

Evaluation of the effectiveness of the use of the TDI (Traffic Densification Index) for the prediction of the behavior of nano-modified asphalt mixtures against permanent deformation

Evaluación de la efectividad del uso del índice TDI (Traffic Densification Index) para la predicción del comportamiento de las mezclas asfálticas nanomodificadas frente a la deformación permanente

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Abstract

This article shows the results of a study on the evaluation of the use of the TDI (Traffic Densification Index) for the prediction of the behavior of a conventional asphalt mixture and two nano-modified asphalt mixtures (one with 2% of carbon nanotubes, CNTs, and another with 3% of organophilic nanoclay, NA) against permanent deformation. The mixtures were designed with equivalent granulometries and different asphalt binders (a conventional and two nano-modified binders). The design of the mixtures was made according to the Superpave method, and the TDI of the mixture was determined from the curves obtained in the compaction test (%G_{mm} vs number of cycles). For each mixture under study, two slabs measuring 50 x 18 x 5 cm were compacted on the BBPAC slabs compactor of IFSTTAR (Institut Français des Sciences et Technologies des Transports, de L'Aménagement et des Réseaux). These slabs were subsequently subjected to the permanent deformation test in the French traffic simulator, Orniéreur. The TDI obtained was compared with the performance of the mixtures in the permanent deformation test. The results obtained show that the TDI was not effective in predicting the behavior, in terms of permanent deformation, of asphalt mixtures with asphalt binders different from the conventional binder (nano-modified).

Keywords: Traffic densification index; nano-modified asphalt mixtures; prediction; permanent deformation

Resumen

Este artículo muestra los resultados de un estudio sobre la evaluación del uso del índice TDI (Traffic Densification Index) para la predicción del comportamiento de una mezcla asfáltica convencional y dos mezclas asfálticas nanomodificadas (una con 2% de nanotubos de carbono - NTC y otra con 3% de nanoarcilla organofílica - NA) frente a la deformación permanente. Las mezclas fueron diseñadas con granulometrías equivalentes y ligantes asfálticos distintos (un convencional y dos nanomodificados). El diseño de las mezclas fue realizado según el método Superpave y a partir de las curvas obtenidas en el ensayo de compactación (%G_{mm} vs número de giros) fue determinado el índice TDI de las mezclas. Para cada mezcla estudiada, fueron compactadas dos placas, con dimensiones de 50 x 18 x 5 cm, en la máquina compactadora BBPAC del IFSTTAR (Institut Français des Sciences et Technologies des Transports, de L'aménagement et des Réseaux); estas placas fueron, posteriormente, sometidas al ensayo de deformación permanente en el simulador de tráfico francés Orniéreur. El índice TDI obtenido fue comparado con el desempeño de las mezclas en el ensayo de deformación permanente. Los resultados obtenidos indican que el índice TDI no se mostró eficaz al momento de predecir el comportamiento, cuanto a la deformación permanente, de las mezclas asfálticas con ligante asfálticos distintos al convencional (nanomodificados).

Palabras clave: Índice de densificación del tráfico; mezclas asfálticas nanomodificadas; predicción; deformación permanente

1. Introduction

During the last years, several studies (Soares, 2014); (Onofre et al., 2011); (Lopes et al., 2011); (Nascimento, 2008); (Mahmoud and Bahia, 2004); (Bahia et al., 1998) have been seeking to develop a way to predict the performance of the asphalt mixture from parameters related to the compaction test, which is performed as part of the Superpave mixture design method (Superior Performance Asphalt Pavements). In this test, the mixtures are compacted by the kneading effect and, with the data obtained, it is possible to create a curve that relates the increase in gross specific gravity, which is equal to a percentage of the theoretical maximum specific gravity measured (%G_{mm}) of the mixture, and the number of turns applied. This is called the densification curve.

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From the data used to construct the densification curve, it is possible to determine two indices: the Construction Densification Index (CDI) and the Traffic Densification Index (TDI). According to (Bahia et al., 1998), the CDI parameter is determined as being equal to the area under the densification curve in the interval from the initial ($N_{initial}$) number of turns to the number of turns corresponding to a value of 92% of the G_{mm} (theoretical maximum specific gravity measured in the Rice test) of the mixture (Figure 1). Consequently, the CDI parameter would be related to the energy required to compact the asphalt mixture in the field during the construction of the pavement, which, in turn, is related to the workability of the asphalt material. Therefore, an asphalt mixture with a high CDI value would reflect the need for large energy consumption to achieve compaction during road construction.

Regarding the TDI, for (Mahmoud and Bahia, 2004), this index represents the amount of energy required to compact the mixture from a density corresponding to 92% of the G_{mm} up to a density corresponding to 98% of the G_{mm} . The value of the index is equal to the area under the densification curve between the two points mentioned above (Figure 1) and would be related to the capacity of the mixture, once hardened, to resist permanent deformation. The 98% G_{mm} limit is used to calculate the TDI because it is a critical density, which corresponds to the time the mixture is in the plastic fracture zone. For (Nascimento, 2008), the higher the TDI values, the better the expectations that the asphalt layer will resist the stresses imposed by the traffic of the vehicles during its service life.

