v. 4, n. 10, 2024

Journal of
Engineering
Research

PERFORMANCE OF RECYCLED ASPHALT PAVEMENT AS GRANULAR LAYERS OF NEW FLEXIBLE PAVEMENT IN LIGHT OF PAVEMENT MECHANICS CONCEPTS: A REVIEW

Lisley Madeira Coelho
Instituto Militar de Engenharia

Antônio Carlos Rodrigues Guimarães
Instituto Militar de Engenharia

Sergio Neves Monteiro
Instituto Militar de Engenharia

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.31741024250310

Abstract: A possible solution to the pavement shortage is the use of local alternative materials that have lower costs than traditional ones, with the product from milling asphalt pavement being one of these alternative materials, as long as good technical quality is guaranteed. The pavement recycling technique emerged in mid-1915 and the term RAP (Reclaimed Asphalt Pavement) of American origin is used internationally to characterize the milled material. Research has been carried out to reuse this material, however, the deepening of knowledge of its characteristics and mechanical performance parameters in the face of traffic demands is still notable. This article provides a comprehensive analysis of the use of recycled asphalt pavement (RAP) as granular layers in new flexible pavements, using an approach based on the principles of pavement mechanics. The study reviews existing literature, addressing both the benefits and challenges associated with incorporating RAP into paving projects. Examines the evolution of pavement design models, highlighting the importance of considering not only the modulus of resilience, but also permanent deformation when designing flexible pavements. Furthermore, the results of previous studies on the performance of RAP as a granular layer are discussed, addressing its mechanical response under different loading and environmental conditions. The need to understand the specific properties of RAP, such as its heterogeneous composition and the effect of residual asphalt binder, is highlighted for effective application on pavements. Through a critical review of existing literature, the article offers valuable insights for researchers and professionals in the field of paving, contributing to the advancement of knowledge and practices related to the use of RAP in granular layers of flexible pavements.

Keywords: Pavement mechanics, RAP, granular layers, mechanical behavior.

INTRODUCTION

In the context of adopting techniques that approach the construction of more sustainable infrastructures, the road construction industry has placed emphasis on the reuse and recycling of asphalt materials in pavement rehabilitation or reconstruction projects. This policy, in addition to the obvious environmental benefits, can also contribute to reducing construction and maintenance costs associated with road pavements.

The pavement recycling technique emerged in mid-1915 and the term RAP (Reclaimed Asphalt Pavement), of American origin, is used internationally to characterize the milled material.

Milled is a term generally used to describe the material that is produced through the process of milling asphalt layers during pavement rehabilitation procedures. Most of the time, milling only affects the coating layer, but it can be carried out on other layers of the pavement.

Throughout history, RAP has been used together with new bituminous materials, whether by hot or cold mixing. However, a considerable amount of this material is still not used. As an alternative to mitigating this waste, the use of RAP as an aggregate in base and sub-base layers becomes an attractive option.

Previous reports on the use of RAP as a base layer material emerged in the early 2000s and focused on evaluating the performance of RAP in this role, mainly on elastic properties, particularly resilient modulus (MR) (Kim et al, 2007; Maher et al., 1997).

In the United States, flexible pavement structures are typically designed in accordance with the mechanistic empirical pavement design guidelines (MEPDG) initially published by AASHTO (1993) and other revisions made (NCHRP 1-37 A, 2004); (AASTHO, 2020). In all revisions, MEPDG uses elastic analysis theory to calculate deformations at critical locations that could result in failure of the pavement structure. MR is considered the only parameter for material characterization in the pavement structure design process according to the Mechanistic Empirical Pavement Design Guideline (MEPDG) (AASHTO, 1993). For this reason, previous studies focused on characterizing RAP based on MR.

In Brazil, MeDiNa, a mechanistic-empirical sizing method and program proposed by the Transport Research Institute (IPR) and the National Department of Transport Infrastructure (DNIT), considers in addition to the resilience module, the characteristic of permanent deformation as data input for the design of flexible floors.

As Brazil is an extensive country with different materials, both soils and granular aggregates, knowledge of the characteristics of these materials is important for more efficient choices, economically and structurally, as there are materials that are more susceptible to greater accumulation of permanent deformation and others that contribute significantly to the dissipation of wheel load stresses without accumulating significant deformations.

For this reason, over the years Brazilian research related to the permanent deformation behavior of soils and crushed stone has been carried out: Guimarães (2001), Guimarães (2009), Malysz (2004), Malysz (2009), Silva (2009), Delgado (2012), Osten (2012), Zago (2016), Lima (2016), Norbak (2018), Roza, Lima and Motta (2018) and Lima (2020). In these, the study by Guimarães (2009) stands out, which proposed a permanent deformation prediction model, which is also in the new permanent deformation standard of the DNIT Transport Research Institute, the first national one, called Paving – Soils – Determination of permanent deformation – Test instruction (DNIT 179, 2018)) and inserted into the Software, already mentioned, MeDiNa.

RAP, due to its composition and special characteristics (heterogeneous granulometry, type of residual binder, specific mass, and source rock) manifests a mechanical behavior that is different from that of natural aggregates. The way these properties affect their elastic responses under loading is necessary information for pavement design procedures.

Several models for predicting the responses of pavement materials have been developed over the years, however, it is necessary to investigate the applicability of prediction models to mixtures containing RAP, due to the potential for variation in the properties of these materials in relation to base materials. more standardized aggregates in pavement structures.

Literature indicates that RAP tends to have a higher resilience modulus (MR) compared to virgin aggregates (AV), leading to an expectation of better performance. Maher, Gucunski, and Papp (1997) were among the first researchers to evaluate the performance of unbound aggregates containing RAP in terms of MR, and concluded that a mixture of AV including RAP resulted in higher MR compared to pure AV.

In the 2000s, many researchers continued to evaluate RAP as a basic pavement material and carried out MR tests (ALAM; ABDELRAHMAN; SCHRAM, 2010); (DONG; HUANG, 2013); (CLIATT; PLATI; LOIZOS, 2016). The conclusions of some of these studies such as Song and Ooi (2010) state that the MR of 100% RAP samples is greater than that of a natural aggregate. Kim, Labuz and Dai (2007) and Hoppe et al. (2015) concluded that a mixture of 50% aggregate and 50% RAP presents greater stiffness than samples with 100% natural aggregate at higher confining pressures.

However, despite the higher MR, RAP can accumulate more pronounced permanent deformations (PD) than virgin aggregates (SOLEIMANBEIGI; EDIL, 2015); (KOOTSTRA et al., 2010) (EDIL; TINJUM; BENSON, 2012); (BILODEAU; PAIN´;

DEPATIE, 2013); (ULLAH; TANYU; HOPPE, 2018). According to Viyanant, Rathje and Rauch (2007), the asphalt binder film present on the particles makes the compacted RAP susceptible to excessive deformation over time and creep rupture under constant deviating stresses present in the pavement structure.

As the viscosity of the asphalt binder depends on temperature (ROBERTS et al., 1996); (ASTMD422-63, 2007), temperature change can affect the geotechnical properties of compacted RAP. Therefore, Soleimanbeigi and Edil (2015) suggested thermal conditioning to enhance and improve the geotechnical properties of RAP used as a base layer or landfill fill. Thermal conditioning has already been analyzed in seabed sediments (HOUSTON; HOUSTON; WILLIAMS, 1985), in peat (EDIL; FOX, 1994); (HANSON, 1996)), in mixtures of recycled asphalt shingles (SOLEIMANBEIGI; EDIL; BENSON, 2014) (SOLEIMANBEIGI; EDIL; BENSON, 2015) and demonstrated to be effective in reducing the compressibility of these materials.

PAVEMENT MECHANICS

Pavement mechanics arose from the need to study the pavement as a system of layers, and is currently a very important discipline for civil engineers, as it encompasses the study of the performance of the materials used together with the stress analysis of the structure as a whole. According to Santos (2015), several factors influence the mechanics of pavements in the design and durability of the structure, such as: traffic applied to the pavement, the climate of the region where the pavement is located and the materials used in the layers.

The concept of Pavement Mechanics is constantly evolving, and was introduced in Brazil by Prof. Jacques de Medina, initially as a subject at COPPE in his master's degree course in civil engineering, in the 1970s. COPPE Geotechnics, named in 1997 as Jacques de Medina Laboratory, carries out continuous research in this aspect. From the article by Motta and Medina (2006), some historical facts about pavement mechanics in Brazil can be highlighted:

- In 1977, the study of materials in triaxial repeated load equipment began, the first in the country, and since then it has received improvements and updates;
- The first Brazilian master's thesis with results from dynamic soil tests using repeated load triaxial equipment was carried out by Ernesto Preussler (PREUSSLER, 1978), inaugurating a new phase of national studies and pavement design in the country;
- The first doctoral thesis on pavement mechanics in the country was that of Ernesto Preussler (PREUSSLER, 1983) which resulted in a method for sizing the reinforcement of asphalt pavements standardized by the National Department of Highways (DNER) years later (PRO 269 /94);
- In 1986, the first standard for dynamic triaxial soil testing was established through a partnership between COPPE and the DNER's Road Research Institute (IPR), currently the National Department of Transport Infrastructure (DNIT);
- The first book published in Brazil on Pavement Mechanics was by Medina in 1997;
- This book entitled Pavement Mechanics is in its third edition in 2015

and is written by Jacques de Medina and Laura Motta.

Among the main concepts is the resilience of each material and the emphasis on considering the deformability of the different materials that make up the pavement structure, with the set of materials being subject to withstanding the stresses and transferring them to the lower layers and subgrade.

