



# RUTTING IN ASPHALT MIXTURES – A REVIEW\*

Hugo Alexander Rondón Quintana\*\*

Carlos Alfonso Zafra Mejía\*\*\*

Fredy Alberto Reyes Lizcano\*\*\*\*

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## ABSTRACT

Vehicles that drive over a pavement structure induce load and unload cycles that generate recoverable (resilient) and permanent (plastic) deformations within pavement layers. Pavement has been studied since the 1960s with the purpose of understanding the visco-elasto-plastic behavior of asphalt mixtures. This, in turn, has the purpose of evaluating and understanding the origin of the main damage mechanisms that the designers of flexible pavement design methods seek to control. One of the main damage mechanisms for these types of pavements is rutting. Based on the reviewed literature related to rutting in asphalt mixtures, this article depicts and describes, in summary, the main variables that influence the occurrence of said phenomenon in pavement. The end of the article presents the evolution of equations developed through theoretical and experimental studies to predict the phenomenon of rutting.

*Keywords:* rutting, asphalt pavement, asphalt mixture, mathematical equations.

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\*\* Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas, Bogotá – Colombia (E-mail: harondonq@udistrital.edu.co) Orcid: <https://orcid.org/0000-0003-2946-9411>

\*\*\* Grupo de Investigación en Ingeniería Ambiental - GIAUD, Universidad Distrital Francisco José de Caldas, Bogotá - Colombia (E-mail: czafra@udistrital.edu.co) Orcid: <https://orcid.org/0000-0002-4061-4897>

\*\*\*\* Facultad de Ingeniería, Pontificia Universidad Javeriana, Bogotá - Colombia (E-mail: fredy.reyes@javeriana.edu.co) Orcid: <https://orcid.org/0000-0002-6407-168X>

## AHUELLAMIENTO EN MEZCLAS ASFÁLTICAS – REVISIÓN

### **RESUMEN**

Los vehículos que pasan por encima de una estructura de pavimento inducen ciclos de carga y descarga que generan deformaciones recuperables (resilientes) y permanentes (plásticas) en las capas del pavimento. El pavimento se ha estudiado desde la década de 1960 con el fin de comprender el comportamiento visco-elasto-plástico de las mezclas asfálticas y así evaluar y comprender cómo se generan los principales mecanismos de daño que se buscan controlar en los métodos de diseño de pavimentos flexibles. Uno de los principales mecanismos de daño en estos tipos de pavimentos es el ahuellamiento. De acuerdo a la revisión de la literatura relacionada con el ahuellamiento en mezclas asfálticas, en este artículo se muestran y describen, de forma resumida, las variables que influyen la aparición de dicho fenómeno en el pavimento. El final del artículo contiene la evolución de las ecuaciones, desarrolladas mediante estudios teóricos y experimentales, que buscan predecir el fenómeno del ahuellamiento.

*Palabras clave:* ahuellamiento, pavimento asfáltico, mezcla asfáltica, ecuaciones matemáticas

## INTRODUCTION

Rutting is one of the main damage mechanisms of asphalt layers in asphalt pavements [1-13]. This phenomenon is the permanent vertical displacement or deformation that accumulates in pavement due to the repetitive passing of vehicles, which causes the formation of thin longitudinal depressions throughout the trajectory of tires (see Figure 1), together with the lateral dilation of the asphalt mixture [14]. This can generate structural or functional failures (serviceability level reduction in the roadway, accidents associated to hydroplaning or sliding in rainy days) in pavement, which can occur in any layer of the structure (subgrade, subbase, base and asphalt layer) [10, 15]. However, researchers such as [16-17] have demonstrated that the greater part of rutting occurs in the asphalt layer.

Figure 1. Image of an asphalt layer with rutting [14]



The overall rutting depth is composed of loss of materials, densification and lateral plastic flow [18]. According to [2, 6, 19-22], the phenomenon of rutting in asphalt mixtures occurs mainly because of densification during construction and the apparition of shear deformations during the useful life of pavement. [23] reports, based on studies conducted by AASHO (American Association of State Highway Officials) in 1962 and on real scale tests, that from the total of rutting the greater component is shear. A similar observation is found in [24-27]. [28-29] mention that permanent deformation in asphalt mixtures, measured in laboratory tests under cyclic load, occurs in three phases. On the first phase, deformation is rapidly accumulated as a product of densification in the asphalt layer caused by initial loads. In this phase, the aggregate in the mixtures helps to generate deformation mainly because of particle rearrangement caused by the densification of material (reducing air voids' content). On a second phase, the deformation rate is reduced and reaches a constant value. However, in this phase, microcracks begin to occur and the material starts to lose stiffness. With the continuation of cyclic loads, microcracks gradually propagate and join, forming macrocracks and giving rise to the appearance of the third phase, in which the rate of

deformation increases and rapidly accumulates deformation. The first two described phases have been broadly reported by other researchers [30]. In situ, pavement rutting increases within the first years of operation and then stabilizes with time. In general, resilient deformation remains constant while permanent deformation is reduced with the number of load cycles [31]. [32] propose, based on the computer simulation on finite elements and on the studies carried out by [22, 33], four states in the generation of rutting: 1) densification caused by further traffic compaction; 2) apparition of shear deformations and a slip plane under the edge of the tire (hump initiation) as a combined product of the reduction in asphalt mixture shear strength with high pavement temperature and of the repeated action of traffic loads; 3) the critical global shear plane continues to slip, humps continue to develop, and permanent deformation increases up to a maximum rut depth; 4) continued instability ceases to result in an increase in rut depth, but instead results in a broadened rut basin as traffic wander compacts or moves the dilated portion of the mixture.

Understanding the way this damage mechanism occurs in asphalt pavement is a complex task. This is because there are multiple variables that influence its origination. Additionally, most studies on the subject are carried out within a laboratory and extrapolating these results to those obtained on a real scale increases the degree of complexity. Despite the broad number of studies carried out on the subject, there is not yet a definitive model that characterizes and predicts rutting resistance in asphalt mixtures in service. This article presents and describes, in summary, the most significant variables that influence the generation of this damage mechanism in asphalt mixtures. Likewise, the simplified equations most used for predicting the accumulation of permanent deformation in asphalt mixtures is presented. The information presented in this article can serve as a source for consultation for researchers that develop constitutive equations and regression models associated to the phenomenon of rutting in asphalt mixtures.

## 1. FACTORS THAT AFFECT RUTTING RESISTANCE

According to [34], rutting is mainly affected by three factors: mix (gradation, geometry and type of aggregate, and asphalt type and content), load (tire pressure, type of axis), and environment (temperature, moisture, precipitation). Predicting this phenomenon in asphalt mixtures is generally attempted by controlling its stiffness. In Table 1, the three main factors that affect rutting in asphalt mixtures are summarized.

Table 1. Factors that affect rutting in asphalt mixtures [19]

	Factor	Change in factor	Rutting resistance
Aggregate	Surface texture	Smooth to rough	Increases
	Geometry	Round to angular	Increases
	Size	Increase in maximum size	Increases
Asphalt	Stiffness	Increase	Increases
Mixture	Asphalt content	Increase	Decreases
	Air voids content	Increase	Decreases
	Compaction degree	Increase	Increases
In-situ conditions	Temperature	Increase	Decreases
	Stress or strain	Increase	Decreases
	Load repetition	Increase	Decreases
	Water	Dry to wet	Decreases

### 1.1 Load

It has been broadly acknowledged that the accumulation of permanent deformation in asphalt mixtures increases with load magnitude [1, 4, 7, 12, 25, 34-44], and decreases with confinement pressure [45-46]. On the other hand, the type and form of vehicle tires influences the rutting phenomenon, given that the load distribution on the pavement is different depending on the tire used [27, 47]. [7] points out that, based on the analysis of damage mechanisms of multiple in-service pavements, trucks with simple or tandem load axis generate greater fatigue cracking than those that are tridem or greater. On the contrary, they conclude that the greatest vertical permanent deformations are generated by vehicles that distribute their load in tridem or greater axis.