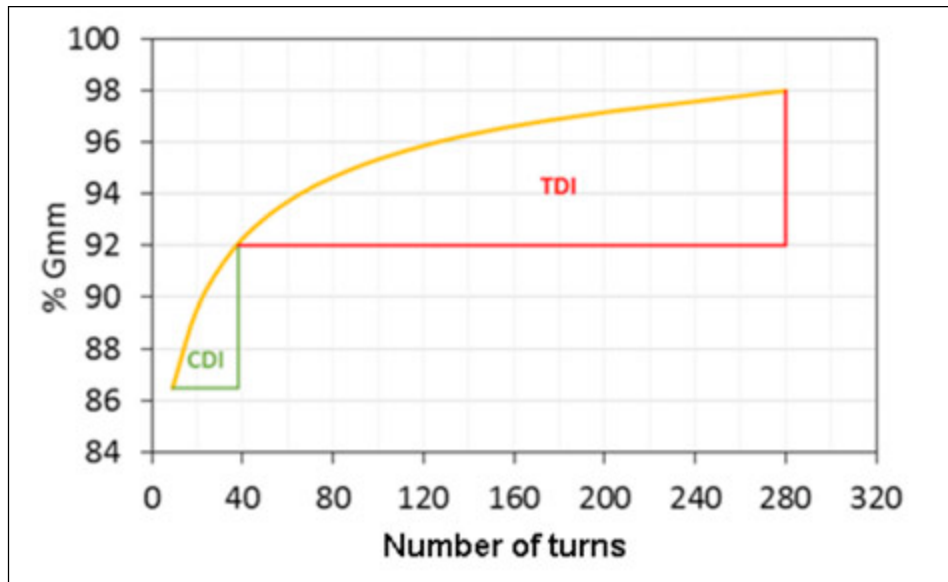


Figure 1. Graphic representation of CDI and TDI

For a high traffic volume, (Bahia and Faheem, 2007) suggest that the TDI value, to obtain a good performance against permanent deformation, should be 1200. However, these authors emphasize that such limits have to be validated in the field. Concerning Brazilian roads, (Nascimento, 2008) recommends that one of the criteria adopted for the design of dense-graded asphalt mixtures is that the TDI value be higher than 400. However, the use of such an index may not be adequate to predict the behavior of non-conventional asphalt mixtures, such as mixtures with recycled material, polymers or other types of additives.

In that sense, in order to contribute to the existing knowledge, this work shows and evaluates the results of the research on the possibility of using the TDI to predict the behavior against permanent deformation of nano-modified asphalt mixtures, tested in the French traffic simulator Ornièreur.

2. Materials

The following materials were used for the design and production of the mixtures under study: conventional asphalt binder, organophilic nanoclay (NA), carbon nanotube (CNT), mineral aggregates and hydrated lime CH-1. The conventional binder and nanoclays were used to produce two types of modified binders: an NA-modified asphalt binder and a CNT-modified asphalt binder. With these materials, three asphalt mixtures were designed in the laboratory; a reference mixture without additives, a mixture modified with carbon nanotubes (CNT) and a mixture with organophilic nanoclay (NA).

The organophilic nanoclay is composed of carbon (45.5%), silicon (33.42%), aluminum (16.08%), iron (3.60%), chlorine (0.80%), titanium (0.31%), potassium (0.27%) and strontium (0.02%). These data were obtained through X-ray fluorescence. Also, the nanoclay has a crystalline structure made up of layers of silica tetrahedra and aluminum octahedra (dioctahedral structure), with a particle size of 1×500 nm and a density of 1.7. The morphological aspect of the silicate layers of the nanoclays is shown in the photomicrograph of (Figure 2).

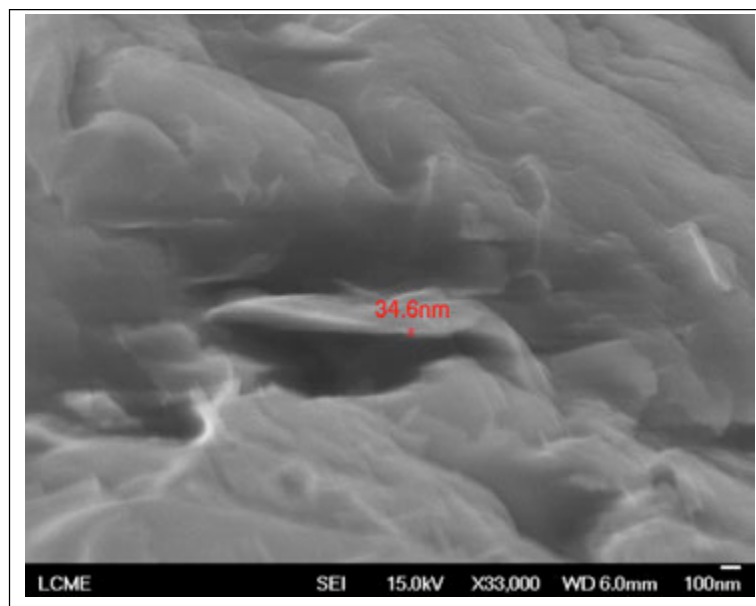


Figure 2. Nanoclay photomicrograph with a zoom of 33,000 times

The nanoclay (NA) used comes from the clay mineral montmorillonite and is modified by quaternary ammonium salts (organic cation). The organic cation used in preparing the organophilic nanoclay is dimethyl ammonium, with two alkyl chains. This salt is a surfactant; that is to say, one end has alkyl chains with hydrophobic and non-polar characteristics, with an affinity for oils, and the other end has hydrophilic and polar characteristics and with an affinity for water.