Regarding the analysis of stresses and deformations of the asphalt pavement, which is the basis of the mechanistic method, in asphalt pavements with a granular base, the hypothesis is that the asphalt coating works in flexion while the other layers work in compression.

Coatings in general are subjected to compressive stresses on the surface and consequently tensile stresses arise in the lower fibers due to flexion, while the other layers are mainly subjected to compression as there is no effect of shear stress resulting from the passing of the wheel. This information can be seen in figure 1.

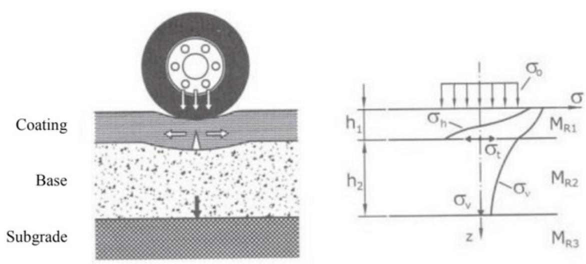

Figure 1: Stresses in a floor. Source: (MEDINA; MOTTA, 2015)

In general, many efforts have been dedicated to studying the mechanics of pavements to better understand their behavior and performance. A more analytical understanding of the problem is sought, despite the existence of a portion of empiricism that must be minimized as much as possible.

The adequate performance of a pavement is the result of a good pavement design project obtained through mechanistic analysis that makes the structural set of its layers compatible with regard to the resistance and deformability of the materials. The selection of materials and construction control are also an important part of the success of a pavement.

The evolution of software and the increase in structural knowledge of pavements and applied materials make it possible to calculate stresses, deformations and displacements with increasing ease.

It is important that the pavement design project is continually evolving, enabling it to be improved whenever new laboratory technologies emerge and new research results become available. The fundamental factors that influence the structure of the pavement, such as traffic volume and environmental conditions, must always be taken into consideration.

MeDiNa – National Dimensioning Method, named in honor of Prof. Jacques de Medina, precursor of Pavement Mechanics and responsible for countless research in Brazil, is the new Brazilian sizing method that is based on mechanistic-empirical criteria. It is based on software previously called SisPavBR, which was a first adaptation of the SisPav program developed by Franco (2007).

In mechanistic-empirical methods, the stresses and deformations that occur in the layers of the pavement structure must be analyzed as a function of the load imposed by vehicle traffic and compared with permissible values of the parameters chosen for the design. Material assessments are carried out in non-perfectly elastic media (soils, granular materials and asphalt mixtures) through tests that reproduce the stress state and environmental conditions to which the pavements will be subjected in the field, and the structure's responses are compared with criteria pre-established sizing methods to determine the thicknesses of the pavement layers.

According to Batista (2007), the structural behavior of pavements in this type of method is evaluated through analytical and/or numerical simulations and for this it is necessary to know the deformability parameters of the materials making up the pavement layers.

To calculate these stresses, deformations and displacements, the theory of elasticity has generally been used, considering materials according to two distinct stress-strain behaviors: linear elastic behavior and non-linear elastic behavior (FRANCO, 2007).

The theory of elasticity is applied, for simplification, to non-perfectly elastic media and even to visco-elastic ones: soils, granular materials, and asphalt mixtures. In the computer programs, the sizing of the thicknesses of the asphalt pavement layers is verified based on a proposed initial structure ("pilot") and criteria for the rupture parameters considered.

MeDiNa follows a basic analysis scheme of a mechanistic-empirical method, which takes into consideration, materials and their properties, and external parameters including traffic and environmental factors. The defects considered are those of fatigue (asphalt mixture, soil-cement mixture, materials treated with cement) and permanent deformation of soils and granular materials.

Furthermore, the program offers two analysis options: structure sizing in which layer thicknesses are adjusted and structural assessment, where it only checks whether a given structure satisfies the criteria, both consider all the designer's data, allowing the design life to be identified. It is worth noting that, for automatic sizing, one layer must be selected at a time and its thickness will be modified until the adjustment criteria are satisfactory. The program, at the end, provides the level of reliability used, which is associated with the design traffic volume, deflection basins for construction control, the predicted cracked area in the pavement at the end of the period with the monthly evolution of damage and deformation total permanent resulting from the contribution of the layers below the coating.

RESILIENCE MODULE

The resilience modulus (MR) is obtained from the results of triaxial repeated load tests, being defined as the relationship between the deviation stress ($\sigma 1$ - $\sigma 3$) and the axial resilient deformation, Δr, which is understood as the relationship Δh by $h0$ where, Δh is the maximum vertical displacement and $h0$ is the initial reference length of the cylindrical specimen.

Referring to the influence of deviation stress and confining pressure on the resilience behavior of granular and cohesive soils, stabilized with lime, Fossberg (1969) reports that granular soils show increases in the resilience modulus with increases in confining stress., however, this parameter is independent of the voltage deviation, for voltage levels below that of rupture; for cohesive soils, the resilience modulus is independent of the confining pressure, but is a function of the deviation stress.

Chou (1977) mentions that the resilience modulus decreases rapidly with increases in σd, for low stress levels, and for greater increases in σd, only reduced increases in MR occur. Therefore, for stabilized materials that have friction and cohesion characteristics, an intermediate behavior between the extremes already discussed can be expected.

Fossberg (1969), working with a soil-lime mixture subjected to a triaxial stress state in drained and undrained conditions, obtained MR values above 690 MPa for the mixture, concluding that resilient deformations increase with increases in stress deviation, small variations occur when the mixture is subjected to repeated loads at low stress levels.

This author also concluded that the MR grows with increases in the confining pressure and reduction in the deviation tension, presenting this parameter and the ratio of the main tensions with a development that resembles the linear.

MODELS FOR REPRESENTING THE RESILIENT BEHAVIOR OF SOILS

The resilience modulus depends on the nature of the soil, its texture, the plasticity of the fine fraction, its humidity, its density and the state of stress. The triaxial repeated load test is carried out on unsaturated soils, almost always in free drainage conditions; This situation better simulates field conditions (MEDINA, 1997).

Medina and Motta (1988), through the results of dynamic triaxial tests carried out on tropical soils, observed four different models of resilient behavior: granular, cohesive, combined and constant. These models, and respective equations, are represented in Figure 2. They establish mathematical expressions that represent relationships between the resilience modulus and the acting stresses, according to the nature of the materials and their humidity and density conditions. These relationships are dependent on constants k determined experimentally through cyclic triaxial tests.

PERMANENT DEFORMATION

In general, the factors that cause a decrease in the shear strength of soils and crushed stone tend to increase permanent deformation (PD) when the material is subjected to the action of vehicle traffic. Previous research has indicated that the main factors affecting permanent deformation in soils are as follows:

- Stress: stress state, rotation of principal stresses with wheel load displacement and stress history.
- Charging: magnitude, number of applications, duration, frequency and charging sequence.
- Humidity: percentage, material permeability, degree of saturation and pore pressure.
- Aggregate: type of aggregate, particle shape, particle size, percentage of fines, maximum grain size and real specific gravity of the grains.

According to Lekarp and Dawson (1998), Werkmeister, Ralf and Dawson (2002), and Guimarães (2009), an adequate pavement will be well designed initially through efficient selection of materials that must present resistance and stiffness characteristics capable of resisting accumulation of permanent deformation without resulting in severe irreversible deformations on the pavement surface.

The deformation behavior of granular materials, for example, must be evaluated based on permanent deformation and elastic deformation responses together. The boundaries between plastic shakedown, plastic creep, and incremental collapse zones cannot be distinguished based solely on the total permanent deformation response. That is, the shape of the accumulated permanent deformation, the change in the rate of permanent deformation and the change in elastic deformation must be used together to evaluate the behavior of the material (SOLIMAN; SHALABY, 2015).

Collins and Boulbibane (2000) already stated that it is essential to develop theoretical models that allow the prediction of permanent deformation and that, to this end, laboratory studies are necessary for soils and aggregates through triaxial tests of repeated loads in an attempt to represent as much as possible the material behavior and possible performance in the pavement layer. For Lima (2016), the

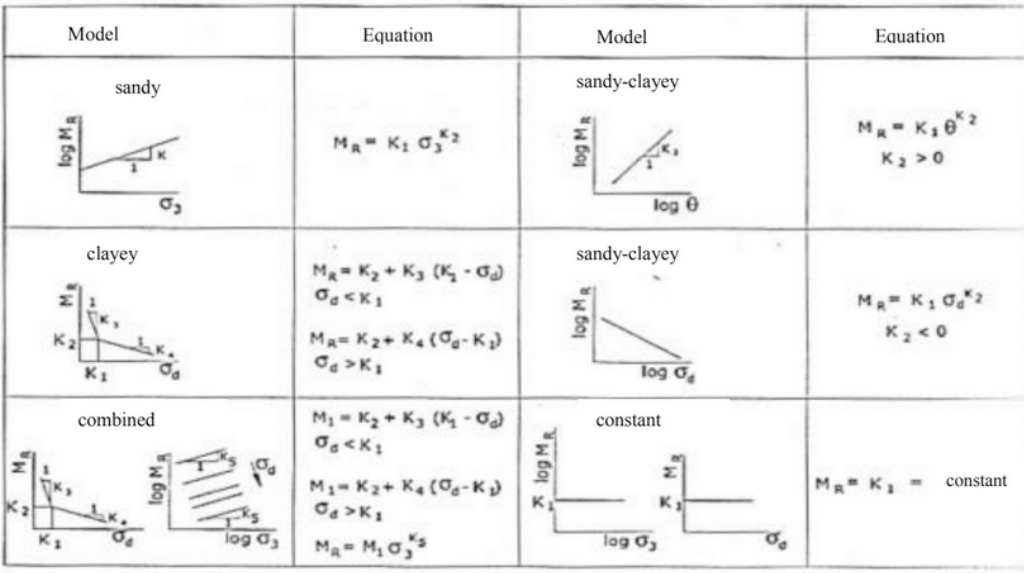

Figure 2: Resilient soil behavior models. Source: (MOTTA; MEDINA, 2006)