The accumulation of rutting is also a function of load velocity. The greater the velocity, the less deformation in the asphalt mix [4, 48]. [3], conducting simulations in the finite element program ABAQUS and in real scale tests, report that the vertical deformation when a vehicle passes by at 20 km/h is twice as great as when it passes by at 90 km/h. [49] conclude that deformation caused by a vehicle at 10 cm/s is equivalent to that caused by 10 vehicles with the same load passing at 100 cm/s. [50] conducted simulations in ABAQUS for a pavement structure comprised of 17 cm of asphalt layer and 40 cm of base and subbase. They used the elasto-visco-plastic equation for simulations and concluded that the rutting phenomenon decreases in pavement if load velocity increases. Likewise, they observed an increase of 100% in permanent deformations when load velocity was reduced from 60 to 10 km/h.

## 1.2 Temperature

The behavior of an asphalt mix can be considered elastic at low temperatures and/or high load velocities. At medium and high temperatures, elastic equations lead to underestimated pavement responses [51]. These materials display a visco-elastic or purely viscous behavior at high temperatures and/or when loads are applied at small velocities. Therefore, in general, the total deformation of an asphalt mixture under cyclic load is divided into one elastic component, a viscoelastic and a viscoplastic component. In general, the referenced literature reports that an increase in temperature generates a decrease in the stiffness of asphalt mixtures, increasing the susceptibility to the rutting phenomenon [1, 4, 12, 23, 34, 43, 45-46, 49, 52-58]. Therefore, rutting occurs mainly during the summer [59-61].

## 1.3 Density and Compaction

It is generally reported that an increase in density generates a decrease in susceptibility to rutting in asphalt mixtures [19, 31, 59]. According to [34], two samples with the same air content can undergo different responses to permanent deformation, given that void arrangement can differ when different compaction methods are used. [52] mentions that the construction of asphalt layers in cold climates may lead on occasion to low compaction densities in the mix, which results in a reduction in rutting resistance. [56, 62-63] report that the Marshall impact compaction method for asphalt mixtures within the laboratory is not suitable for evaluating the degree of rutting susceptibility in in-situ asphalt mixtures, given that in-situ compaction is done through kneading. [56, 64] compacted samples of an asphalt mixture using the Marshall method and the one recommended by SUPERAVE (gyratory compactor). They found significant differences in permanent deformation and resilient modulus measurements. Apparently, mixes designed through the SUPERAVE method offer more resistance to permanent deformation and stiffness than those designed through the Marshall method. [65] investigated the effect on resistance to permanent deformation by compacting three asphalt mixtures (of a similar volumetric composition) with four compaction modes: gyratory, vibratory, and roller. They concluded that the asphalt samples manufactured with a gyratory compactor and using a vibratory hammer in the laboratory generate more stiff mixes with greater resistance to permanent deformation compared to those compacted with a roller. This is perhaps due to the influence of confinement in molds used for compacting samples. According to [66], in situ, a great part of the accumulation of permanent deformation is due to an inadequate compaction of asphalt layers. In situ, the compaction method is different from that in the laboratory. The mixtures are compacted by kneading and the density achieved depends on multiple factors such as the weight and type of the compacting equipment, the boundary conditions, the

stiffness of the platform, among others. In general terms, the tendency of the mixtures manufactured in the laboratory is to be stiffer and show greater resistance to permanent deformation than those compacted with a roller and in situ. As it was mentioned above, this might be caused by the confinement of the molds used to compact the samples in the laboratory [14, 65-66].

#### 1.4 Aggregate and Asphalt

According to [67], gradation has a higher impact on minimizing rutting in asphalt mixtures when compared to improving or modifying the asphalt. According to [19, 68-69], aggregates with dense gradations and a coarse texture are desirable for controlling the rutting phenomenon. [70-71] mention that mixes manufactured with aggregates that have coarse gradations help to increase rutting resistance. However, [72] state that mixes manufactured with intermediate gradations have greater rutting resistance than those made with coarse gradations, because mixes using aggregates with coarse gradations are more difficult to compact. Apparently, the use of aggregates with greater particle size helps to reduce rutting potential in asphalt mixtures subjected to high load pressures [73]. An excess in the content of fine granular particles in the asphalt mixture can result in a significant reduction in rutting resistance [12,52,74]. However, [75] observed that, based on indirect tensile tests, there is an increase in permanent deformation resistance when the content of fine particles is increased between 2% and 10%. Additionally, they conclude that increasing the filler makes mixes more susceptible to moisture and, therefore, these tend to reduce their resistance to rutting when in the presence of water. [76] mention that asphalt mixtures manufactured with aggregates that have a high presence of sand particle sizes are more susceptible to the phenomenon of rutting. It appears that mixes manufactured with aggregates that have angular faces obtained through crushing processes develop less deformation under cyclic load than mixes manufactured with the same particle size distribution, but using aggregates with rounded faces [52, 74, 77-80]. A similar observation was registered by [9], but they clarify that the effect of fractured faces is greater as the asphalt is less stiff. [81] discovered, through a micro-structural simulation, that angular aggregates within the asphalt mixture generate a better interconnection of aggregates, which results in an increase in stiffness. [82,83] obtained the same conclusion by running a computer simulation with discrete elements method (DEM) in 3D.

In general terms, an increase in the accumulation of permanent deformation is reported as the air voids increase in the asphalt mixture. [12, 45, 84-85]. Asphalt mixtures increase their stiffness and, therefore, their rutting resistance as the content of air voids decreases and the content of particles with angular or fractured faces increases [19, 86-87]. [88] indicated, however, that a reduction in air void content, which is the

product of an overuse of asphalt binder, increases the potential for rutting in asphalt mixtures. In other words, a reduction of air void contents actually reduces the potential for rutting, as long as said voids are filled with optimal asphalt contents and it is not an excessive increase, given that using excess binder produces important deformations [12, 34, 52, 74, 89].

Low viscosity asphalts generate less stiff asphalt mixtures, which are more susceptible to deformation under cyclic load [88, 90]. [91], based on Wheel Tracking type tests, observed that asphalts that are less penetrable and that have a greater softening point generate mixes less susceptible to rutting. [46, 70] concluded that increasing the PG range of asphalt generates mixes that are more resistant to the phenomenon of accumulating permanent deformations. In general, mixes that used modified asphalts display less rutting compared to those manufactured with conventional binders [11, 13-14, 34, 75, 92-101].

### 1.5 Tests and Equipment

The response to rutting in asphalt mixtures differs depending on the type of test performed. Likewise, there is no laboratory test that can accurately predict the response observed in situ [95, 102-103]. The most used laboratory tests for measuring permanent deformations in asphalt mixtures can be classified as:

1. Uniaxial stress tests performed on unconfined cylindrical samples under monotonic load, creep or cyclic (Figure 2).
2. Triaxial stress tests performed on confined cylindrical samples under monotonic load, creep or cyclic. Cyclic triaxial tests are carried out by applying a constant confinement pressure and subjecting asphalt mixtures to conditions of stress similar to those produced by the passing of vehicles on the surface. An equipment that allows to conduct these types of tests is the AMPT (Asphalt Mixture Performance Tester, see Figure 3).
3. Diametral or indirect tensile tests performed under cyclic load or creep. The load is applied vertically by compression in the diametral plane of a cylindrical specimen of the asphalt mixture (Figure 4).
4. Wheel-Track or small-scale deformation type tests. The samples in these tests are prefabricated beams, and, in these, deformation of an asphalt mixture is measured in function of the number of applied cycles (Figure 5). Some examples of the equipment most used throughout the world to perform these types of tests are APA (Asphalt Pavement Analyzer, AASHTO TP 63), Wheel-Track from Hamburg, and the French Pavement Rutting Tester (FPRT).



Figure 2. Creep Uniaxial Test Schematic [104]



Figure 3. AMPT Equipment [14].



Figure 4. Indirect Tensile Test Schematic [14].