The carbon nanotubes (CNTs) used show several layers, an external diameter ranging from 50 to 80 nm, an internal diameter from 5 to 15 nm, a length from 10 to 20 μm , a density of 2.1 and a specific surface area from 60 to 80 m^2/g . The results of the X-ray fluorescence test, carried out in a Philips machine model PW 2400, showed that the CNT is mainly made up of carbon (97.37%), nickel (1.86%), iron (0.55%), chlorine (0.20%) and sulfur (0.02%). These results suggest that the material has a high degree of purity since its carbon percentage is greater than 95%. (Figure 3) shows a microphotograph of the CNT.

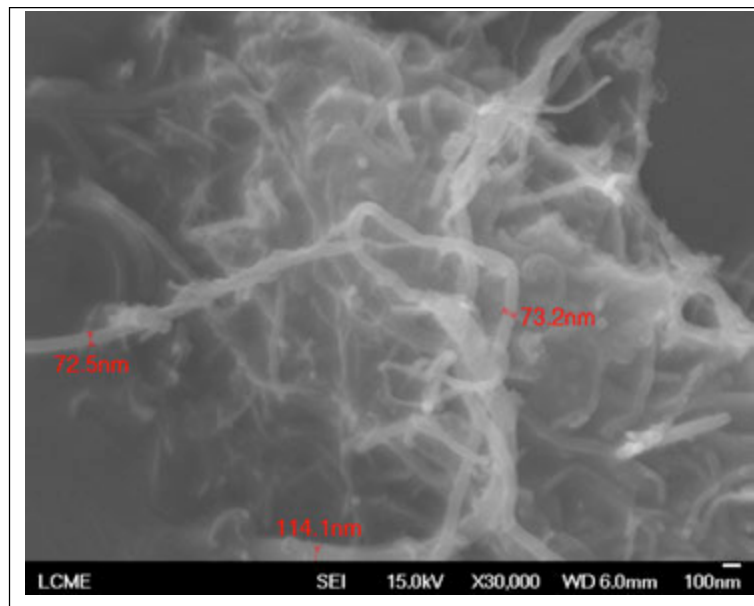


Figure 3. Carbon nanotubes photomicrograph with a zoom of 33,000 times

The asphalt binder used is conventional with a Performance Grade (PG) of 58-22. As for the other two nano-modified binders, one of them was produced by mixing conventional asphalt binder and 2% CNT and the other by mixing the conventional binder with 3% NA. The percentages of concentration of nanomaterials in the asphalt binder were defined from values present in several studies previously consulted (You et al., 2011); (Yao et al., 2012); (Zare-Shahabadi et al., 2010); (Jahromi and Khodaii, 2009); (Ashish et al., 2016); (Melo and Trichês, 2016); (Amin et al., 2016); (Steyn et al., 2013); (Hasan et al., 2012). To incorporate the nanomaterials, a high shear mixer was used, at a speed of 5,000 RPM, with an asphalt binder temperature of 150 °C (viscosity of 1.486 poise) and compatibilization of 100 minutes. (Table 1) shows the physical and rheological properties of the binders used.

Table 1. Asphalt binder properties

Properties	Conventional Binder	Binder with 3% NA	Binder with 2% CNT
Performance grade - PG (Table 3 of AASHTO M320, 2017)	58-22	64-22	64-16
Penetration (ASTM D5, 2019)	57 (1/10 mm)	55 (1/10 mm)	54 (1/10 mm)
Softening Point (ASTM D36, 2014)	47.9 °C	50.2 °C	51.9 °C
Heat susceptibility index (HSI)	-1.44	-0.92	-0.55
Viscosity at 135 °C (20 RPM) (ASTM D4402, 2015)	2.922 poise	4.125 poise	4.050 poise
Viscosity at 150 °C (50 RPM) (ASTM D4402, 2015)	1.486 poise	2.070 poise	2.050 poise
Viscosity at 175 °C (100 RPM) (ASTM D4402, 2015)	0.597 poise	0.850 poise	0.815 poise



The results in (Table 1) show that the binders modified with nanomaterials had a reduction in the penetration and an increase in the softening point. This resulted in a lower sensitivity to thermal variations, as it can be verified in the heat susceptibility index (HSI) values. This effect was more significant when CNTs were used, even when the percentage of this additive was lower than that of NA. In this sense, considering that the softening point and the HSI are generally related to the occurrence of permanent plastic deformation in asphalt mixtures, it is possible that the less susceptible the asphalt binder is to temperature, the smaller the contribution of the binder to the appearance of rutting in the asphalt layer. Therefore, regarding this phenomenon, it could be said that the behavior of the asphalt binder will improve with the addition of nanomaterials.

The apparent viscosity results showed a rheological alteration of the asphalt binder due to the addition of the nanomaterials. Thus, it can be verified that the flow resistance of nanocomposites, when submitted to stress, is higher than the flow resistance of the conventional asphalt binder. Therefore, these results would show the same trend as the softening point values.