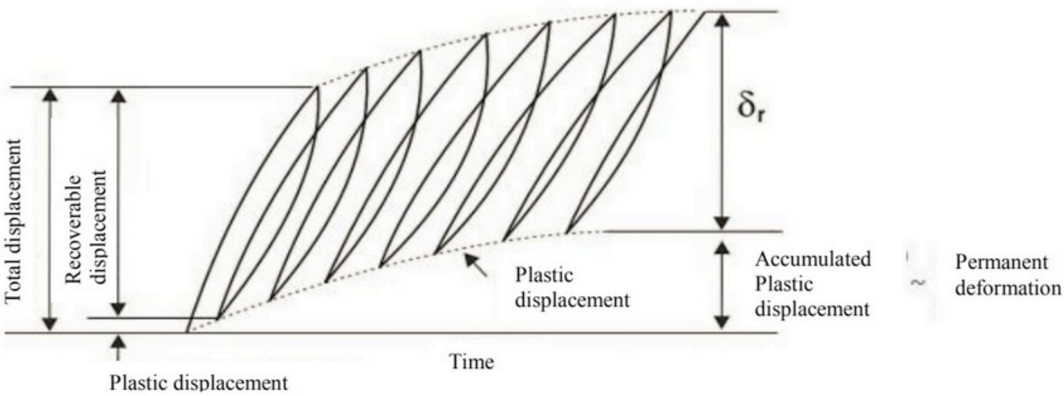

Figure 3: Representation of the displacements suffered by a specimen subjected to dynamic loads in the triaxial (BERNUCCI et al., 2010).

most recent models for predicting permanent deformations are based, above all, on the shakedown concept.

In general, according to the European standard EN 13286-7 (CEN, 2004), permanent deformation tests can be used for different purposes (classification, evaluation of maximum allowable stress levels, modeling of permanent deformations) and the number of tests to be executed and the stress states depend on the objective.

INFLUENCE OF TENSIONS

Without a doubt, the state of stress is a very important factor that influences permanent deformation in soils, and research already carried out usually uses laboratory tests to quantify this influence. Laboratory tests must seek to reproduce all field operating conditions as much as possible. This is the case with the calculation of permanent deformation.

In general, it is content with obtaining parameters that can be used in mechanistic analysis. A restriction made for triaxial equipment with repeated loads refers to its impossibility of simulating the inversion of the main stresses that occurs in a soil element subjected to the action of the moving wheel load, as well as the induction of shear stresses.

It is noteworthy that in 2008, during the first International Conference on Transport Geotechnics in 2008, held in Nottingham (UK), work was presented by Japanese researchers related to the development of equipment that allows the aforementioned stress inversion.

Taking into consideration, conventional triaxial equipment, it can be considered that the increase in the deviation stress generates an increase in the total permanent deformation, as can be seen in Lekarp and Dawson (1998), Odermatt (2000), Guimarães (2001), among many others. Regarding the isolated influence of confining stress, the decrease in confining stress generates an increase in permanent deformation.

Other studies were conducted in such a way as to consider the effect of the ratio between vertical tension (V1) and horizontal tension (V3), that is, the relationship, with this relationship being directly associated with shear stress. In other words, the effect of this relationship would be associated with the effect of shear stress, the inversion of which is associated with the action of the horizontal movement of vehicles, mentioned above.

Lashine et al. (1971, apud Lekarp (1999)), carried out triaxial tests with crushed rock in partially saturated and drained conditions, finding that the axial (vertical) permanent deformation tended to a constant value and directly related to the ratio between the deviation stress and the confining stress. According to the authors, similar results were obtained by other researchers.

Lekarp and Dawson (1998) consider that rupture in granular materials subjected to the action of repeated loads is a gradual process and not a sudden collapse, as in the case of static tests.

The behavior of a soil in terms of permanent deformation is related to the history of stresses to which it has been subjected, that is, in the case of pavements, to the sequence of loading application.

INFLUENCE OF LOADING

From studies of triaxial tests of repeated loads, it is verified the existence of two behaviors regarding permanent deformation:

- the deformation is increasing until the specimen ruptures,
- the deformation is increasing until a state of equilibrium is reached, when the increase ceases.

Some tests were limited, at most, to ten thousand load application cycles. This procedure does not seem to be very suitable, because in the first load application cycles the shape of the permanent deformation curve is very different from that presented in the rest of the cycles, in which, generally, a tendency to accommodation is observed, as shown in Guimarães (2001).

Motta (1991) indicates that the rate of increase in permanent deformation must be observed, and when this value becomes close to zero the test can be stopped.

In the case of granular materials, Morgan (1966 apud Lekarp (1999)), carried out triaxial repeated load tests with a number of load applications exceeding 2,000,000 cycles, observing that the permanent deformation still showed growth at the end of the test.

Barksdale (1972) concluded that the permanent deformation presented by a granular material he studied varied linearly with the number N of load application, and that from a relatively high number of load application the rate of accumulated permanent deformation may present a sudden growth.

On the other hand, Brown and Hide (1975 apud Lekarp (1999)), investigating the behavior of well-graded granite crushed stone, observed the emergence of an equilibrium state after approximately 1,000 loading cycles. Paute, Hornych and Bernaben (1996) argue that the rate of increase in permanent deformation in granular materials subjected to repeated loads constantly decreases to such a point that it is possible to define a limit value for the accumulated permanent deformation.

LEVELS OF BEHAVIOR

Materials change their behavior due to different influencing factors, considering intrinsic and external ones, and even if they are in similar conditions, they change with just variations in tension, being able to accommodate or even collapse.

The four types of behavior, also called levels or domains (A, B, C and AB) can be described as follows:

- Behavior A - plastic shakedown, plastic accommodation or simply shakedown: At this level there is an accumulation of plastic response for a finite number of load applications until the response becomes “completely” resilient, with an increase in plastic deformation close to mathematical zero, reaching a state of equilibrium. A material with this type of behavior generally presents low accumulated permanent deformations and represents the material that is in plastic accommodation, that is, it does not contribute much to subsidence in the pavement.

- Behavior B – plastic creep: It is the intermediate domain between A and C. In this case the material does not go into shakedown, despite initially presenting a similar behavior to A, and there is a progressive increase in permanent deformation after a large number of load applications even this has a low rate of increase in permanent deformation, an almost constant rate. In this type of behavior, permanent deformation is acceptable to a certain extent, as the material can collapse depending on the number of load cycles applied as this tends to accumulate.

- Behavior C – incremental collapse: Generally, it occurs due to the high applied tension that collapses the material in a few cycles of load applications. The material in this behavior presents a decrease in elastic deformation and a successive increase in plastic with each load application. Material not suitable for most paving cases, which may result in excessive wheel track sinking (ATR) and pavement failure.

- AB Behavior: It was indicated as an intermediate domain between B and A. Type AB behavior presents significant initial permanent deformations followed by plastic accommodation, that is, after a significant amount of plastic deformations it enters into shakedown. In other words, it presents plastic shakedown-like behavior, but with a greater initial magnitude of accumulation of permanent deformation. This type of behavior was first observed in studies of tropical lateritic soils.

In addition to the influence of the nature of the materials, these behavioral changes are linked to the conditions imposed during the test and its initial state (structural arrangement), which is dependent on the sample preparation stage.

Due to the fact that the material changes its behavior with variation in tension, it is essential to study different tensions, preferably those that can represent the material in different layers of the pavement. A material that is in domain B, for example, is a material that improperly placed in layers subjected to stress states that would leave it in region B, or even higher stresses, would collapse, however

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.31741024250310

it can be applied to a layer in lower voltages reach, thus entering into shakedown. Likewise, a material with AB behavior that may initially present large permanent deformations and subsequently accommodate, must have its application studied in order to consider these initial sags, but not discard it before checking the pavement structure and for the expected traffic.

Werkmeister S. and Dawson and Wellner (2004) indicated that the use of type A behavior is appropriate, behavior at level B can be accepted depending on some factors such as the type of traffic and the material that is in domain C is not It must never be applied to a floor.

However, it is worth noting that the European Standard EN 13286-7 (CEN, 2004) is based on the classification and thesis of Werkmeister S. and Dawson and Wellner (2004). This classification, together with the additional behavior identified by Guimarães (2009) has been used by Brazilian researchers.

COMPACTION AND HUMIDITY

The influence of moisture content on the process of PD occurrence is also relevant, given that the action of inserting the incorrect volume of water into the material used to execute the layers can cause harmful consequences to the structure by compromising the achievement of the desired compaction. Ribeiro (2013) reports that the presence of an adequate amount of water in the soil can positively influence the cohesion of materials, however, a small increase in quantity can generate, among other consequences, a significant increase in DP and a decrease in MR.