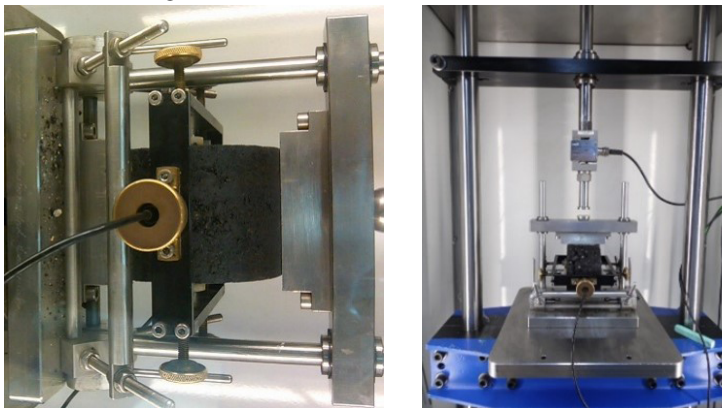


Figure 5. Small Scale Track Test [14].



5. Simple shear tests, applying of creep, cyclic and dynamic load. Samples are similar to those used in diametral tests.
6. X-ray tomography tests. In this test, an asphalt mixture can be described at a micro-mechanical level in 3D by analyzing air voids and form, texture, and configuration of the aggregate. Likewise, it is possible to obtain an estimate of the asphalt binder's stiffness within the asphalt mixture and the stiffness between particle contacts. A more detailed description of these types of tests can be consulted in [105].
7. Full scale tests (Figure 6-8). These offer a good representation of field conditions, given that this method ensures the simulation of the pavement system of and the loads that it will actually have to support on its structure, along with the lateral movement of vehicles and the use of real velocities for load application. These tests require designing and constructing tracks that can be longitudinal or circular. In these circular tracks, the loaded tire velocity is limited to centrifugal force [106]. The main disadvantage of this type of technology is that it requires the construction of real scale costly structures and using sophisticated instruments and equipment for measuring and calculating deflections and stresses, as well as for the moisture control of every layer of pavement [11].

Figure 6. Texas Mobile Load Simulator (TxMLS) Schematic [107].

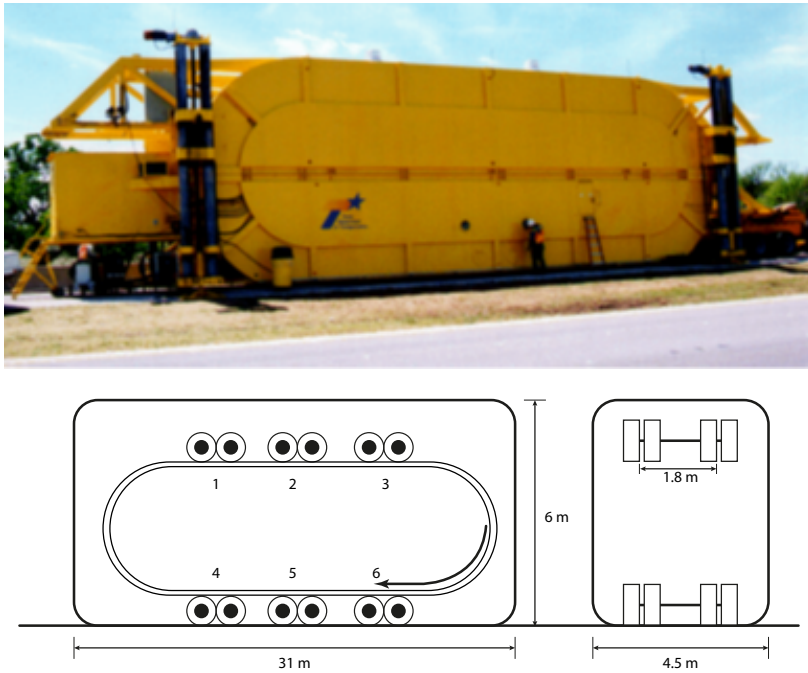


Figure 7. National Airport Pavement Test Facility (NAPTF) [42].

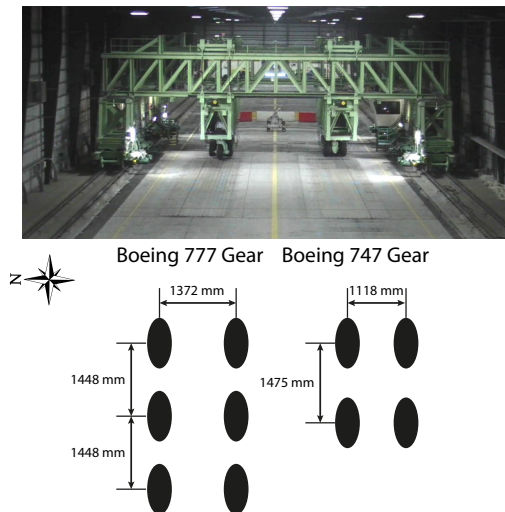


Figure 8. Fatigue full scale test [108].



A detailed description of these tests can be consulted in [14].

## 1.6 Others

Other parameters that impact the generation of rutting in asphalt mixtures are bad quality in the materials that comprise the mix [109], a defective constructive process [110], and low stiffness in the support (base, subbase, subgrade, etc.) of the asphalt layer [15].

## 2. EQUATIONS FOR PREDICTING PERMANENT DEFORMATION

The generalized equation for determining useful life affected due to rutting in asphalt mixtures is the following [111]:

$$N_f = k_1 \left( \frac{1}{\varepsilon_z} \right)^{k_2} \quad (1)$$

$N_f$  is the number of load cycles required for the mix to fail due to rutting,  $\varepsilon_z$  is the vertical deformation in the mix and  $k_1$  and  $k_2$  are parameters obtained through regression.

Other simple equations obtained through regression that can be consulted in the referenced literature are presented below.

$$\varepsilon_p = a + b \log N ; \text{ semi-logarithmic Barksdale model [112]} \quad (2)$$

$\varepsilon_p$  is the axial deformation,  $N$  is the number of load cycles,  $a$  and  $b$  are parameters obtained through regression.

$$\varepsilon_{vp} = (a_1\sigma + a_2\sigma^2)t^b; [113-114] \quad (3)$$

$\varepsilon_{vp}$  is the axial visco-plastic deformation,  $t$  is the load time,  $\sigma$  is the creep stress,  $a_1$ ,  $a_2$  and  $b$  are parameters obtained through regression.

$$\log D = a + b \log N + c(\log N)^2 + d(\log N)^3; [115] \quad (4)$$

$D$  is the displacement,  $N$  is the number of load cycles,  $a-d$  are parameters obtained through regression.

$$\varepsilon_p = c\sigma N^a; [116] \quad (5)$$

$a$  and  $c$  are parameters obtained by regression.

$$\ln \dot{\varepsilon} = A + B \ln \sigma_{vm} + C\sigma_H + DT; [117] \quad (6)$$

$\dot{\varepsilon}$  is the permanent deformation rate,  $\sigma_{vm}$  is the vertical stress in compression,  $\sigma_H$  is the horizontal stress in compression,  $T$  is the temperature,  $A-D$  are parameters obtained through regression.

$$\varepsilon_p = A \left( \frac{t}{10^3} \right)^B = \frac{C(\sigma_1 - \sigma_3)}{|E^*| \left( \frac{t}{10^3} \right)^B}; C = \frac{V_b}{V_b + V_v}; [118] \quad (7)$$

$A$  is a coefficient that depends on the volumetric composition of the mixture,  $B$  is a coefficient that varies between 0.14 to 0.37,  $V_b$  is the asphalt content in volume,  $V_v$  is the void content in volume,  $|E^*|$  is the dynamic modulus,  $\sigma_1$  is the vertical stress,  $\sigma_3$  is the confining pressure.

$$\varepsilon_p = \mu\varepsilon N^\alpha; \text{VESYS Model [119-120]} \quad (8)$$

$\mu$  is a constant of proportionality between the permanent and the resilient deformation,  $\varepsilon$  is the permanent deformation for the first 200 load cycles,  $\alpha$  is a parameter that takes into account the decrease in the deformation rate with  $N$ .