Regarding the performance grade (PG), an increase of this parameter was verified for high temperatures as a consequence of adding nanomaterials; specifically, the increase of the PG was 6 °C. Regarding the PG at low temperatures, this parameter was not altered by the addition of the NA, but it did with the addition of CNTs. The incorporation of CNTs increased the stiffness modulus and reduced the relaxation rate compared to the conventional binder results, which would be related to a lower capacity to dissipate stresses due to thermal contraction. Thus, the use of this additive made the binder susceptible to possible thermal cracking. In this case, the addition of NA reduced the performance of the binder by 6 °C, so it would not be advisable to use this binder in regions with a very cold climate.

The natural aggregate used is basaltic and was tested to determine the values of the most important physical properties related to the acceptance of that material according to the Superpave method criteria for heavy traffic volume roads. (Table 2) shows the results of the physical characterization tests.

Table 2. Physical characteristics of aggregates

Physical Characteristics	Results	Superpave Criteria
Actual specific gravity of coarse aggregate (ASTM C127, 2015)	2.953 g/cm ³	n/a
Apparent specific gravity of coarse aggregate (ASTM C127, 2015)	2.880 g/cm ³	n/a
Absorption of coarse aggregate (ASTM C127, 2015)	0.85%	n/a
Actual specific gravity of fine aggregate (DNER-ME 084, 1995)	2.974 g/cm ³	n/a
Actual specific gravity of the filler material (DNER-ME 085, 1994)	2.804 g/cm ³	n/a
Coarse aggregate angularity* (ASTM D5821, 2017)	100%/100%	100%/100% min.
Fine aggregate angularity (ASTM C1252, 2017)	49.2%	45% min.
Flat and elongated particles (ABNT NBR 5564, 2014)	9.6%	-
Clay lumps (AASHTO T176, 2017)	61.2%	50% min.
Hardness (Los Angeles) (ASTM C131, 2014)	11.6%	35-45% max.
Soundness (ASTM C88, 2018)	2.1%	10-20% max.
Friable Particles (AASHTO T112, 2017)	0%	0.2-10% max.

* 100%/100% means that 100% of the coarse aggregate has one or more fractured faces, and 100% has two or more fractured faces



According to (Table 2), the angularity values of the coarse and fine aggregates are appropriate. The coarse aggregate is entirely fractured, as it is made by crushing, which guarantees a high degree of internal friction between the particles. The fine aggregate has a higher angularity than the minimum because of the fractured faces and roughness of the particles. These characteristics will allow the asphalt mix to have good resistance to permanent deformation. Concerning the shape of the particles, it is tolerable even if it is close to the maximum value. This result allows good workability of the mixture, avoids a high consumption of binder and decreases the possibility of fracture of the aggregates during compaction. The sand equivalent test results, used to determine the number of clay lumps, were also satisfactory, showing that the number of clay minerals found on the surface of the aggregates will not compromise the integrity of the mixture. The aggregates also showed little abrasion, measured on the Los Angeles machine, showing that the particles will be resistant to various handling processes such as crushing, storage, mixing, compaction, and vehicle traffic stresses. The aggregates lost 2.1% in weight in the soundness test, showing high resistance to disintegration caused by the weather. Similarly, no friable particles were identified.

The definition of the granulometric curve (Figure 4) was based on the Superpave method criteria for a maximum nominal size of 19 mm. Thus, this curve was formed of 43% coarse aggregate (passing through a 3/4" sieve and retained on a No. 4 sieve), 15.5% fine aggregate (passing through a No. 4 sieve and retained on a No. 200 sieve), 40% stone dust; and 1.5% lime.

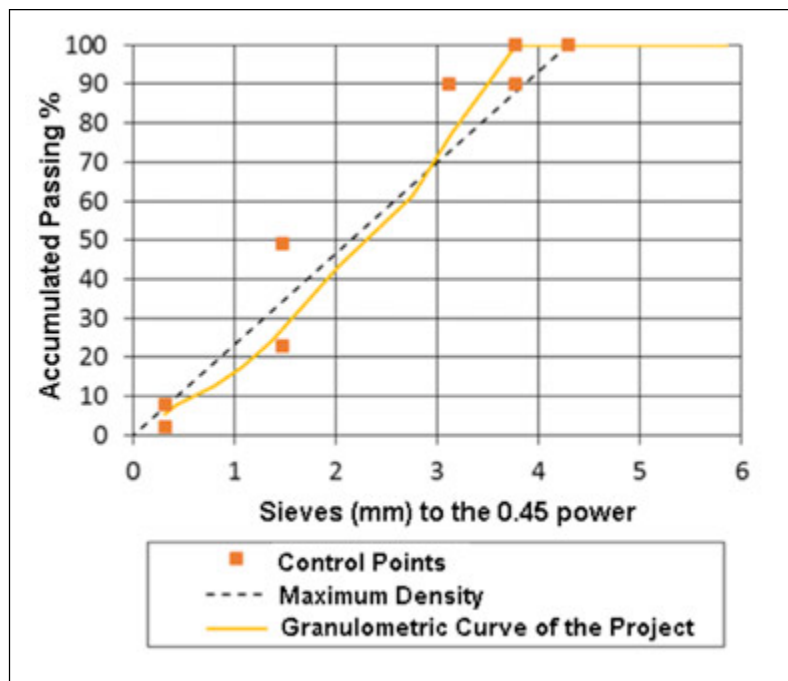


Figure 4. Granulometric curve

The hydrated lime used is type CH-I, dolomitic, classified according to the (AASHTO M303, 2019) standard as type II. (Table 3) shows the physical and chemical characteristics of this material.