According to Guimarães (2009), the moisture content of a soil in the reinforcement layers of the subgrade, sub-base and base in the field depends on the compaction humidity and the variation in humidity after compaction. From this, a moisture content close to the optimum is adopted for carrying out laboratory tests to determine the technological properties of the soils. Field experience shows that when this recommendation is not followed, there is an acceleration in the deterioration of the executed section, generating unforeseen costs during re-execution.

Even if a variation of two percentage points around the optimum humidity is allowed, regardless of the nature of the soil, there is a risk of altering the behavior of materials that present the steepest compaction curve and, consequently, compromising the degree of compaction and post-execution performance. According to Guimarães (2009), research into the influence of compaction moisture content, varying around the optimum moisture content, on accumulated DP is desirable, as is quality control of the compaction process.

Furthermore, according to the same author, the apparent dry mass (MEAS) and the degree of compaction have an important influence on the behavior of soils subjected to the action of repeated loads. The DP resistance of soils tends to increase with the increase in the specific mass of the material. Barksdale (1972) studied the behavior of various granular materials and observed an average increase of 185% in total DP when the material reached a compaction degree of 95%, instead of 100%.

Barksdale (1972) and Lekarp (1999) mention that changing compaction, increasing the energy applied, considerably reduces DP. These same authors mention that the greater contact between the particles that make up the material and their interlocking, due to the increase in the apparent dry mass, is the biggest reason for this reduction. Another important detail is the compaction process in the sample, as each method (by impact, vibration or kneading) can present different deformations.

It must be noted here that the best compaction energy needs to be investigated for some Brazilian soils that may present a characteristic compaction limit as presented by Junior (2005).

PERMANENT DEFORMATION PREDICTION MODELS

Prediction models for the specific permanent deformation of paving materials have been developed based on data obtained in the laboratory, through triaxial tests with repeated loads, in addition to field simulators. These models present various information regarding the conditions of the pavement according to the design carried out, such as variables of shear resistance of soil and crushed stone.

For the development of analytical models, which are much more complex, one must understand the behavior and properties of materials, which can be evaluated through a series of laboratory tests where it is possible to simulate the properties of the material under cyclic load, with the models being characterized mathematically. These models treat the pavement as a structure and are based on analyzing the response of the pavement layers and the entire multilayer structure. These models can take into consideration, numerous parameters that may influence the permanent deformation behavior. (LEKARP; ISACSSON; DAWSON, 2000) and (CERNI S.AND CARDONE; VIRGILI, 2012)

The parameters obtained to compose the models depend on the procedures used to shape the specimens and the test methods. These variations, together with uncertainties in forecasting traffic and weather conditions, make it very difficult to estimate the depth of subsidence. Therefore, the use of more simplified models is justified (HUANG, 1993).

In view of the analysis of the main prediction models proposed over the last few decades, the problem of adequately representing the behavior of a soil with regard to DP is notorious, due to the set of factors, conditions, mathematical formulations involved in this process, almost always with variables different in each case.

Guimarães (2009) described that the concern with the perfect modeling of the behavior obtained in tests does not guarantee the practical implementation of a developed model, if these formulations cannot be associated with the sizing methods. Figure 1 briefly presents the main PD prediction models, proposed in the literature consulted, for the materials that make up the granular layers of the pavement structure, with some of their characteristics, attributes and conditions for validating this tool.

Authors	Models	Parameters
MONISMITH (1975)	$\varepsilon_p = A.N^B$	A e B
MAJIDZADEH *et al.* (1976)	$\varepsilon_p/N = A(D,w).N^{-m}$	A e m
LENTZ e BALADI (1981)	$\varepsilon_{1,p}=\varepsilon_{0,95}.\ln(1-q/S)^{-0,15}+\{\frac{n.(\frac{q}{S})}{[1-m.(\frac{q}{S})]}\}.\ln(N)$	n e m
UZAN (1981)	$\varepsilon_p(N)/\varepsilon_r = \mu.N^{-\alpha}$	α e μ
BARKSDALE (1984)	$\varepsilon_{1,p} = a + b.\log(N)$	a e b
TSENG e LYTTON (1989)	$\delta_{a(N)} = (\varepsilon_0/\varepsilon_r).e^{-(\rho/N)\beta}.\varepsilon_v.h$	ρ e β
GUIMARÃES (2009)	$\varepsilon_p^{esp} = \Psi_1.\sigma_3^{\Psi 2}\sigma_d^{\Psi 3}.N^{\Psi 4}$	$\Psi_1\Psi_2\Psi_3\Psi_4$

Table 1 – Main permanent deformation models for granular materials. Source: Adapted from (CABRAL, 2021).

In the model by Monismith, Ogawa and Freeme (1975), parameters A and B are calculated with the help of some basic statistical software, but they can also be obtained in the literature, by comparison. Its data is generated from triaxial tests, applying load cycles (N) of less than 100,000 cycles.

The study of the model by Majidzadeh, Buranrom and Karakomzia (1976) was developed with the granular fraction of silty and clayey soils, from the state of Ohio/ USA. The parameter "m" normally varies between 0.82 and 0.95, and for soils with a dynamic modulus greater than 40MPa, "m" can be considered constant. Parameter "A" is a function of humidity, density and voltage deviation.

The sands were tested using the Lentz and Baladi (1981) model, where the regression parameters (m and n) vary with the confining stress. The authors reported that the results were obtained for a single sandy subgrade soil, with a good correlation between the calculated and tested deformation, but requiring further research with other materials to create a more consistent database.

In the proposition of Uzan (1981), considered limited by the obligation for the elastic deformation to be constant throughout the test, the parameter α is defined such that α=1−B, and the parameter μ, is such that μ = A.B/ϵr, where ϵr is the resilient or elastic deformation. These parameters are also "open" and can be obtained from the literature. Uzan (1981) presents a table organized by pavement layers and deformability parameters extracted from research by other authors.

Barksdale (1972) developed his studies with varied base materials, using triaxial tests of repeated loads for N greater than 105 cycles, proposing the model with "a" and "b" being constant for a given level of stress and axial permanent deformation proportional to the logarithm of the number N of load applications.

The mathematical expression of the Tseng and Lytton (1989) model, designed from a database, is "closed", not allowing the addition of new information, and its parameters ρ and β and the relationship ϵ0/ϵr are derived from the DP trials. The application of this model is not recommended for Brazilian pavements, as it does not include tropical soils in the database. All models mentioned are for soils used in granular layers of the pavement, in addition to the subgrade.

The proposal by Guimarães (2009) to predict the effect of DP relates the deformation with the deviation and confining stresses, in kgf/cm2, as well as the number N of repeated load applications. This model was considered satisfactory with a correlation of 0.91 and was tested for 8 Brazilian soils, in addition to simple graded basalt crushed stone typical of the southern region of the country. However, when a constant confining stress is adopted, it makes it difficult to obtain the regression parameters (Ψ1, Ψ2, Ψ3 and Ψ4), being considered a limiting factor. This model was used as a reference for the development of the Brazilian standard (DNIT 179, 2018) which specifies the test procedures for determining DP for granular materials used in pavement layers.

OBTAINING PERMANENT DEFORMATION IN THE LABORATORY

The Brazilian standard (DNIT 179, 2018) describes the DP test method, in addition to indicating the criteria for checking accommodation. Other international standards also consider this type of test, but also multistage/multiple stage tests – EM (multistage; MS), in which different stress states are applied for certain numbers of cycle applications in the same specimen. Standards such as EN 13286-7 (CEN, 2004), European, AG:PT/T053 (AUSTROADS, 2006) and T15 (NZTA, 2006), Australian tests, encompass multi-stage trials.

The structures of triaxial equipment around the world vary little in relation to the reading of displacements and the size of the test specimens, and different frequencies can also be used depending on the capacity of the equipment and the resistance of the materials.

PERMANENT DEFORMATION TEST ACCORDING TO BRAZILIAN STANDARDS

Although during the MR test there is the possibility of reading a portion of the DP, to determine its estimate and respective prediction model it is necessary to carry out specific tests with higher load cycles. Details such as the number of cycles and analysis of tendency to accommodation are specific to the permanent deformation test. According to standard DNIT 134 (2018), to perform the MR test, it is recommended to apply 500 repetitions for each pair of tensions during the conditioning phase and 10 load cycles for 18 different pairs of tensions in the recording phase. of deformations. The DP testing instructions necessarily recommend the application of at least 150,000 load pulses, that is, a very high number of repetitions to evaluate the deformability of the soil.

As already mentioned in the previous subitem, the standard that describes the test instructions for determining permanent deformation in Brazil is DNIT 179 (2018), and allows tests on soils, graded crushed stone, in addition to materials that are not chemically stabilized. For each test specimen, at least 150,000 load cycles are applied for each stress pair, described in Table 2.

Pair number	Voltage pairs		
	σ3 (kPa)	σd (kPa)	σ3/σ1
01	40	40	2
02		80	3
03		120	4
04	80	80	2
05		160	3
06		240	4
07	120	120	2
08		240	3
09		360	4

Table 2: Voltage states indicated for determining DP. Source: Adapted from the standard (DNIT 179, 2018)

The indicated stress pairs are considered typical for the DP test, other pairs being admitted if the objective is to verify the limit of allowable stresses for the subgrade or other layer of the pavement. According to the standard, if the objective of the test is to determine the permanent deformation behavior model, it is necessary to use several test specimens and, in each one, apply a specific pair of stresses.

Figure 4 illustrates the main equipment for carrying out the DP test on granular paving materials. The apparatus consists of a pneumatic press, triaxial cell or chamber, axial load transducer and vertical displacement measurement system (LVDT – Linear Variable Differential Transformer), in addition to the tripartite cylindrical mold with base and two steel clamps, as well as a ring complementary (collar) properly presented in top view and in section.