$$\varepsilon_p = \left( \frac{q}{a} \right)^b N; [35] \quad (9)$$

$q$  is the deviator stress,  $a$  and  $b$  are parameters obtained through regression.

$$\varepsilon_p = aN^{1-m}; \text{ Ohio State Model [121]} \quad (10)$$

$1-m$  is an exponent which is a function of temperature.

$$\varepsilon_p = H \frac{(\sigma_v - \sigma_H)}{|E^*|} \left( \frac{N}{1000f} \right)^B; [122] \quad (11)$$

$\sigma_v$  and  $\sigma_H$  are vertical and horizontal stress, respectively,  $f$  is the load frequency (20 Hz suggested),  $B$  is a parameter that depends on the volumetric composition of the mixture (0.25 suggested),  $H$  is a coefficient that depends on the asphalt content (115 suggested).

$$y = a + bN^{0.5}; [25] \quad (12)$$

$y$  is the displacement,  $a$  and  $b$  are parameters obtained through regression.

$$\frac{\varepsilon_p}{N} = a\sigma^b; [88] \quad (13)$$

$a$  and  $b$  are parameters obtained through regression.

$$\varepsilon_1^p = \varepsilon_o \exp\left(-\frac{\rho}{N}\right)^\beta; [123] \quad (14)$$

$\varepsilon_o$ ,  $\rho$  and  $\beta$  are parameters obtained through regression.

$$\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = \log\frac{T^a}{b} + c \log N; [124] \quad (15)$$

$\varepsilon_r$  is the resilient deformation,  $a$ - $c$  are parameters obtained through regression.

$$\gamma_p = a \exp^{b\tau} \gamma_r N^c; \text{ Westrack Model [125-126]} \quad (16)$$

$\gamma_p$  is the critical permanent shear strain,  $\gamma_r$  is the resilient shear strain,  $\tau$  is the shear stress,  $a$ ,  $b$ ,  $c$  are parameters obtained through regression.

$$\varepsilon_p = \varepsilon_r k_1 N^{[k_2 \ln(T) + k_3]} \exp^{[k_4 T^{k_5 (\%AV)}]}; [45] \quad (17)$$

$\%AV$  is the air void content in percentage,  $k_i$  are parameters obtained through regression.

$$D = \sum_i^n 10^a T_i^b \left( \frac{c}{V} N \right)^d \left[ \frac{\tau_i}{\tau_{oi}} \right]^e ; [49] \quad (18)$$

$D$  is the displacement,  $V$  is the speed load,  $\tau$  is the shear stress,  $a-e$  are parameters obtained through regression.

$$\varepsilon_p = 10^a N^b \sigma^c T^d ; [84] \quad (19)$$

$a-d$  are parameters obtained through regression.

$$\varepsilon_p = \sum_i^n \frac{\sigma_i^a t_i^b}{c} ; [127] \quad (20)$$

$a-c$  are parameters obtained through regression.

$$D = a + b \ln D_{CR} + c \ln D_{BI} + d \ln D_{BA} ; [128] \quad (21)$$

$D$ ,  $D_{CR}$ ,  $D_{BI}$  and  $D_{BA}$  are the total displacement, measured in the asphalt wearing surface, in the asphalt intermediate layer and in the asphalt base layer, respectively,  $a-d$  are parameters obtained through regression.

### 3. CONCLUSIONS

This study described the main variables that influence the phenomenon of rutting in asphalt mixtures. Likewise, it presents the most used equations for modelling said damage mechanism. Considering the literature reviewed, the following was concluded:

The main causes of the generation of this damage mechanism in flexible pavements are increasing the number and magnitude of cyclic loads and reducing their velocity, increasing temperature in the area, reducing the degree of compaction in the mix, manufacturing mixes with high air void contents and high fine particle contents, using soft asphalts or asphalts with low stiffness, using excess of aggregates and inadequate asphalts, executing a defective constructive process, and using support layers with low stiffness.

The mathematical equations used for attempting to predict the accumulation of permanent deformations developed in in-situ asphalt mixtures, as well as within the laboratory, generally focus on relating permanent deformation with the number of load cycles. However, the greatest deficiency of these mathematical relations is they

are not capable of predicting, using a single equation, the deformation that an asphalt mixture will undergo when subjected to different load magnitudes and environmental conditions. This is because regression parameters for said equations are not constants for the material but rather state variables (changing with the type of test, geometry of samples, border conditions, volumetric composition of mixes, etc.). Few equations simulate aspects associated to durability (climate effect, aging, among others) and to the compaction process of asphalt mixtures (within the laboratory and in situ).

## REFERENCES

- [1] S.A. Khedr, “Deformation mechanism in asphaltic concrete”, *Journal of Transportation Engineering*, vol. 112, no. 1, pp. 29-45, 1986. 10.1061/(ASCE)0733-947X(1986)112:1(29)
- [2] A.C. Collop, D. Cebon and M.S.A. Hardy, “Viscoelastic approach to rutting in flexible pavements”, *Journal of Transportation Engineering*, vol. 121, no. 1, pp. 82–93, 1995. 10.1061/(ASCE)0733-947X(1995)121:1(82).
- [3] J.S. Chen, C.H. Lin, E. Stein and J. Hothan, “Development of a mechanistic-empirical model to characterize rutting in flexible pavements”, *Journal of Transportation Engineering*, vol. 130, no. 4, pp. 519-525, 2004. 10.1061/(ASCE)0733-947X(2004)130:4(519).
- [4] T.F. Fwa, S.A. Tan and L.Y. Zhu, “Rutting prediction of asphalt pavement layer using C- $\sigma$  Model”, *Journal of Transportation Engineering*, vol. 130, no. 5, pp. 675-683, 2004. 10.1061/(ASCE)0733-947X(2004)130:5(675).
- [5] A. Saleeb, R.Y. Liang, H. Al Qablan and D. Powers, “Numerical simulation techniques for HMA rutting under Loaded Wheel Tester”, *International Journal of Pavement Engineering*, vol. 6, no. 1, pp. 57–66, 2005. 10.1080/10298430500068704.
- [6] A.R. Archilla, “Use of Superpave Gyratory Compaction data for rutting prediction”, *Journal of Transportation Engineering*, vol. 132, no. 9, pp. 734-741, 2006. 10.1061/(ASCE)0733-947X(2006)132:9(734).
- [7] H.K. Salama, K. Chatti and R.W. Lyles, “Effect of heavy multiple axle trucks on flexible pavement damage using in-service pavement performance data”, *Journal of Transportation Engineering*, vol. 132, no. 10, pp. 763-770, 2006. 10.1061/(ASCE)0733-947X(2006)132:10(763).
- [8] B. Saurabh, P.P. Vassilis and D.P. Katerina, “Identification and modeling of permanent deformations of asphalt concrete”, *Journal of Engineering Mechanics*, vol. 132, no. 3, pp. 231-239, 2006. 10.1061/(ASCE)0733-9399(2006)132:3(231).
- [9] B. Huang, X. Chen, X. Shu, E. Masad and E. Mahmoud, “Effects of coarse aggregate angularity and asphalt binder on laboratory-measured permanent deformation properties of HMA”, *International Journal of Pavement Engineering*, vol. 10, no. 1, pp. 19–28, 2009. 10.1080/10298430802068915.