Table 3. Physical and chemical characteristics of hydrated lime

Characteristics	Value
Loss on ignition	18.6%
Insoluble residue	1.9%
Carbon dioxide (CO ₂)	2.5%
Calcium oxide (CaO)	45.1%
Magnesium oxide (MgO)	33.5%
Total non-volatile oxides (CaO + MgO)	96.5%
Total non-hydrated oxides	27.6%
Non-hydrated CaO oxides	0.0%
Calcium (Ca)	32.2%
Magnesium (Mg)	20.2%
Density	3.0

3. Method

3.1 Asphalt mixture design

The optimum content of the asphalt binder in the mixtures was determined according to the recommendations of the standards (AASHTO M323, 2017) and (AASHTO R35, 2017). The compaction of the 150 mm diameter cylindrical cores was conducted in the Superpave gyratory compactor under the following conditions: compaction angle of 1.25°, compaction pressure of 0.6 MPa and rotation speed of 30 RPM. The design was made so that the mixtures could withstand a high volume of traffic ($N_{initial} = 9$ turns, $N_{design} = 125$ turns and $N_{maximum} = 205$ turns). The optimum binder content was determined to meet the following Superpave method criteria, for a maximum aggregate size of 19 mm: air volume (V_a) at $N_{initial} > 11\%$, at $N_{design} = 4\%$ and at $N_{maximum} > 2\%$; voids in mineral aggregate (VMA) $\geq 13\%$; voids filled with asphalt (VFA) between 65% and 75%; and, filler/asphalt ratio between 0.8 to 1.6. For the design of the asphalt mixture, the conventional asphalt binder was used.

3.2 Compaction of cylindrical cores to determine the Traffic Densification Index (TDI)

After the design of the reference asphalt mixture was completed, three cylindrical cores with a diameter of 150 mm and the same optimum binder content as the reference mixture were compacted for each of the three mixtures studied. In this stage, the cores were compacted in the Superpave gyratory compactor up to a number of turns to obtain a density of 98% of the G_{mm} .

To calculate the TDI, the areas under the densification curves ($\%G_{mm}$ vs. number of turns) generated during core compaction were determined. The areas were determined by using the rectangularization technique (Figure 5) as shown in (Equation 1) and (Equation 2).

$$TDI = \sum_{N@92\%G_{mm}}^{N@98\%G_{mm}} A_N \quad (1)$$

$$A_N = \left[\left(\frac{\%G_{mm}@N + \%G_{mm}@(N+1)}{2} \right) \right] - \%G_{mm}@LI \quad (2)$$

Where: TDI is the Traffic Densification Index; $N@92\%G_{mm}$ is the turn number equivalent to 92% of the G_{mm} ; $N@98\%G_{mm}$ is the turn number equivalent to 98% of the G_{mm} ; A_N is the area of any N rectangle; $\%G_{mm}@N$ is the percentage of G_{mm} in a turn N ; $\%G_{mm}@(N+1)$ is the percentage of G_{mm} in a turn $(N+1)$; $\%G_{mm}@LI$ is the percentage of G_{mm} in the initial limit, which in the case of the TDI is 92%.



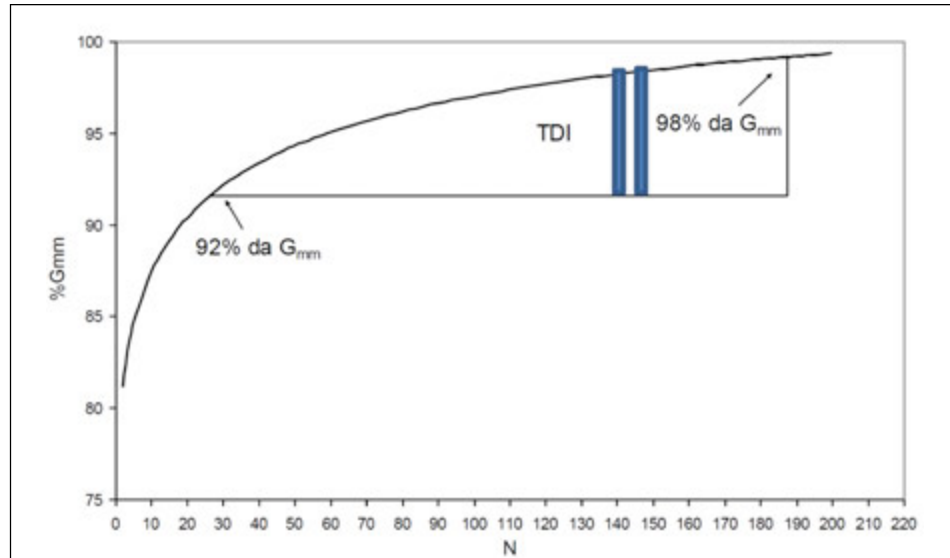


Figure 5. Diagram of the rectangularization method to calculate the TDI

3.3 Resistance to permanent deformation of asphalt mixtures

The resistance to permanent deformation of asphalt mixtures was determined in rectangular plates of 50 x 18 x 5 cm, tested in the French traffic simulator Orniéreur, following the recommendations of the French standard (AFNOR NF P98-253-1, 1993). For the test, two plates were compacted for each of the three mixtures under study. The plates were made with the same optimum binder content and the same volumetric characteristics obtained in the design of mixtures by the Superpave method for the reference mixture. The plates were compacted on the BBPAC compacting table of IFSTTAR (Institut Français des Sciences et Technologies des Transports, de L'aménagement et des Réseaux) following the recommendations of the French standard (AFNOR NF P98-250-2, 1991).