The size of the tripartite cylinder depends on the particle size of the soil sample to be tested. In the case of soil or material without gravel (material that completely passes through the 4.8 mm sieve), the internal dimensions are 100 mm in diameter and 200 mm in height, however for stony soil and crushed stone the cylinder must be 150 mm in diameter and 300 mm in height, obeying the ratio of maximum particle diameter to specimen diameter of 1:4.

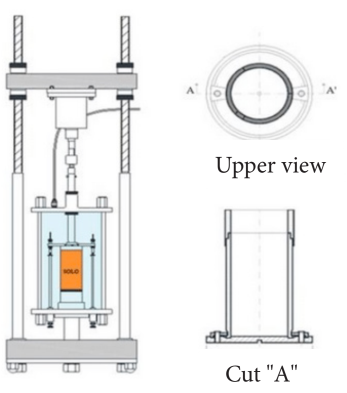

Figure 4: Equipment for carrying out the triaxial repeated load test. Source: Standard (DNIT 179, 2018)

The equipment shown in Figure 3 still requires some complementary accessories that are used in the test specimens, such as: porous stone and a rubber membrane, which provides protection against air entry. All pressure regulation for bypass and confining voltages using compressed air is automated by specific software, based on pre-established conditions.

The recommended load application frequency is 2Hz (120 cycles/minute), however, this pneumatic charging system allows repeated voltages to be applied with load frequencies of 1 to 5Hz, depending on the type of equipment, with a charging time of 0.1s and 0.9s for the rest interval.

The study of soil behavior is carried out using data obtained from tests that consist of the total permanent sinking of the sample after application of the load cycle and varying values of pre-determined stress pairs. This irreversible deformation basically occurs in three stages throughout the experiment, as shown in Figure 5.

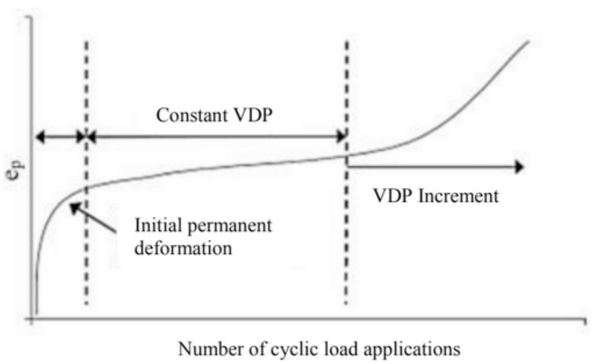

Figure 5 – Typical behavior of a soil regarding DP. Source: (MALYSZ, 2004)

In the first moment there is an increasing occurrence of deformation, reaching a constancy in the second stage and presenting a possible increase in the final part of the load application. As shown by Malysz (2004) in Figure 5, the results for the DP values of these tests are expressed in graphs where the three phases of soil behavior can be observed during the application of loads throughout the experiment.

The beginning of the last stage of this behavior, the increase in VDP (Permanent Deformation Value), is characterized as the beginning of the pavement rupture process from the formation of ATR. This increase in DP speed is more observed when the materials are stressed by high deviation stresses, characterizing the "incremental collapse" type behavior (WERKMEISTER; DAWSION; WELLER, 2001).

RECYCLING ASPHALT PAVEMENTS

The idea of recycling pavements emerged in 1915 and gained emphasis in the mid-1970s, in the United States, due to the need to reduce costs caused by the embargo of the Organization of the Petroleum Exporting Countries (OPEC). In Brazil, pavement recycling was applied for the first time in 1960 in Rio de Janeiro, at which time asphalt material from streets was removed with hammers and transported to plants for new mixing. However, it was only in 1980 that the recycling of the first highway, Via Anhanguera, was carried out on the stretch between São Paulo and Campinas.

Currently, the recycling of asphalt pavements has become a requirement in the contemporary world. Driven by environmental awareness, economic and social benefits. It is a sustainable approach that promotes the preservation of natural resources and waste reduction. Resolution N°14 (2021) is one of the actions that demonstrate this, in which it makes the use of RAP mandatory in restoration works, capacity adaptation and expansion of the National Department of Transport Infrastructure - DNIT, developed within the scope of the Headquarters and Regional Superintendents.

For Bernucci et al. (2010) pavement recycling is the process of reusing aged and deteriorated asphalt mixtures to produce new mixtures, using the remaining aggregates and binders from milling, with the addition of rejuvenating agents, asphalt foam, petroleum asphalt cement (CAP) or petroleum asphalt emulsion (EAP), when necessary, and also addition of hydraulic binders.

According to Fonseca (2009), pavement recycling is a rehabilitation technique where all or part of the existing pavement layer is reused in the construction of a new layer, whether or not incorporating new materials, thus allowing to obtain a pavement with similar characteristics or superior to the old floor.

The decision on the most appropriate type of recycling for highway restoration is subject to several factors. In an initial analysis, it is crucial to assess the level of deterioration of the different layers of the pavement and identify those that require replacement. Figure 6 provides, in an illustrative way, a suggestion from the Federal Highway Administration (FHWA) on the most appropriate recycling option at each stage of deterioration, taking into consideration, the pavement serviceability index (PCI).).

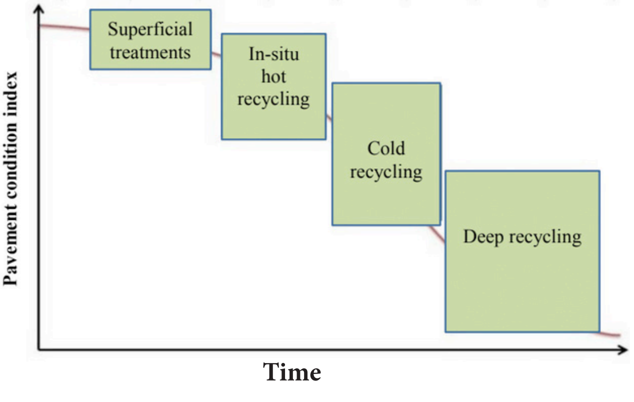

Figure 6 – Recommended type of recycling for different pavement condition indices.

Source: (FHWA, 2018)

Milling is defined as the main technique for recycling pavement with the removal of the old asphalt surface layer, which can be done using hot or cold techniques (DNIT, 2007).

According to PIRES (2014), the milling process consists of reobtaining the aggregates in granular form, despite them being surrounded by an old and worn asphalt coating, and with a modified granulometric arrangement.

The granulometric composition of the milled material will depend on the degree of oxidation of the asphalt coating, the ambient temperature, the condition of deterioration of the pavement, the cutting thickness and the condition of the teeth of the milling machine (BALBO, 2007).

Milling is presented as a solution to functional or structural problems of the existing pavement, it has advantages in its use, such as the conservation of aggregates, binders and energy, environmental preservation, and the restoration of existing geometric conditions. However, the milled material removed through the asphalt pavement milling process, known worldwide as RAP (Reclaimed Asphalt Pavement), has the disadvantage of being heterogeneous, requiring greater treatment criteria when reused in the coating layer.

The issue of milling variability also limits comparisons between studies, as highlighted by MCGARRAH (2007) in his review study. Research with recycled mixtures evaluates different properties, with different types of RAP and virgin aggregates. These different materials and processes produce variations in the evaluated properties. Therefore, no study can be directly compared to the other, however it is possible to verify some behavioral trends.

TYPES OF ASPHALT PAVEMENT RECYCLING

The United States asphalt recycling association (Asphalt Recycling and Reclaiming Association – (ARRA, 2001)) defines five main categories for different recycling methods: Cold recycling; Hot recycling; Hot in-place recycling; Cold in-place recycling; Deep recycling (Full depth complaint).

IN SITU COLD RECYCLING

In this recycling approach, the material present on the pavement surface is reused in the same location, resulting in a more efficient and economical execution compared to the process in a plant. This is due to the considerable reduction or elimination of material transportation. The technique involves a series of machines that operate sequentially, forming a recycling "train" responsible for milling the material. The recyclers are equipped with a cylinder, in which, as they advance, the milled material is pulverized and suspended until it reaches the mixing chamber (WIRTGEN GROUP, 2012).

The material from milling is mixed with the stabilizing agent (cement, lime or asphalt material) and returned in a single pass (DNIT, 2006). The mixture is applied to the milled area, compacted with a roller, leveled and, finally, compacted by vibrating and pneumatic rollers, while receiving water application (WIRTGEN GROUP, 2012).

COLD RECYCLING IN A PLANT

Cold recycling in a plant occurs when, after removing the material from the pavement, it is transported to a mixing plant. The process begins by milling the asphalt coating layer, which is then sent to the processing plant, where the material is recycled and subsequently taken back to the site for application, leveling and compaction (DNIT, 2006).

Although this technique is not the most economical due to additional costs with material transportation and longer service execution times, cold recycling in a plant allows greater control over the composition of the mixtures, since the final product is generated from the combination of aggregates in precise proportions, previously selected (WIRTGEN GROUP, 2012).

Furthermore, WIRTGEN GROUP (2012) describes this technique as being very efficient in cases where the project foresees the execution of layers lower than the recycled layer; in the case of using milled material stored from other works; when the constituent material of the pavement is very variable and a selection process is necessary, or the material is very hard and does not allow crushing.