- [10] H. Wang, Q. Zhang and J. Tan, “Investigation of layer contributions to asphalt pavement rutting”, *Journal of Materials in Civil Engineering*, vol. 21, no. 4, pp. 181-185, 2009. 10.1061/(ASCE)0899-1561(2009)21:4(181).
- [11] D. Yinfei, C. Jiaqi, H. Zheng and L. Weizheng, “A review on solutions for improving rutting resistance of asphalt pavement and test methods”, *Construction and Building Materials*, vol. 168, pp. 893-905, 2018. 10.1016/j.conbuildmat.2018.02.151.
- [12] R. Guo, T. Nian and F. Zhou, “Analysis of factors that influence anti-rutting performance of asphalt pavement”, *Construction and Building Materials*, vol. 254, 119237, 2020. 10.1016/j.conbuildmat.2020.119237.
- [13] Z. Zhao, J. Jiang, F. Ni, Q. Dong, J. Ding and X. Ma, “Factors affecting the rutting resistance of asphalt pavement based on the field cores using multi-sequenced repeated loading test”, *Construction and Building Materials*, vol. 253, 118902, 2020. 10.1016/j.conbuildmat.2020.118902.
- [14] H.A. Rondón y F.A. Reyes, “Pavimentos: materiales, construcción y diseño”, Ed. ECOE, Bogotá D.C., Colombia, 2015, 614 p.
- [15] H.A. Rondón, “Comportamiento de un material granular no tratado en ensayos triaxiales cíclicos con presión de confinamiento constante (PCC) y variable (PCV)”, Ph. D. thesis, Facultad de Ingeniería, Universidad de Los Andes, Bogotá D.C., Colombia, 2008.
- [16] J.B. Sousa, J.A. Deacon, S. Weissman, J.T. Harvey and C.L. Monismith, “Permanent deformation response of asphalt aggregate mixes”, Report SHRP-A-415. Washington, DC: Strategic Highway Research Program, National Research Council, 437, 1994.
- [17] D. Chen, J. Bilyeu, T. Scullion, D.F. Lin and F. Zhou, “Forensic evaluation of the premature failures of Texas specific pavement study 1 sections”, *Journal of Performance of Constructed Facility*, vol. 17, no. 2, pp. 67-74, 2003. 10.1061/(ASCE)0887-3828(2003)17:2(67).
- [18] Y. Ali, M. Irfan, S. Ahmed and S. Ahmed, “Empirical correlation of permanent deformation tests for evaluating the rutting response of conventional asphaltic concrete mixtures”, *Journal of Materials in Civil Engineering*, vol. 29, no. 8, 2017. 10.1061/(ASCE)MT.1943-5533.0001888.
- [19] J.B. Sousa, J. Craus and C.L. Monismith, “Summary report on permanent deformation in asphalt concrete”, SHRP-A/IR-91-104, Washington DC: Strategic Highway Research Program, National Research Council, 1991.
- [20] T.D. White, J.E. Haddock, A.J.T. Hand and H. Fang, “Contributions of pavement structural layers to rutting of hot mix asphalt pavements”, NCHRP Rep. 468, Washington DC: National Cooperative Highway Research Program, Transportation Research Board, National Research Council, National Academy Press, 2002.
- [21] E. Coleri, J.T. Harvey, K. Yang and J.M. Boone, “A micromechanical approach to investigate asphalt concrete rutting mechanisms”, *Construction and Building Materials*, vol. 30, no. 5, pp. 36–49, 2012. 10.1016/j.conbuildmat.2011.11.041.

- [22] E. Coleri, J.T. Harvey, K. Yang and J.M. Boone, “Investigation of asphalt concrete rutting mechanisms by X-Ray computed; tomography imaging and micromechanical finite element modeling”, *Materials and Structures*, vol. 46, no. 6, pp. 1027–1043, 2013. 10.1617/s11527-012-9951-x.
- [23] A. Hofstra and A.J.G. Klomp, “Permanent deformation of flexible pavements under simulated road traffic conditions”, in: *Proceedings, Third International Conference on tire Structural Design of Asphalt Pavements*, vol. I, London, U.K., pp. 613-621, 1972.
- [24] S.F. Brown, “The characterization of cohesive soils for flexible pavement design”, in: *Proc. Design Parameters in Geotechnical Engineering*, London, British Geotechnical Society, vol. 2, pp. 15-22, 1979.
- [25] J. Eisenmann and A. Hilmer, “Influence of wheel load and inflation pressure on the rutting effect at asphalt-pavements - experiments and theoretical investigations”, in: *Proceedings, Sixth International Conference on the Structural Design of Asphalt Pavements*, vol. I, Ann Arbor, pp. 392-403, 1987.
- [26] L.A. Myers, C. Drakos and R. Roque, “The combined effects of tire contact stresses and environment on surface rutting and cracking performance”, in: *Proceedings of the Ninth International Conference on Asphalt Pavements*, Copenhagen, Denmark, 2002.
- [27] I.L. Al-Qadi, P.J. Yoo, M.A. Elseifi and S. Nelson, “Creep behavior of hot-mix asphalt due to heavy vehicular tire loading”, *Journal of Engineering Mechanics*, vol. 135, no. 11, pp. 1265-1273, 2009. 10.1061/(ASCE)0733-9399(2009)135:11(1265).
- [28] F. Zhou and T. Scullion, “Discussion: three stages of permanent deformation curve and rutting model”, *International Journal of Pavement Engineering*, vol. 3, no. 4, pp. 251–260, 2002. 10.1080/1029843021000083676.
- [29] P. Chaturabong and H.U. Bahia, “Mechanisms of asphalt mixture rutting in the dry Hamburg Wheel Tracking test and the potential to be alternative test in measuring rutting resistance”, *Construction and Building Materials*, vol. 146, pp. 175–182, 2017. 10.1016/j.conbuildmat.2017.04.080.
- [30] S. Price, Y. Mehta, L.M. McCarthy, “Evaluation and modeling of repeated load test data of asphalt concrete for mechanistic-empirical pavement design”, *Journal of Materials in Civil Engineering*, vol. 19, no. 11, pp. 993-999, 2007. 10.1061/(ASCE)0899-1561(2007)19:11(993).
- [31] C.L. Monismith and A.A. Tayebali, “Permanent deformation (rutting) considerations in asphalt concrete pavement sections”, In: *Proceedings, The Association of Asphalt Paving Technologists*, Williamsburg, Virginia, vol. 57, pp. 414-463, 1988.
- [32] R. Simms, D. Hernando and R. Roque, “A new paradigm to explain the development of instability rutting in asphalt pavements”, *Road Materials and Pavement Design*, 2019. doi: 10.1080/14680629.2019.1568286.

- [33] C. Villiers, R. Roque and B. Dietrich, “Interpretation of transverse profiles to determine the source of rutting within an asphalt pavement system”, *Transportation Research Record*, no. 1905, pp. 73–81, 2005. 10.3141/1905-09.
- [34] R.A. Tarefder, M. Zaman and K. Hobson, “A laboratory and statistical evaluation of factors affecting rutting”, *International Journal of Pavement Engineering*, vol. 4, no. 1, pp. 59–68, 2003. 10.1080/10298430310001593263.
- [35] S.F. Brown and C.A. Bell, “The prediction of permanent deformation in asphalt pavements”, *Proceeding Association of Asphalt Paving Technologists*, vol. 48, pp. 438-476, 1979.
- [36] D.R. Middleton, F.L. Roberts and T. Chira-Chavala, “Measurements and analysis of truck tire pressures on Texas highways”, *Transportation Research Record*, no. 1070, pp. 1-8, 1986.
- [37] S.W. Hudson and S.B. Seeds, “Evaluation of increased pavement loading and tire pressures”, *Transportation Research Record*, no. 1207, pp. 197-206, 1988.
- [38] O.K. Kim and C.A. Bell, “Measurement and analysis of truck tire pressures in Oregon”, *Transportation Research Record*, no. 1207, pp. 100-110, 1988.
- [39] K. Mahboub, “Asphalt concrete creep as related to rutting”, *Journal of Materials in Civil Engineering*, vol. 2, no. 3, pp. 147-163, 1990. 10.1061/(ASCE)0899-1561(1990)2:3(147).
- [40] B.A. Vallergera, C.L. Monismith and A.A. Tayebali, “Early rutting of asphalt concrete pavement under heavy axle loads in hot desert environment - A case history”, *Transportation Research Record*, no. 1473, pp. 25-34, 1995.
- [41] J.E. Haddock, A.J.T. Hand, H. Fang and T.D. White, “Determining layer contributions to rutting by surface profile analysis”, *Journal of Transportation Engineering*, vol. 131, no. 2, pp. 131-139, 2005. 10.1061/(ASCE)0733-947X(2005)131:2(131).
- [42] K. Gopalakrishnan and M.R. Thompson, “Assessing damage to airport pavement structure due to complex gear loads”, *Journal of Transportation Engineering*, vol. 132, no. 11, pp. 888-897, 2006. 10.1061/(ASCE)0733-947X(2006)132:11(888).
- [43] M.R. Pouranian, R. Imaninasab and M. Shishehbor, “The effect of temperature and stress level on the rutting performance of modified stone matrix asphalt”, *Road Materials and Pavement Design*, vol. 21, no. 5, pp. 1386–1398, 2020. 10.1080/14680629.2018.1546221.
- [44] K.A. Ghuzlan, B.W. Al-Mistarehi and A.S. Al-Momani, “Rutting performance of asphalt mixtures with gradations designed using bailey and conventional Superpave methods”, *Construction and Building Materials*, vol. 261, 119941, 2020. 10.1016/j.conbuildmat.2020.119941.
- [45] Y. Seo, O. El-Haggan, M. King, S.J. Lee and R. Kim, “Air void models for the dynamic modulus, fatigue cracking and rutting of asphalt concrete”, *Journal of Materials in Civil Engineering*, vol. 19, no. 10, pp. 874-883, 2007. 10.1061/(ASCE)0899-1561(2007)19:10(874).
- [46] X. Shu and B. Huang, “Evaluation of Tennessee HMA mixture using simple performance tests”, in: *Transportation and Development Innovative Best Practices - TDIBP 2008*,