The permanent deformation test was carried out in the traffic simulator at 60 °C, through the passage of 30,000 cycles of a single axle with a single wheel on the surface of the plates applying a vertical load of 5 kN, frequency of 1 Hz and internal tire pressure of the wheel of 0.6 MPa. In this test, the passing of the wheel going forwards and backwards corresponds to one cycle. The depth of rutting generated by the wheel was measured at 100; 300; 1,000; 3,000; 10,000 and 30,000 cycles at 15 points (Figure 6) located on the surface of the plates. The result of the total permanent deformation is equal to the average of the measurements made after the test is completed, and it was calculated according to (Equation 3).

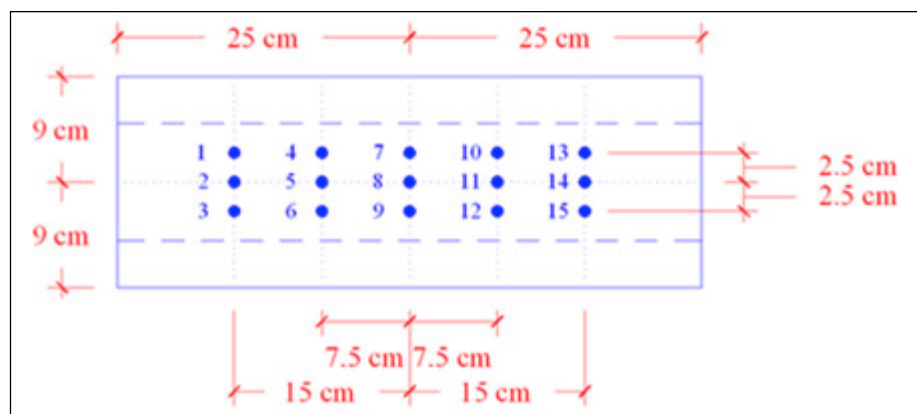


Figure 6. Rutting reading points on asphalt mixture plates



$$P_i(\%) = 100 \times \frac{\sum_j (m_{ij} - m_{0j})}{15 \times ES} \quad (3)$$

Where: P_i % is the average rutting percentage on the surface of the plate in cycle i ; j is the reading point of permanent deformation in the plate, which varies from 1 to 15; m_{ij} is the measurement of the depth in cycle i , of point j ; m_{0j} is the measurement of the initial depth in cycle 0 of point j ; ES is the thickness of the plate.

3.4 Analysis of the effectiveness of using the TDI to predict the permanent deformation of asphalt mixtures

Once the permanent deformation test was completed, the analysis was made to relate the TDI and the rutting observed in the tested plates. This analysis was carried out to evaluate the ability of the TDI to predict the behavior of asphalt mixtures to permanent deformation.

4. Presentation and discussion of results

4.1 Mixture design

(Figure 7) shows the densification curves of the cylindrical cores produced in the Superpave gyratory compactor. In the figure, the curves correspond to the binder contents used for the design of the mixtures. Also shown is the optimum content curve, estimated at 4.35%. This binder content established in the reference mixture design was also used to produce the nano-modified mixtures. (Table 4) shows the volumetric characteristics of the designed asphalt mixture, which meet the requirements of the Superpave specification.

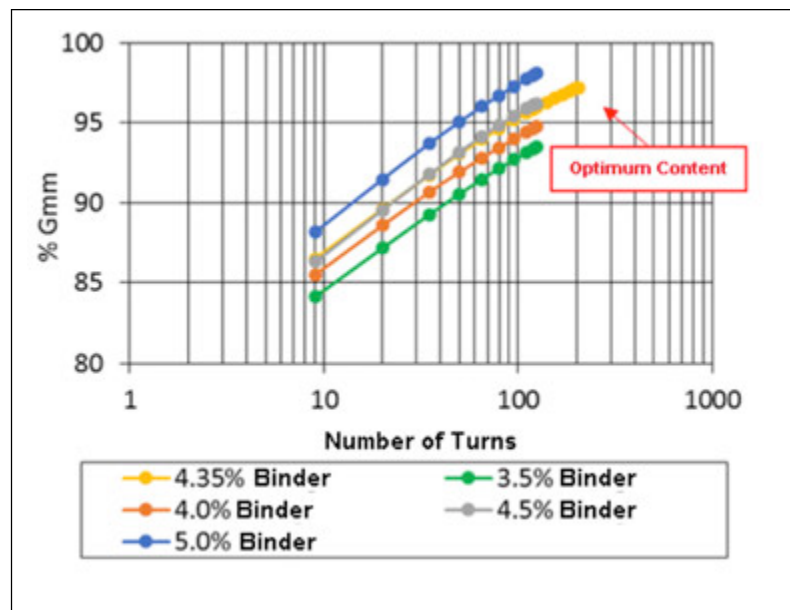


Figure 7. Densification curves of asphalt mixtures



Table 4. Volumetric properties of the designed asphalt mixture

Properties	Results	Superpave Specification Criteria
Content (%)	4.35	-
% G_{mm} ($N_{initial}=9$)	86.5	< 89
% G_{mm} ($N_{design}=125$)	95.9	= 96
% G_{mm} ($N_{maximum}=205$)	97.2	< 98
G_{mb} ($N_{design}=125$) (g/cm^3)	2.577	-
G_{mm} (g/cm^3)	2.685	-
Va (%)	4.01	= 4,00
VMA (%)	14.12	≥ 13.0
VFA (%)	71.57	65-75
Filler/asphalt ratio	1.37	0.8-1.6

4.2 Core Compaction for TDI Determination

(Table 5) shows the TDI values, calculated according to (Equation 1) and (Equation 2) for the reference mixture, as well as those nano-modified with CNT and NA.