IN SITU HOT RECYCLING

It consists of softening the existing coating layer by heating it with heat, followed by scarifying part or all of the asphalt material. The material is mixed with new heated asphalt aggregates and binders. The materials are mixed and distributed on site using a traditional paver, without the need for a mixing plant. In this type of recycling, it is not necessary to remove the original material from the construction site (DNIT, 2006).

This recycling method has the main objective of rehabilitating the functional characteristics of the pavement only in the wearing layer; it cannot be used in cases where the pavement contains pathologies in the structural layers (CUNHA, 2010).

HOT RECYCLING IN A PLANT

It is the recycling process where the degraded pavement is removed by milling and transported to the plant where the recycled mixture will be produced. In the hot recycling technique, the deteriorated pavement is combined with new aggregates

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.31741024250310

and asphalt binder with added heat to generate the recycled mixture. For this recycling technique, intermittent plants (gravimetric) or drum plants (drum-mixer) can be used. After production, the mixture is released and compacted using conventional equipment, similar to the execution of conventional asphalt concrete (DNIT, 2006).

DEEP RECYCLING

Deep recycling is a rehabilitation process carried out without the addition of heat and involves the total removal of the asphalt coating with pre-determined fractions of the base, sub-base and/or sub-grade layers. These materials are crushed and mixed, and may be added with virgin aggregates and/or stabilizing additives, in order to form a homogeneous base material. Typically, these stabilizing additives increase the mechanical resistance and structural resistance of the pavement, supporting the expected load capacity (ARRA, 1997).

MECHANICAL BEHAVIOR OF RECYCLED MIXTURES

The decline in the use of RAP to develop hot mixes has created the need to evaluate the recycling potential of RAP in the base layer of the pavement structure as an unbound aggregate. The application of RAP as a base material dates back to the early 1980s. Defoe (1982) reported that RAP was used as a stabilized bituminous base in Michigan.

Garg and Thompson (1996) reported a field investigation of a RAP-based asphalt paving project in Illinois. No transverse cracks or fatigue cracks were found after two years of traffic and drop weight deflectometer (FWD) data indicated that the RAP base provided sufficient structural support and subgrade protection. However, there are some potential problems with using unbound RAP base and therefore most states do not recommend using pure RAP in the base layer (MCGARRAH, 2007). Deformation and stability are the main concerns with unalloyed RAP as a base material.

Maher, Gucunski and Papp (1997) were pioneers in the late 1990s when characterizing RAP based on the resilience modulus (MR) and evaluating aggregate performance using the paving mechanistic empirical design guide parameter (MEPDG). The results of their research indicated that when RAP is mixed with virgin aggregate (AV), the mixture results in a higher MR than AV.

In the early 2000s, several researchers also attempted to characterize RAP as a basic base layer material, based on MEPDG parameters, and virtually all reported that increasing the percentage of RAP in RAP-AV mixtures increases the MR (DOMITROVIC; RUKAVINA; LENART, 2019).

Kim, Labuz and Dai (2007) researched the mechanical properties of materials and carried out tests for specimens with varying percentages of RAP and aggregates. The study investigated the effect on material stiffness, concluding that 50% aggregate/50% RAP samples had equal stiffness to 100% aggregate samples at lower confining pressures, while at higher confinement levels the RAP were more rigid. Hoppe et al. (2015) emphasized that a RAP ratio of up to 50% increased the stiffness of the overall base layer material.

In a study by Song and Ooi (2010), they concluded that the resilience modulus of 100% RAP is greater than that for a virgin aggregate. Dong and Huang (2013) performed laboratory tests to evaluate the unbound RAP, crushed limestone, and crushed gravel prepared with similar gradation and compaction level. The results of the study showed that RAP exhibited a higher resilience modulus when compared to unbonded aggregates.

Norbak (2018) concluded that RAP aggregates experienced lower stresses compared to conventional limestone aggregates. Cliatt, Plati, and Loizos (2016) also concluded that the RAP aggregate materials investigated had values equal to or greater than virgin aggregates.

Based on these results, it was proclaimed that RAP performs better than AV alone, because of the greater stiffness represented through modulus results.

Although researchers seem to unanimously agree that MR increases with increasing RAP content in the base course, when it comes to permanent deformation the same consistency does not exist.

Some researchers have pointed out that samples containing RAP tend to accumulate greater permanent deformation (PD) than VA.

Mohammad et al. (2006), evaluated the resilient modulus and permanent deformation properties of seven treated and untreated pavement materials. The materials were crushed limestone, calcium sulfate mixture (BCS), BCS treated with granulated blast furnace slag (GGBFS) or BCS-slag, BCS treated with fly ash (BCS – fly ash), recycled asphalt pavements (RAP), foamed asphalt – treated mixture of 50% RAP with 50% soil cement (FA-50RAP-50SC) and 100% RAP treated with foamed asphalt (FA-100RAP).

The results demonstrated that the RAP material exhibited an initial accelerated rate of permanent deformation with increasing load repetitions and then reached a stable stage. Furthermore, although the resilience modulus of FA-50RAP-50SC was close to that of crushed limestone, the permanent deformation was considerably greater. This result proved to the authors that the resilience modulus test alone is not adequate for characterizing the base materials of the pavement.

The authors also reported that the permanent deformation of RAP 100% treated with asphalt-foam was the highest among the materials investigated, followed by RAP 50% treated with asphalt-foam with 50% soil cement and the crushed limestone material.

Concluding that the treatment of RAP material with foamed asphalt degraded its properties, increasing permanent deformation under repeated loading.

Jeon, Steven and Harvey (2009) conducted multi-stage PD tests at 100% RAP and 100% AV and concluded that at low stress levels, RAP showed greater deformation than AV, but at higher stress levels the tendency was reversed. Overall, RAP was found to be stiffer than typical aggregate base material.

Attia (2010) conducted triaxial repeated load tests at 100% RAP, 50% RAP- 50% AV, and 100% AV at confining stresses of 20 and 70 kPa and corresponding cyclic deviatoric stresses of 40 and 480 kPa, respectively, and reported a decreased PD when RAP is mixed with AV, showing better performance than AV alone.

Arshad and Ahmed (2017) reached similar conclusions in which the increase in residual cumulative strains was negligible when RAP contents varied from 0 to 50%.

Research has reported that the problem of excessive deformations in the case of RAP as a base layer can be mitigated if the properties of RAP to be mixed with VA are carefully examined (ULLAH; TANYU; HOPPE, 2018); (ULLAH; TANYU, 2019). Ullah, Tanyu and Hoppe (2018) presented a study that reports that, if the gradation of RAP-AV mixtures contributes to a dense mass, it is possible to reduce PD.

The studies by Dong and Huang (2013) and Soleimanbeigi and Edil (2015) focused on evaluating the effects of temperature on the creep behavior of the RAP base course. The results of these studies showed that when RAP specimens were compacted at room temperature but tested at elevated temperatures, permanent deformation

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.31741024250310

increased and modulus of resilience decreased.

However, when the specimens were compacted at higher temperatures and tested at room temperature, a significant reduction in permanent deformation and a greater modulus of resilience were observed.

Overall, using RAP for a base layer material is a sustainable rehabilitation technique and reduces costs. However, proper characterization of the stress-dependent behavior within the pavement structure layer, RAP properties such as binder content, specific gravity and bedrock, and these significantly affect the performance of the mixture in terms of MR test results and DP and can significantly affect the overall accuracy of pavement response predictions.

CONCLUSIONS

This article reviews concepts of pavement mechanics and discusses the use of RAP in granular layers inferior to the asphalt coating, aiming to attract the attention of researchers, engineers and contractors to the importance of continuously studying the behavior of recycled asphalt material and its suitability in construction applications. engineering.

Every year, huge amounts of RAP waste are generated, which require special processes, including reuse and recycling, and the use of this material as an aggregate in base and sub-base layers has become an attractive option, as it can use it in greater quantities in these layers.

Although the results of the present study provide some useful guidance on the mechanical behavior of mixtures containing RAP, especially in relation to modulus of resilience and permanent deformation, it is crucial to recognize that their use in pavements demands a personalized and adaptive approach for each project. The selection of RAP and its effectiveness in granular layers are influenced by factors such as moisture content, granulometry, type of source rock aggregate material, bitumen content and condition, as well as crushing (grinding) technique.

At the same time, triaxial repeated load tests play a crucial role in the mechanistic analysis of pavements, providing essential information on structural strength, deformations, model validation, material evaluation and design optimization. These tests are essential to ensure the safety, durability and efficiency of road pavements throughout their useful life. Therefore, given the variability of RAP properties, it becomes even more necessary to carry out specific triaxial tests for each material and in each project, in order to determine its performance under current traffic and climate conditions.

Given this evident scenario, it is clear that there is a growing demand for the development and improvement of mechanical models capable of anticipating the behavior of RAP on pavements. These models must encompass the variability of RAP properties, its performance under repeated loads and changing environmental conditions. Furthermore, long-term field studies are essential to evaluate the effective performance of RAP on pavements over time.

REFERENCES

AASTHO. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd ed*. Washington, DC;, 2020.

ALAM, T.; ABDELRAHMAN, M.; SCHRAM, S. Laboratory characterisation of recycled asphalt pavement as a base layer. *Int. J. Pavement Eng.*, v. 11, n. 123-131, 2010.

ARSHAD, M.; AHMED, M. Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pavements. *Constr. Build. Mater*, v. 151, p. 83–97, 2017.

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION. *Pavement Recycling Guidelines for State and Local Governments Participant's Reference Book.* U.S. Department of Transportation, FHWA-SA-98-042. Washington, D.C., 1997.