- Proceedings of the First International Symposium on Transportation and Development Innovative Best Practices 2008*, Beijing, China, pp. 517-522, 2008.
- [47] J. Hua and T. White, “A study of nonlinear tire contact pressure effects on HMA rutting”, *International Journal of Geomechanics*, vol. 2, no. 10. 1061/(ASCE)1532-3641(2002)2:3(353).
- [48] L. Al-Qadi, P. Yoo, M. Elseifi, I. Janajreh, G. Chehab and A. Collop, “Characterization of pavement damage due to different tire configurations”, in: *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*, vol. 74, pp. 921–961, 2005.
- [49] K. Su, L.J. Sun and Y. Hachiya, “Rut prediction for semi-rigid asphalt pavements”, in: *First International Symposium on Transportation and Development Innovative Best Practices, TDIBP 2008*, ASCE, pp. 486-491, 2008.
- [50] B. Ali, M. Sadek and I. Shahrour, “Finite-Element Model for urban pavement rutting: analysis of pavement rehabilitation methods”, *Journal of Transportation Engineering*, vol. 135, no. 4, pp. 235-239, 2009. 10.1061/(ASCE)0733-947X(2009)135:4(235).
- [51] M.A. Elseifi, I.L. Al-Qadi and P.J. Yoo, “Viscoelastic modeling and field validation of flexible pavements”, *Journal Engineering Mechanic*, vol. 132, no. 2, pp. 172–178, 2006. 10.1061/(ASCE)0733-9399(2006)132:2(172).
- [52] A.R. Archilla and S. Madanat, “Development of a pavement rutting model from experimental data”, *Journal of Transportation Engineering*, vol. 126, no. 4, pp. 291-299, 2000. 10.1061/(ASCE)0733-947X(2000)126:4(291).
- [53] J. Uzan, “Characterization of asphalt concrete materials for pavement deformation”, *International Journal of Pavement Engineering*, vol. 4, no. 2, pp. 77–86, 2003. 10.1080/10298430310001593272.
- [54] F. Zhou, D.H. Chen, T. Scullion and J. Bilyeu, “Case study: evaluation of laboratory test methods to characterize permanent deformation properties of asphalt mixes”, *International Journal of Pavement Engineering*, vol. 4, no. 3, pp. 155–164, 2003. 10.1080/10298430410001659755.
- [55] S.T. Dunhill, G.D. Airey, A.C. Collop and A. Scarpas, “Advanced constitutive modelling of bituminous materials”, *International Journal of Pavement Engineering*, vol. 7, no. 3, pp. 153–165, 2006. 10.1080/10298430600630528.
- [56] K.M. Khan and M.A. Kamal, “Impact of Superpave mix design method on rutting behavior of flexible pavements in Pakistan”, *The Arabian Journal for Science and Engineering*, vol. 33, no. 2B, pp. 379-390, 2008.
- [57] F. Morea, R. Zerbino and J. Agnusdei, “Wheel tracking rutting performance estimation based on bitumen low shear viscosity (LSV), loading and temperature conditions”, *Materials and Structures*, vol. 47, no. 4, pp. 683–692, 2014. 10.1617/s11527-013-0088-3.

- [57] Z.A. Alkaissi, “Effect of high temperature and traffic loading on rutting performance of flexible pavement”, *Journal of King Saud University - Engineering Sciences*, vol. 32, no. 1, pp. 1-4, 2020, doi: 10.1016/j.jksues.2018.04.005.
- [58] F. Linden and J. Van der Heide, “Some aspects of the compaction of asphalt mixes and its influence on mix properties”, in: *Proc. Association of Asphalt Paving Technologists*, vol. 56, pp. 408-426, 1987.
- [59] C. Celauro, “Influence of the hourly variation of temperature on the estimation of fatigue damage and rutting in flexible pavement design”, *International Journal of Pavement Engineering*, vol. 5, no. 4, pp. 221–231, 2004. 10.1080/10298430512331336592.
- [60] S. Biswas, L. Hashemian and A. Bayat, “Investigation on seasonal variation of thermal-induced strain in flexible pavements based on field and laboratory measurement”. *International Journal of Pavement Research and Technology*, vol. 9, no. 5, pp. 354–362, 2016. 10.1016/j.ijprt.2016.08.008.
- [61] B.L. Swami, Y.A. Mehta and S. Bose, “A comparison of the Marshall and Superpave mix design procedures for materials sourced in India”, *International Journal of Pavement Engineering*, vol. 5, no. 3, pp. 163–173, 2004. 10.1080/10298430412331309115.
- [62] F. Roberts, M. Mohammad and L.Wang, “History of hot mix asphalt mixture design in the USA”, *Journal of Materials Civil Engineering*, vol. 14, no. 4, pp. 279–93, 2002. 10.1061/(ASCE)0899-1561(2002)14:4(279).
- [63] I.M. Asi, “Performance evaluation of SUPERPAVE and Marshall asphalt mix designs to suite Jordan climatic and traffic conditions”, *Construction and Building Materials*, vol. 21, pp. 1732-1740, 2007. 10.1016/j.conbuildmat.2006.05.036.
- [64] A.E. Hunter, L. McGreavy and G.D. Airey, “Effect of compaction mode on the mechanical performance and variability of asphalt mixtures”, *Journal of Transportation Engineering*, vol. 135, no. 11, pp. 839–851, 2009. 10.1061/(ASCE)0733-947X(2009)135:11(839).
- [65] T. Xu and X. Huang, “Investigation into causes of in-place rutting in asphalt pavement”, *Construction and Building Materials*, vol. 28, pp. 525-530, 2012. 10.1016/j.conbuildmat.2011.09.007.
- [66] C.S. Hughes, “Experimental mixes to minimize rutting”, Boston: ASCE, Boston Society of Civil Engineers Section, pp. 931-942, 1990.
- [67] F.T.S. Aragão, A.R.G. Pazos, L.M.G.D. Motta and Y.R. Kim, “Effects of morphological characteristics of aggregate particles on the mechanical behavior of bituminous paving mixtures”, *Construction and Building Materials*, vol. 123, pp. 444–453, 2016. 10.1016/j.conbuildmat.2016.07.013.
- [68] M. Shaheen, A. Almayah and S. Tighe, “Effects of high friction aggregate and PG plus binder on rutting resistance of hot mix asphalt mixtures”, *International Journal of Pavement Engineering*, vol. 18, no. 4, pp. 292–302, 2017. 10.1080/10298436.2015.1065996.