Table 5. TDIs for asphalt mixtures

Asphalt mixtures	Binder %	TDI
Reference (CAP 50-70)	4.35	1010.7
NA (CAP 50-70 + 3% NA)	4.35	751.37
CNT (CAP 50-70 + 2% CNT)	4.35	757.59

According to the results of (Table 5), the TDI of the reference mixture was at least 25% higher than the index calculated for the nano-modified mixtures. Therefore, it is possible to confirm that the addition of the nanomaterials in the asphalt binder generated a reduction in the resistance to densification, improving the workability of the mixtures and, consequently, it can be concluded that the nano-modified mixtures would need less energy to be compacted at the same level as the reference mixture.

If the limits proposed by (Bahia and Faheem, 2007) are considered, the mixtures created would not meet the resistance to permanent deformation requirements since all the TDI values found were below 1200. However, if we consider the minimum limit of 400, as suggested by (Nascimento, 2008), all the mixtures produced with the optimum content would show a good performance against permanent deformation.

4.3 Resistance to permanent deformation of asphalt mixtures

To compare the behavior against permanent deformation, two plates of each type of asphalt mixture were compacted and tested in the French traffic simulator Orniéreur. (Figure 8) shows the formation results according to the number of cycles for the three mixtures produced.



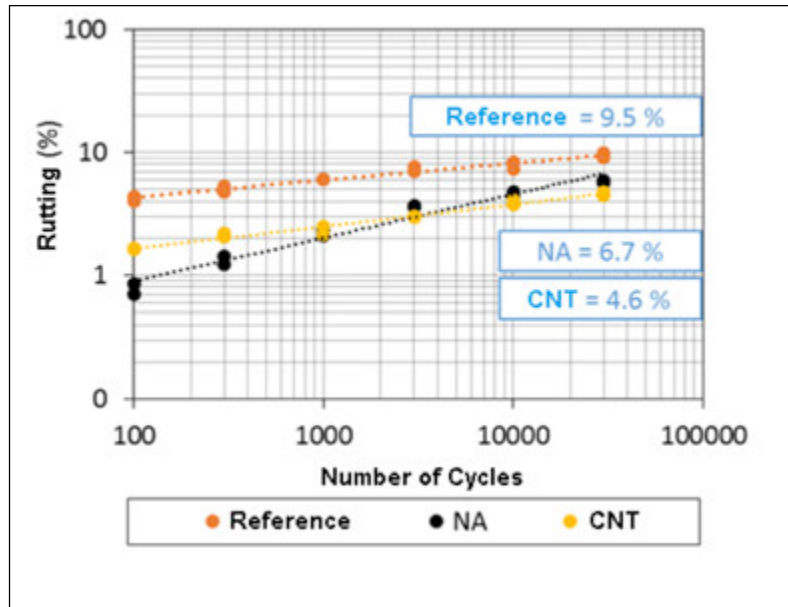


Figure 8. Comparative plot of the performance of the mixtures produced against permanent deformation

The rutting on the asphalt pavement layer's surface is associated with several factors, especially the granulometric composition and the appropriate design of the mixture (optimum binder content). However, the properties of the asphalt binder directly influence the response of the mixture to permanent deformation. Based on this approach, the different behavior responses shown in (Figure 8) are related to the characteristics of the asphalt binders used, as the binder content and the granulometric composition were not altered. To better understand the results, (Table 6) shows the improvement obtained by the nanocomposites, presented as a percentage of the reduction of the permanent deformation, compared to the reference mixture, for 30,000 cycles.

Tabla 6. Reduction in deformation (30,000 cycles)

Asphalt Mixture	Rutting (%)	Reduction in deformation (%)
Reference (CAP 50-70)	9,5	-
NA (CAP 50-70 + 3% NA)	6,7	29,5
CNT (CAP 50-70 + 2% CNT)	4,6	51,6

As shown in (Figure 8) and (Table 6), the reference mixture and the mixtures nano-modified with NA and CNT present rutting of 9.5%, 6.7% and 7.6% at 30,000 cycles, respectively. Adding 3% NA and 2% CNT to the mixture reduces the deformation by 29.5% and 51.6%, respectively, compared to the reference mixture. According to French specifications (IFSTTAR), the test value for 30,000 cycles must be a maximum of 10% for asphalt layers (Manuel LPC, 2007). However, some European specifications (European Commission, 1999) limit permanent deformation to 5% for dense mixtures to be used as heavy traffic asphalt layers. In this case, only the asphalt mixture with 2% CNT would meet these requirements.