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION. *Basic Asphalt Reclaiming Manual*. [S.l.], 2001.

ASTM INTERNATIONAL, WEST CONSHOHOCKEN, PA. *Standard Test Method for Particle-Size Analysis of Soils. ASTM D422-63*. [S.l.], 2007. Www.astm.org.

ATTIA, M. *Characterization of the Structural Behavior of Reclaimed Asphalt Pavement as Pavement Base Layer*. Tese (Doctorate Thesis) — North Dakota State University, 2010.

AUSTROADS WORKING GROUP. *Determination of permanent deformation and re- silient modulus characteristics of unbound granular materials under drained conditi- ons.AG:PT/T053*. [S.l.], 2006.

BALBO, J. T. *Pavimentação Asfáltica: Materiais, projeto e restauração*. first. [S.l.]: Oficina de Textos, 2007.

BARKSDALE, R. D. Laboratory evaluation of rutting in base course materials. *In Procee- dings of the Third International Conference on Structural Design of Asphalt Pavements*, 1972.

BATISTA, L. C. M. *Determinação de parâmetros de deformabilidade de camadas de um pavimento a partir de ensaios de campo.* Dissertação (Dissertação de Mestrado) — Universidade de Brasília., 2007.

BERNUCCI, L. B.; MOTTA, L. M. G. da; CERATTI, J. A. P.; SOARES, J. B. *Pavimentação asfáltica: formação básica para engenheiros*. fourth. [S.l.]: PETROBRAS: ABEDA, 2010.

BILODEAU, J.; DOR´, G.; DEPATIE, J. Mitigation of permanent deformation of base layer containing recycled asphalt aggregates. *Can J Civ Eng*, 2013.

CABRAL, W. S. *EXPLORAÇÃO, ANÁLISE COMPARATIVA E MODELAGEM DA DEFORMAÇÃO PERMANENTE DE MATERIAIS GRANULARES DA MICROREGIÃO DE MOSSORÓ/RN*. Tese (Tese de Doutorado) — Universidade Federal do Ceará, Fevereiro 2021.

CERNI S.AND CARDONE, F.; VIRGILI, A. Characterisation of permanent deformation behaviour of unbound granular materials under repeated triaxial loading. *Construction and Building Materials*, n. 28, p. 79–87, 2012.

CHOU, Y. *Analysis of permanent deformations of flexible airfield pavements.* [S.l.]: Federal Aviation Administration, 1977.

CLIATT, B.; PLATI, C.; LOIZOS, A. Investigating resilient modulus interdependence to moisture for reclaimed asphalt pavement aggregates. *Procedia Eng*, v. 143, p. 244–251, 2016.

COLLINS, I. F.; BOULBIBANE, M. Geomechanical analysis of unbound pavements based on shakedown theory. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 126, n. 1, p. 50–59, jan 2000.

CUNHA, C. M. *Reciclagem de Pavimentos Rodoviários Flexíveis: Diferentes Tipos de Reciclagem.* Dissertação (Dissertação (Mestrado) — Instituto Superior de Engenharia de Lisboa: Departamento de Engenharia Civil, 2010.

DEFOE, J. H. Use of recycled asphalt materials in the construction of a bituminous stabilized base. *Final Rep., Michigan Dept. of Transportation*, 1982.

DELGADO, B. G. *Análise da Deformabilidade de um Solo Tropical do Oeste do Maranhão Como Material de Sublastro na Estrada de Ferro Carajás*. Dissertação (Dissertação de Mestrado) — Universidade Federal de Ouro Preto, Ouro Preto, MG, 2012.

DEPARTAMENTO Nacional de Infraestrutura de Transportes. Pavimentação – Solos – Determinação do módulo da deformação permanente– Instrução de ensaio. Rio de Janeiro, 2018.

DEPARTAMENTO Nacional de Infraestrutura de Transportes. Pavimentação – Solos – Determinação do módulo de resiliência – Método de ensaio. Rio de Janeiro, 2018.

DNIT- DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES. *Manual de Restauração de Pavimentos Asfálticos*. [S.l.], 2006.

DOMITROVIC´, J.; RUKAVINA, T.; LENART, S. Effect of freeze-thaw cycles on the resilient moduli and permanent deformation of rap/natural aggregate unbound base mixtures. *Transp. Geotech.*, v. 18, p. 83–91, 2019.

DONG, Q.; HUANG, B. Laboratory evaluation on resilient modulus and rate dependencies of rap used as unbound base material. *J. Mater. Civ. Eng*, v. 26, p. 379–383, 2013.

EDIL, T.; TINJUM, J.; BENSON, C. Recycled unbound materials. *Minnesota Department of Transportation Research Services, Office of Policy Analysis, Research & Innovation.*, 2012. University of Wisconsin-Madison.

EDIL, T. B.; FOX, P. J. Field test of thermal precompression. *Proceedings of Settlement'94, Specialty Conference of the American Society of Civil Engineers, Geotechnical Engineering Division*, p. 1274–1286, 1994. College Station, TX, June 16–18, ASCE, Reston, VA.

EUROPEAN COMMITTEE FOR STANDARDIZATION. *Unbound and Hydraulically Bound Mixtures.Unbound and Hydraulically Bound Mixtures-EN 13286-7*. [S.l.], 2004.

FEDERAL HIGHWAY ADMINISTRATION – FHWA. *Overview of Project Selection Guidelines for Cold In-place and Cold Central Plant Pavement Recycling.* Fhwa-hif-17-042. Washington, Estados Unidos,, 2018.

FOSSBERG, P. E. Some deformations characteristics of a lime stabilized clay. *Highway Research Record*, 1969.

FRANCO, F. A. C. P. *Método de dimensionamento mecanístico-empírico de pavimentos asfálticos – SisPav.* Tese (Tese (Doutorado)) — Universidade Federal do Rio de Janeiro, 2007.

GARG, N.; THOMPSON, M. R. Lincoln avenue reclaimed asphalt pavement base project. *Transportation Research Record*, n. 1547, p. 89–95, 1996.

GUIDE FOR DESIGN OF PAVEMENTS STRUCTURES. *American Association of State Highway and Transportation Officials*. Washington D.C., 1993.

GUIMARãES, A. C. R. *Estudo de Deformação Permanente em Solos e Teoria do Shake- down Aplicada a Pavimentos Flexíveis.* Tese (Dissertação de Mestrado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro, 2001.

GUIMARãES, A. C. R. *Um Método Mecanítico-Empírico para a Previsão da Deformação Permanente em Solos Tropicais Constituintes de Pavimentos.* Tese (Tese de Doutorado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro, 2009.

HANSON, J. L. *hermal Precompression of Peat*. Tese (Ph.D. thesis) — University of Wisconsin–Madison, Madison, 1996.

HOPPE, E.; LANE, S.; FITCH, M.; SHETTY, S. Feasibility of reclaimed asphalt pavement (rap) use as road base and subbase material;. *Report no VCTIR 15-R6*, 2015. Virginia Center for Transportation Innovation and Research, University of Virginia. Charlottesville: Charlottesville, VA, USA,.

HOUSTON, S. L.; HOUSTON, W. N.; WILLIAMS, N. D. Thermo-mechanical behaviour of seafloor sediments. *J. Geotech. Eng.*,, v. 111, n. 11, p. 1249–1263, 1985.

HUANG, Y. H. *Pavement analysis and design*. [S.l.]: Prentice-Hall, 1993.

JEON, E.; STEVEN, B.; HARVEY, J. Comprehensive laboratory testing and performance evaluation of recycled pulverized hot-mix asphalt material. *Transportat. Res. Record: J. Transport. Res. Board*, p. 42–52, 2009.

JUNIOR, J. D. S. *O efeito da energia de compactação em algumas propriedades dos solos do estado do Ceará utilizados em pavimentação*. Dissertação (Mestrado) — Universidade Federal do Ceará. Fortaleza, 2005.

KIM, W.; LABUZ, J.; DAI, S. Resilient modulus of base course containing recycled asphalt pavement. *J. Transp. Res. Board*, n. 27-35, 2007.

KOOTSTRA, B.; EBRAHIMI, A.; EDIL, T.; BENSON, C. Plastic deformation of recycled base materials. *Proceedings of GeoFlorida*, 2010. Advances in analysis, modeling and design.

LEKARP, F. *Resilient and Permanent Deformation Behavior of Unbound Aggregates under Repeated Loading*. Tese (Doutorado) — KTH Royal Institute of Technology, Stockholm, Sweden, 1999.

LEKARP, F.; DAWSON, A. Modelling permanent deformation behavior of unbound granular materials. *Construction and Building Materials*, v. 12, n. 1, p. 9–18, 1998.

LEKARP, F.; ISACSSON, U.; DAWSON, A. State of the art. ii: Permanent strain response of unbound aggregates. *Journal of Transportation Engineering ASCE*, v. 126, n. 1, p. 76–83, 2000.

LENTZ, R. W.; BALADI, G. Y. Constitutive equations for permanent strain of sand subjected to cyclic loading. *Transportation Research Record*, p. 50–54, 1981.

LIMA, C. D. A. *Estudo da Deformação Permanente de Duas Britas Graduadas para Uso em Camadas de Pavimentos.* Tese (Dissertação de Mestrado) — Programa de Engenharia Civil da COPPE/UFRJ, Rio de Janeiro, RJ., 2016.

LIMA, C. D. A. de. *Avaliação da Deformação Permanente de Materiais de Pavimen- tação a Partir de Ensaios Triaxiais de Cargas Repetidas*. Tese (Tese de Doutorado) — UFRJ/COPPE, Rio de Janeiro, 2020.

