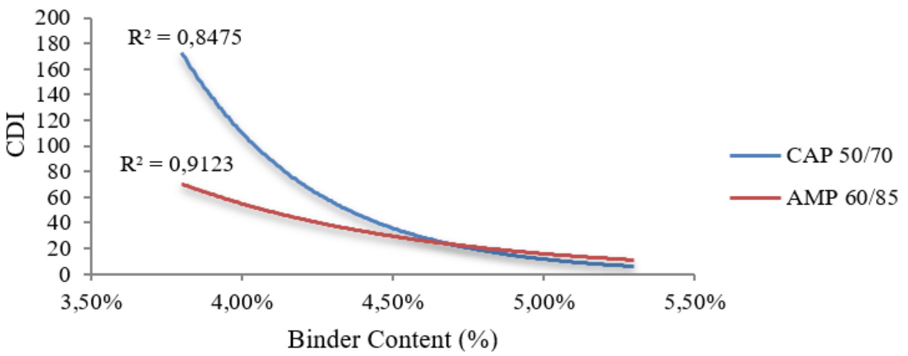
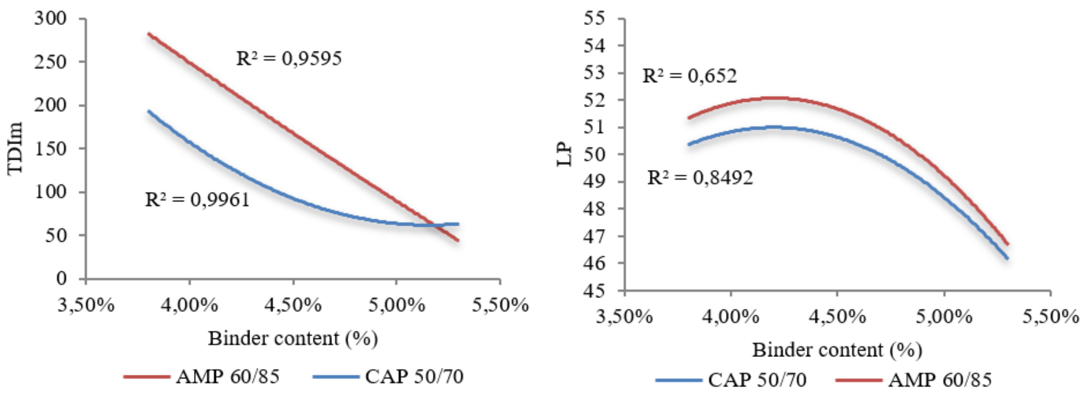


Figure 9. Correlation between CDI and binder content for asphalt mixtures compacted at $N_{maximum}$.



(a) (b)

Figure 10. Correlation between TDIm and binder content (a) and Correlation between LP and binder content (b) for asphalt mixtures compacted at $N_{maximum}$.

Nevertheless, in relation to N_{design} compacted mixtures, CDI values were higher for mixtures using AMP 60/85. This divergence in results can be explained by comparing asphalt mixtures containing different asphalt binder contents (4.0% AMP 60/85 and 4.5% CAP 50/70) compacted up to N_{design}. It can be seen from the illustrated curves that asphalt mixtures with 4.0% AMP compacted to the maximum also have higher CDI values compared to asphalt mixtures with 4.5% CAP 50/70. In practice, these results indicate that asphalt mixtures using AMP 60/85 binder, when compacted at $N_{maximum}$, appear to have achieved the necessary bonding to be less susceptible to permanent deformation than mixtures using conventional asphalt binder.

From Figure 10a, it can be noted that the TDIm parameter has an increasing tendency proportional to the reduction in binder content. Moreover, it is noted that asphalt mixtures using AMP 60/85 binder had higher TDIm values compared to asphalt mixtures with CAP 50/70. Therefore, from the tests results and considering that TDIm index represents asphalt mixture susceptibility to the stresses imposed by traffic, in a way that high TDIm values are related to better performance over time, it is assumed that asphalt mixtures with lower binder contents will be more resistant to traffic demand.

Observing the LP values in Figure 10b, for both curves, it appears that this parameter tended to increase with the reduction in asphalt binder content, showing greater difficulty in locking the solid skeleton of asphalt mixtures with lower asphalt binder content in the compaction phase. Furthermore, it can be stated that asphalt mixtures with AMP 60/85 have greater difficulty in locking the solid skeleton in the compaction phase, which shows lower workability of the mixtures. In general, through the correlations in Figure 9, 10a and b, it can be inferred that compaction parameters are higher the lower the binder content of the mixtures. This behavior is explained by the need for greater energy in the process of compacting these mixtures in the field.