Thus, the asphalt mixtures with nanocomposites had a better performance than the reference mixture; and, also, it can be verified that CNT is more efficient than the nanoclay to resist permanent deformation when the amount added is 2%.

4.4 Analysis of the effectiveness of the use of the Traffic Densification Index (TDI) for the prediction of permanent deformation of asphalt mixtures

The TDI, obtained from the gyratory compaction for the design of the asphalt mixture, has been considered appropriate by some researchers to characterize the mixtures based on the main assumption that the behavior of the material in this kneading process correlates with its stability during the useful life of the hardened material.

(Figure 9) shows the correlation between the TDI and the rutting on the surface of the asphalt slabs. This correlation resulted from the permanent deformation test of the plates created with CAP 50-70 and with NA and CNT nanocomposites.

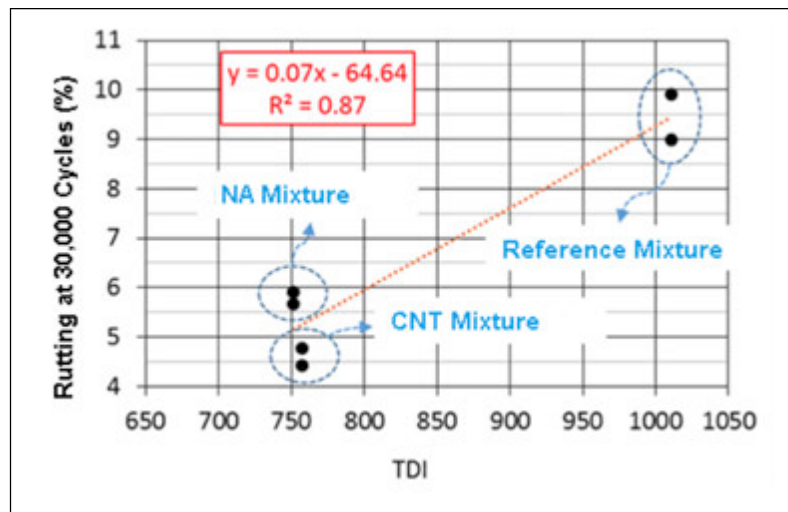


Figure 9. Correlation between the TDI and permanent deformation of asphalt mixtures at 30,000 cycles

(Figure 9) shows a good correlation between the TDI parameter and the rutting for 30,000 cycles. Thus, the two mixtures with the lowest TDI values have the lowest rutting values, while the mixture with the highest TDI value has the highest rutting value. However, this relationship between the TDI and permanent deformation seems to go against the hypotheses defended by the authors previously analyzed, who indicate that the higher the TDI value, the lower the expected permanent deformation should be.

Consequently, the results of (Figure 9) show the lack of effectiveness of the use of the TDI for the prediction of permanent deformation when asphalt mixtures with the same granulometry but with different asphalt binders are compared; in this case, conventional and nano-modified binders. This occurs because the compaction process of the mixtures is performed at high temperatures, which are adjusted to ensure that the various types of asphalt binders, including the nano-modified binders, have the same viscosity during this process. For this reason, associating the TDI in isolation with the overall behavior of asphalt mixtures against permanent deformation is incorrect since, during compaction, the effect of the consistency of the binders is almost completely eliminated.

Similarly, from gyratory compaction, it is not possible to extract rheological characteristics from asphalt binders, such as dynamic modulus, phase angle, elastic behavior, non-recoverable behavior, among other characteristics. Also, aspects related to the adhesiveness and chemical affinity of the binder with the stone matrix, which will jointly contribute to the development against permanent deformation, cannot be extracted.

It is also important to mention that the TDI, which is estimated from the gyratory compaction, is mainly related to the stability of the stone skeleton and the content of asphalt binder, having little influence from the type of

asphalt binder. Therefore, the fact that the mixtures with NA and CNT nanocomposites have the lowest TDI values is related only to the nanomaterials, which improve workability, causing a lubricating effect between the particles and allowing, in that case, to reach the desired densification level for the mixture more easily.

5. Conclusion

The nano-modified asphalt mixtures present high resistance to permanent deformation when compared to the reference asphalt mixture produced with a conventional binder without additives. The incorporation of 3% NA and 2% CNT in the mixture leads to a reduction in permanent deformation of 29.5% and 51.6%, respectively.

Using the TDI proved to be ineffective for the prediction of permanent deformation when comparing asphalt mixtures with the same granulometry and different asphalt binders, in this case, conventional asphalt binder with nano-modified binders with CNT and NA. Therefore, associating this index in isolation with the overall behavior of asphalt mixtures against permanent deformation is incorrect. It is not possible to extract the rheological properties of the asphalt binders from the gyratory compaction, which will interfere with the behavior of the hardened mixture against permanent deformation. The TDI, estimated from the gyratory compaction, is mainly related to the stability of the stone skeleton, to the asphalt binder content, and to the presence of additives that can improve the workability of the mixture, having little influence from the nature and type of the asphalt binder.

Finally, the relationship between the TDI and the resistance to permanent deformation of the mixtures studied did not show outstanding results that could predict the behavior of the nano-modified mixtures. However, despite the lack of promising results in this study, the authors believe that the possibility of correlating the TDI with the mechanical performance against permanent deformation should not be overlooked. Based on other studies, it is understood that promising results can be related to different granulometric compositions of the asphalt mixtures and different nominal maximum sizes of aggregates.

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