- [69] R.J. Pelland, J.S. Gould and R.B. Mallick, "Selecting a rut resistant hot mix asphalt for Boston-Logan international airport, airfield pavements: challenges and new technologies", in: *Proceedings of Airfield Pavements Specialty Conference 2003*, pp. 390-408, 2004.
- [70] E. Sangsefidi, H. Ziari and A. Mansourkhaki, "The effect of aggregate gradation on creep and moisture susceptibility performance of Warm Mix Asphalt", *International Journal of Pavement Engineering*, vol. 15, no. 2, pp. 133-141, 2014. 10.1080/10298436.2012.752824.
- [71] J.M. Matthews and C.L. Monismith, "Effects of aggregate gradation on the creep response of asphalt mixtures and pavement rutting estimates", in: *Effects of Aggregates and Mineral Fillers on Asphalt Mixture Performance*, ed. R. Meininger West Conshohocken, PA: ASTM International, pp. 329-347, 1992. 10.1520/STP24226S.
- [72] E.G. Fernando, J.W. Button and W.W. Crockford, "Rut susceptibility of large stone mixtures", *Journal of Transportation Engineering*, vol. 123, no. 1, pp. 51-59, 1997. 10.1061/(ASCE)0733-947X(1997)123:1(51).
- [73] J.W. Button, D. Perdomo and R.L. Lytton, "Influence of aggregate on rutting in asphalt concrete pavements", *Transportation Research Record*, no. 1259, pp. 141-152, 1990.
- [74] B. Huang, X. Shu and X. Chen, "Effects of mineral fillers on hot-mix asphalt laboratory-measured properties", *International Journal of Pavement Engineering*, vol. 8, no. 1, pp. 1-9, 2007. 10.1080/10298430600819170.
- [75] M. Karakouzian, M.R. Dunning, R.L. Dunning and J.D. Stegeman, "Performance of hot mix asphalt using coarse and skip graded aggregates", *Journal of Materials in Civil Engineering*, vol. 8, no. 2, pp. 101-107, 1996. 10.1061/(ASCE)0899-1561(1996)8:2(101).
- [76] W.R. Meier and E.J. Elnicky, "Laboratory evaluation of shape and surface texture of fine aggregate for asphalt concrete", *Transportation Research Record*, no. 1250, pp. 25-34, 1989.
- [77] T. Fletcher, C. Chandan, E. Masad and K.S. Land, "Measurement of aggregate texture and its influence on hot mix asphalt (HMA) permanent deformation", *Journal of Testing and Evaluation*, vol. 30, no. 6, pp. 524-531, 2002. 10.1520/JTE12340J.
- [78] NCHRP - National Cooperative Highway Research Program, "Aggregate properties and their relationship to the performance of SuperPave-Designed HMA: A critical review", Final Report, Washington DC: National Academy of Science, pp. 9-35, 2005.
- [79] B.D. Prowell, J. Zhang and E.R. Brown, "Aggregate properties and the performance of Superpave designed hot mix asphalt", National Cooperative Highway Research Program Report 539, Washington DC: Transportation Research Board, 2005.
- [80] H. Zhu and J.E. Nides, "Contact based analysis of asphalt pavement with the effect of aggregate angularity", *Mechanics of Materials*, vol. 32, pp. 193-202, 2000. 10.1016/S0167-6636(99)00054-X.

- [81] G. Dondi, A. Simone, V. Vignali and G. Manganelli, “Numerical and experimental study of granular mixes for asphalts”, *Powder Technology*, vol. 232, pp. 31–40, 2012. 10.1016/j.powtec.2012.07.057.
- [82] G. Dondi, A. Simone, V. Vignali and G. Manganelli, “Discrete element modelling of influences of grain shape and angularity on performance of granular mixes for asphalts”, *Procedia - Social and Behavioral Sciences*, vol. 53, pp. 399–409, 2012. 10.1016/j.sbspro.2012.09.891.
- [83] Y. Gao, X. Huang, Z. Qi and J. Zhang, “Characteristics and permanent deformation in HMA”, in: *GeoHunan International Conference, ASCE, Geotechnical Special Publication*, no. 195, pp. 136–142, 2009. 10.1061/41047(354)20.
- [84] E. Coleri, J.T. Harvey, K. Yang and J.M. Boone, “Micromechanical investigation of open-graded asphalt friction courses’ rutting mechanisms”, *Construction and Building Materials*, vol. 44, pp. 25–34, 2013. 10.1016/j.conbuildmat.2013.03.027.
- [85] K.E. Cooper, S.F. Brown and G.R. Pooley, “The design of aggregate gradings for asphalt basecourses”, *Proceeding Association of Asphalt Paving Technologists*, vol. 54, pp. 324–346, 1985.
- [86] A. Golalipour, E. Jamshidi, Y. Niazi, Z. Afsharikia and M. Khadem, “Effect of aggregate gradation on rutting of asphalt pavements”, *Procedia - Social and Behavioral Sciences*, vol. 53, pp. 440–449, 2012. 10.1016/j.sbspro.2012.09.895.
- [87] K. Mahboub and D.N. Little, “Improved asphalt concrete design procedure”, Research Report 474-1F, Texas Transportation Institute, 1988.
- [88] R.D. Barksdale, “Test device for evaluating rutting of asphalt concrete mixes”, *Transportation Research Record*, no. 1418, pp. 1–7, 1993.
- [89] C.L. Monismith, J.A. Epps and F.N. Finn, “Improved asphalt mix design”, *Journal of Asphalt Paving Technologists*, vol. 54, pp. 347–391, 1985.
- [90] P. Sivapatham and H.J. Beckedahl, “Influence of the compaction degree of asphalt on rutting and stiffness: comparison between conventional and innovative asphalt. Airfield and Highway Pavement: Meeting Today’s Challenges with Emerging Technologies”, in: *Proceedings of 2006 Airfield and Highway Pavements Specialty Conference*, pp. 486–497, 2006. 10.1061/40838(191)41.
- [91] J. Yang, H. Lu and H. Zhu, “Approaches to rut depth prediction in semirigid asphalt pavements”, *Journal of Engineering Mechanics*, vol. 135, no. 6, pp. 510–516, 2009. 10.1061/(ASCE)0733-9399(2009)135:6(510).
- [92] M.A. Elseifi, G.W. Flintsch and I.L. Al-Qadi, “Quantitative effect of elastomeric modification on binder performance at intermediate and high temperatures”, *Journal of Materials in Civil Engineering*, vol. 15, no. 1, pp. 32–40, 2003. 10.1061/(ASCE)0899-1561(2003)15:1(32).