MAHER, M.; GUCUNSKI, N.; PAPP, W. J. Recycled asphalt pavement as a base and sub-base material. *ASTM Spec. Technol. Publ.*, v. 1275, p. 42–53, 1997.

MAJIDZADEH, K.; BURANROM, C.; KARAKOMZIA, M. Applications of fracture mechanics for improved design of bituminous concrete. *Dept. of Transportation*, p. 76–91, 1976.

MALYSZ, R. *Um Método Mecanítico-Empírico para a Previsão da Deformação Perma- nente em Solos Tropicais Constituintes de Pavimentos.* Tese (Dissertação de Mestrado) — Universidade Federal do Rio Grande do Sul, UFRGS, Porto Alegre, RS, 2004.

MALYSZ, R. *Desenvolvimento de um equipamento triaxial de grande porte para avaliação de agregados utilizados como camada de pavimentos.* Tese (Tese de Doutorado) — Universidade Federal do Rio Grande do Sul, UFRGS, Porto Alegre, RS, 2009.

MCGARRAH, E. J. *Evaluation of current practices of reclaimed asphalt pavement/virgin aggregate as base course material,*. Dissertação (Mestrado) — Research paper (Master of Science Civil En- gineering)-University of Washington, Seattle, 2007.

MEDINA, J. *Mecânica dos Pavimentos*. first. [S.l.]: Editora UFRJ, 1997.

MEDINA, J.; MOTTA, L. M. G. Design of asphalt pavements using lateritic soils in brazil. *Solos e Rochas*, 1988.

MEDINA, J.; MOTTA, L. M. G. *Mecânica dos Pavimentos.* third. [S.l.]: Editora Interciên- cias, 2015.

MOHAMMAD, L. N.; HERATH, A.; RASOULIAN, M.; ZHANG, Z. Laboratory evaluation of untreated and treated pavement base materials: Repeated load permanent deformation test. *Transportation Research Record: Journal of the Transportation Research Board*, p. 78–88, 2006.

MONISMITH, C. L.; OGAWA, N.; FREEME, C. R. Permanent deformation characteristics of subgrade soils due to repeated loading. *54º Annual Meeting of TRB.*, 1975.

MOTTA, L. M. G. *Métodos de Dimensionamento de Pavimentos Flexíveis, Critério de Confiabilidade e Ensaios de Cargas Repetidas.* Tese (Tese de Doutorado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro, RJ., 1991.

MOTTA, L. M. G.; MEDINA, J. Investigação e desenvolvimento em mecânica dos pavi- mentos na coppe – brasil. *Revista Engenharia Civil. Universidade do Minho - UM*, n. 26, 2006.

NCHRP 1-37 A. *Guide for mechanistic-empirical design of new and rehabilitated pavement structure. Draft Final Report No.* Washington, DC;, 2004.

NORBAK, C. *Caracterização do módulo de resiliência e da deformação permanente de três solos e misturas solos-brita.* Tese (Dissertação de Mestrado) — Programa de Engenharia Civil da COPPE/UFRJ, Rio de Janeiro, RJ., 2018.

NZ TRANPORT AGENCY. *SPECIFICATION FOR REPEATED LOAD TRIAXIAL (RLT) TESTING FOR PAVEMENT MATERIALS.NZTA T15: 2014.* [S.l.], 2006.

ODERMATT, N. *Permanent Deformation in Fine-Grained Subgrade Materials – Triaxial and Accelerated Pavement Tests.* Tese (Doutorado) — Division of Highway Engineering. Royal Institute of Technology., Suécia., 2000.

OSTEN, F. B. V. D. *Avaliação de Quatro Solos Tropicais para Emprego em Sublastro da Estrada de Ferro Carajás.* Tese (Dissertação de Mestrado) — Instituto Militar de Engenharia., Rio de Janeiro,, 2012.

PAUTE, J. L.; HORNYCH, P.; BERNABEN, J. P. Repeated load triaxial testing of granular materials in the french network of laboratories des ponts et chaussées. *In Flexible Pavements, ed. A. G*, p. 53–64, 1996.

PIRES, G. M. *Estudo da estabilização granulométrica e química de material fresado com adição de cimento portland e cinza de casca de arroz para aplicação em camadas de pavimentos*. Dissertação (Dissertação (Mestrado em Engenharia Civil)) — Universidade Federal de Santa Maria, 2014.

PREUSSLER, E. S. *Ensaios Triaxiais Dinâmicos de um Solo Arenoso.* Dissertação (Mes- trado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro, RJ., 1978.

PREUSSLER, E. S. *Estudo da Deformação Resiliente de Pavimentos Flexíveis e Aplicação ao Projeto de Camadas de Reforço*. Dissertação (Doutorado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro, RJ., 1983.

RESOLUçãO N°14. *DNIT Resolução Nº 14.*

RIBEIRO, M. M. P. *Contribuição ao estudo da deformação permanente dos solos de subleito.* Dissertação (Mestrado) — Escola de Engenharia de São Carlos da Universidade de São Paulo, 2013.

ROBERTS, F. L.; KANDHAL, P. S.; BROWN, E. R.; LEE, D. Y.; KENNEDY, T. W. Hot mix asphalt materials, mixture design, and construction,. *National Asphalt Paving Association Education Foundation, Lanham, MD.*, 1996.

ROZA, A. E. D.; LIMA, C. D. A.; MOTTA, L. M. G. Avaliação da correlação entre o módulo de resiliência e a classificação mct de solos finos argilosos. *nais do XXXII Congresso de Pesquisa e Ensino em Transportes, ANPET*, 2018.

SANTOS, M. S. *Desenvolvimento de Modelos de Previsão de Desempenho a Partir da Implantação de Trechos Monitorados na Região de Santa Maria.* Dissertação (Mestrado) — Universidade Federal de Santa Maria., 2015.

SILVA, B. A. *Análise Mecânica de um Pavimento Rodoviário Submetido* à *Oscilação do Lençol Freático Simulada em Modelo Físico de Verdadeira Grandeza.* Tese (Tese de Doutorado) — Programa de Engenharia Civil da COPPE/UFRJ., Rio de Janeiro,, 2009.

SOLEIMANBEIGI, A.; EDIL, T. Thermal conditioning to improve geotechnical proper- ties of recycled asphalt pavements,. *Geotechnical Testing Journal,*, v. 38, n. 1-12, 2015. Doi:10.1520/GTJ20140149.

SOLEIMANBEIGI, A.; EDIL, T.; BENSON, C. Engineering properties of recycled materi- als for use as embankment fil. In: *Geo-Congress 2014 Technical Papers: GeoCharacterization and Modeling for Sustainability, M. AbuFarsakh and L. R. Hoyos, Eds., ASCE, Reston, VA*. [S.l.: s.n.], 2014. p. 3645–3657.

SOLEIMANBEIGI, A.; EDIL, T.; BENSON, C. Effect of temperature on geotechnical properties of recycled asphalt shingle mixtures. *J. Geotech. Geoenviron. Eng*, v. 141, n. 2, 2015.

SOLIMAN, H.; SHALABY, A. Permanent deformation behavior of unbound granular base materials with varying moisture and fines content. *Transportation Geotechnics*, v. 37, n. 4, p. 1–12, jun 2015.

SONG, Y.; OOI, P. Resilient modulus characteristics of varying percent of reclaimed asphalt pavement. In: *In Proceedings of the GeoShanghai International Conference,*. Shanghai, China: [s.n.], 2010. p. 43–50.

TSENG, K. H.; LYTTON, R. L. Prediction of permanent deformation in flexible pavement materials. in: Implication of aggregates in the design, construction and performance of flexible pavements. *ASTM STP 1016*, p. 154–172, 1989.

ULLAH, S.; TANYU, B. Methodology to develop design guidelines to construct unbound base course withreclaimed asphalt pavement (rap). *Construction and Building Materials*, v. 223, p. 463–476, 2019. Https://doi.org/10.1016/j.conbuildmat.2019.06.196.

ULLAH, S.; TANYU, B.; HOPPE, E. Optimizing the gradation of fine processed reclaimed asphalt pavement and aggregate blends for unbound base courses. *Trans. Res. Rec*, n. 2672, p. 57–66, 2018.

UZAN, J. Characterization of granular material. *Transportations Research Record,*, n. 1022, p. 52–59, 1981.

VIYANANT, C.; RATHJE, E.; RAUCH, F. Creep of compacted recycled asphalt pavement. *Can. Geotecnologia. J.*, v. 44, n. 6, 2007.

WERKMEISTER, S.; DAWSION, A.; WELLER, F. Permanent deformation behaviour of granular materials and the shakedown concept. *Transportations Research Record*, n. 1757, p. 75–81, 2001.

WERKMEISTER, S.; RALF, N.; DAWSON, A. R. Deformation behavior of granular materials under repeated dynamic load. *Environmental Geomechanics*, 2002.

WERKMEISTER S.AND DAWSON, A. R.; WELLNER, F. Pavement design for unbound granular materials. *Journal of Transportation Engineering*, 2004.

WIRTGEN GROUP. *Reciclagem a frio: Tecnologia de reciclagem a frio Wirtgen*. Windha- gen, Alemanha, 2012.

ZAGO, J. P. *Avaliação de Quatro Solos Tropicais para Sublastro da Estrada de Ferro Carajás.* Tese (Dissertação de Mestrado) — Universidade Federal de Santa Maria, Santa Maria, RS, 2016.