Figure 11 and 12 show the attempts to relate the CDI and TDIm indices, derived from the compaction curve, and the indices obtained from the uniaxial compression static creep tests, Dt and CM, for mixtures prepared with CAP 50/70 and AMP 60/85 asphalt binders. Figure 11 and 12 indicate that low CDI and TDIm values are related to low creep modulus (CM) values and high total deformation values after the recovery period (Dt), which indicates low capability of asphalt mixtures to resist permanent deformations as CDI and TDIm increases. Moreover, the variables correlations, in general, indicated high affinity between these parameters, enabling the use of CDI and TDIm as initial indicators of the mechanical behavior of asphalt mixtures regarding to permanent deformations.

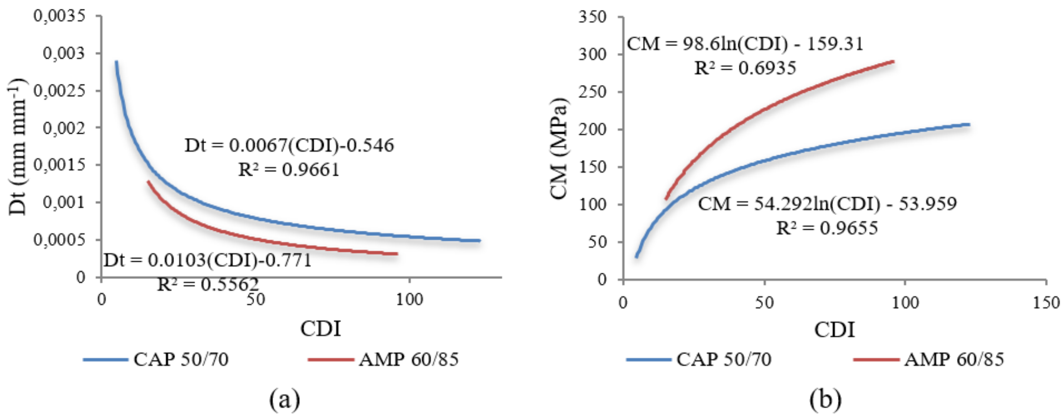


Figure 11. Correlations Dt - CDI (a) and CM - CDI (b).

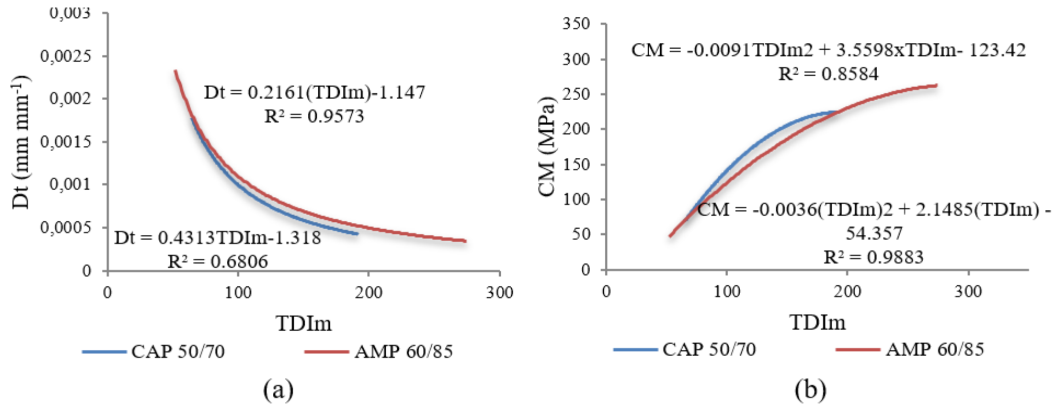


Figure 12. Correlations Dt vs TDIm (a) and CM vs TDIm (b).

Conclusion

From this research can be concluded:

- The number of gyrations and the polymeric binder high viscosity positively influenced the particle interlocking, increasing this mixture performance;
- The static creep test results demonstrates that binder content is determinant for the asphalt mixtures susceptibility to develop permanent deformations;
- The compaction curve indexes indicated that low binder contents mixtures demand more compaction energy and an increasing tendency in asphalt mixture expectation to resist the stresses imposed by the traffic load;
- The compaction indexes can used to predict the resistance to permanent deformation of asphalt mixtures using CAP 50/70 and AMP 60/85 binders.

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