- [93] F. Xiao, S. Amirkhanian and C.H. Juang, “Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures”, *Journal of Materials in Civil Engineering*, vol. 19, no. 6, pp. 475-483, 2007. 10.1061/(ASCE)0899-1561(2007)19:6(475).
- [94] S.J. Lee, S.N. Amirkhanian, B.J. Putman and K.W. Kim, “Laboratory study on the effects of compaction on the volumetric and rutting properties of CRM asphalt mixtures”, *Journal of Materials in Civil Engineering*, vol. 19, no. 12, pp. 1079-1089, 2007. 10.1061/(ASCE)0899-1561(2007)19:12(1079).
- [95] H.A. Rondón-Quintana, C.A. Zafra-Mejía and J.P. Rodríguez-Miranda, “Behavior of a hot mix asphalt using gilsonite and recycled concrete aggregate”, *International Journal of Advanced Science and Technology*, vol. 29, no. 3, pp. 9723-9733, 2020.
- [96] H.A. Rondón, C. Zafra and S. Chavez, “Performance characteristics and mechanical resistance of a hot mix asphalt using gilsonite and blast furnace slag”, *Scientific Review – Engineering and Environmental Sciences*, vol. 28, no. 4, pp. 503–515, 2019. 10.22630/PNIKS.2019.28.4.46.
- [97] H.A. Rondón, J.A. Noguera and C.F. Urazán, “Behavior of gilsonite-modified hot mix asphalt by wet and dry processes”, *Journal of Materials in Civil Engineering*, vol. 28, no. 2, 04015114, 2015. 10.1061/(ASCE)MT.1943-5533.0001339.
- [98] Q. Lv, W. Huang, H. Sadek, F. Xiao and C. Yan, “Investigation of the rutting performance of various modified asphalt mixtures using the Hamburg wheel-tracking device test and Multiple Stress Creep Recovery Test”, *Construction and Building Materials*, vol. 206, pp. 62-70, 2019. 10.1016/j.conbuildmat.2019.02.015.
- [99] L. G. Picado-Santos, S. D. Capitão and J.M.C. Neves, “Crumb rubber asphalt mixtures: a literature review”, *Construction and Building Materials*, vol. 247, 118577, 2020. 10.1016/j.conbuildmat.2020.118577.
- [100] A. Azarhoosh and M. Koohmishi, “Investigation of the rutting potential of asphalt binder and mixture modified by styrene-ethylene/propylene-styrene nanocomposite”, *Construction and Building Materials*, vol. 255, 119363, 2020. 10.1016/j.conbuildmat.2020.119363.
- [101] N.M. Jackson and C.D. Baldwin, “Assessing the relative rutting susceptibility of HMA in the laboratory with the Asphalt Pavement Analyzer”, *International Journal of Pavement Engineering*, vol. 1, no. 3, pp. 203–217, 2000. 10.1080/10298430008901706.
- [102] B. Huang and X. Shu, “Correlating APA to field permanent deformation for HMA mixes at the NCAT Test Track”, in: *GeoHunan International Conference*, ASCE, Geotechnical Special Publication, no. 195, pp. 25-30, 2009. 10.1061/41045(352)4.
- [103] P.A. Garnica, L.J. Gómez and M.J Sesma, “Mecánica de materiales para pavimentos”, Publicación Técnica No. 197, Sanfandila: Secretaría de Comunicaciones y Transportes (SCI) - Instituto Mexicano del Transporte (IMT), 2002.



- [104] M.T. Obaidat, T. Al-Suleiman and G. Abdul-Jabbar, “Quantification of pavement rut depth using stereovision technology”, *Journal of Surveying Engineering*, vol. 123, no. 2, pp. 55-70, 1997. 10.1061/(ASCE)0733-9453(1997)123:2(55).
- [105] R. Tangella, J. Craus, J.A. Deacon and C.L. Monismith, “Summary report on fatigue response of asphalt mixtures”, Report to Strategic Highway Research Program, Washington DC, 147 p., 1990.
- [106] X. Chen and Z. Zu, “Effects of load and temperature on permanent deformation properties of HMA”, in: *GeoHuman International Conference*, ASCE, Geotechnical Special Publication, no. 191, pp. 49-55, 2009. 10.1061/41043(350)7.
- [107] LCPC, “Accelerated Load Testing Facility: The Fatigue Carousel. [Online]. Available: [http://media.lcpc.fr/ext/pdf/gdsequipements/manege\\_200709-en.pdf](http://media.lcpc.fr/ext/pdf/gdsequipements/manege_200709-en.pdf). Consulted on 20 August 2009.
- [108] W.G. Zhang, S.H. Shen, S.H. Wu and L.N. Mohammad, “Prediction model for field rut depth of asphalt pavement based on Hamburg Wheel Tracking Test properties”, *Journal of Materials in Civil Engineering*, vol. 29, no. 9, 04017098, 2017. 10.1061/(ASCE)MT.1943-5533.0001946.
- [109] W.G. Zhang, X.M. Huang, J. Yang and X.H. Chen, “Effect of segregation on rutting resistance of asphalt pavement”, *Construction and Building Materials*, vol. 147, pp. 525–532, 2017. 10.1016/j.conbuildmat.2017.04.194.
- [110] P.K. Schukla and A. Das, “A re-visit to the development of fatigue and rutting equations used for asphalt pavement design”, *International Journal of Pavement Engineering*, vol. 9, no. 5, pp. 355–364, 2008. 10.1080/10298430701690462.
- [111] R.D. Barksdale, “Laboratory evaluation of rutting in basecourse materials”, in: *Proceedings of the 3rd International Conference on Structure Design of Asphalt Pavements*, University of Michigan, pp. 161–174, 1972.
- [112] J.S. Lai and D. Anderson, “Irrecoverable and recoverable nonlinear viscoelastic properties of asphalt concrete”, *Transportation Research Record*, no. 468, pp. 73-88, 1973.
- [113] M. Perl, J. Uzan and A. Sides, “Visco-Elasto-Plastic constitutive law for a bituminous mixture under repeated loading”, *Transportation Research Record*, no. 911, pp. 21–27, 1983.
- [114] D.B. McLean and C.L. Monismith, “Estimation of permanent deformation in asphalt concrete layers due to repeated traffic loading”, *Transportation Research Record*, no. 510, pp. 14-30, 1974.
- [115] P.J. Van de Loo, “Practical approach to the prediction of rutting in asphalt pavements: The Shell Method”, *Transportation Research Record*, no. 616, pp. 15-21, 1976.
- [116] B. Célar, “ESSO road design technology”, in: *Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements*, vol. I, Ann Arbor, pp. 249-268, 1977.

- [117] J. Verstraeten, J.E. Romain and V. Veverka, “The Belgian Road Research Center’s overall approach structural design”, In: *Fourth International Conference on The Structural Design of Asphalt Pavements*, vol. 1, Proc., Ann Arbor, 1977.
- [118] W.J. Kenis, “Predictive design procedures - a design method for flexible pavements using the VESYS structural subsystem”, in: *Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements*, vol. I, Ann Arbor, pp. 101-130, 1977.
- [119] V. Veverka, “Raming van de Spoordiepte bij wegen met cen bitumineuze verharding”, *De Wegentechniek*, vol. 24, no. 3, pp. 25-45, 1979.
- [120] K. Majidzadeh, M.G. Aly, F. Bayomy and A. El-Laithy, “Implementation of a pavement design system”, Vols. 1 y 2, Final Report, EES 578, The Ohio State University Engineering Experiment Station, 1980.
- [121] J. Verstraeten, V. Veverka and L. Francken, “Rational and practical design of asphalt pavements to avoid cracking and rutting”, In: *Proceedings of 5th International Conference on Structural Design of Asphalt Pavements*, Delf University of Technology, 1982.
- [122] K.H. Tseng and R.L. Lytton, “Prediction of permanent deformation in flexible pavement materials”, *J. Assoc. Asphalt Paving Technol.*, vol. 58, pp. 155-156, 1989.
- [123] NCHRP National Cooperative Highway Research Program, “Development of the 2002 Guide for the Design of New and Rehabilitated Pavements-Flexible Pavements Overview”, NCHRP 01-37A. Washington, DC: Transportation Research Board, 2001.
- [124] J.A. Deacon, J.T. Harvey, I. Guada, L. Popescu and C.L. Monismith, “Analytically based approach to rutting prediction”, *Transportation Research Record*, no. 1806, pp. 9-18, 2002. 10.3141/1806-02.
- [125] C.L. Monismith, L. Popescu and J.T. Harvey, “Rut depth estimation for mechanistic- empirical pavement design using simple shear test results”, *Association of Asphalt Paving Technologists*, vol. 75, pp. 1294-1338, 2006.
- [126] Z. Quang, L. Yang and J. Xiang, “The deformation characteristics of asphalt mixture based on dissipation energy”, in: *Proceedings of the Second International Conference on Transportation Engineering*, pp. 1250-1255, 2009. 10.1061/41039(345)207.
- [127] Q.S. Zhang, Y.L. Chen and X.L. Li, “Rutting in asphalt pavement under heavy load and high temperature”, in: *Proceedings of Selected Papers from the 2009 GeoHunan International Conference, Asphalt Material Characterization, Accelerated Testing, and Highway Management (GSP 190)*, pp. 39-48, 2009. 10.1061/41042(349)6.