Four Decades of the Circular Test Track at the Institute of Engineering UNAM Contributing to Pavement Research in Mexico

Noé Hernández, Alexandra Ossa and Francisco A. Rangel

Abstract The circular test track at the Institute of Engineering UNAM was built four decades ago, between 1970 and 1971. Since its construction, this device has been very valuable for the development, research, and validation of flexible pavement design in Mexico. To date, 40 studies have been conducted on the circular track. It is common for each experiment to build three different sections of pavement to maximize the number of variables to be analyzed. With the information obtained from the experimental sections under service, data on the behavior of sections in different locations throughout Mexico, and experimental results from the circular track, a method for the structural design of flexible pavements was developed. This research program was carried out by the Institute of Engineering, UNAM. The latest version of the pavement design method was published in 2014, called the Structural Design of Flexible Pavements (DISPAV-5 3.0), and is currently the most used method in Mexico for the design of such structures. This resource has a mechanistic-empirical background and includes models to predict asphalt fatigue and permanent deformation damage. However, the models are over 15 years old and are unable to incorporate current characteristics of materials and traffic conditions. This paper describes the role and significance of the circular test track in the development of flexible pavement design in Mexico, the characteristics of the variables that influence pavement behavior and future directions proposed to develop a method of pavement design that considers current needs.

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1 Introduction

In 1961, the Ministry of Public Works (now the Secretariat of Communications and Transport, SCT) launched a research program in low traffic volume roads through the Engineering Institute of the Autonomous University of Mexico (UNAM) to address the pavement problems of the time due to the importance of annual investments made for preservation and the increasing trend of such investments. These low traffic volume roads constituted the majority of the national road network at that time. According to Corro (1970), the proposed research guidelines were:

- identify the most important variables that affect the behavior of flexible pavements for low traffic volume roads,
- establish criteria to judge the pavement behavior and set levels of acceptance and service periods,
- conduct experimental research to define test methods that have good correlation with the behavior of the materials used in pavements, and
- review road tests carried out in other countries to determine particular techniques that are applicable to Mexico.

The main objective of the program was to develop a design method for low traffic volume roads, more precisely considering the particular conditions of the country, such as materials and construction processes, traffic characteristics, and climatic conditions. The research included the study of three specially constructed test roads, analysis of the performance of typical road networks, and full-scale tests under repeated loads in a laboratory, which was constructed as a part of the research.

One of the main achievements of the research was the development of a structural design method for flexible pavements (currently called DISPAV-5). This method was originally published in 1974 and has been updated several times to reflect changes experienced by the roads throughout the years. The final update consisted of the migration of the original code to a JAVA environment to run the program independently of the operating system, creating DISPAV-5 version 3.0.

DISPAV-5 is the method most widely used for the design of new construction and the rehabilitation of existing pavements. However, its models used to predict damage are more than 15 years old and are unable to estimate the performance of pavements using current designs with a good level of accuracy. The original performance models were developed with different traffic conditions and materials than Mexican roads currently have. To show these changes, the main variables that influence the performance of pavements (traffic, environment, materials and prediction models) are described. Finally, future directions in which to drive the research efforts in the Engineering Institute are mentioned.

2 Circular Test Track of the Engineering Institute, UNAM

The planning, design and construction of a laboratory with full-scale facilities for testing roads and airfield structures were fundamentals aspects of the research program that the Engineering Institute was commissioned to undertake. The main facilities are a circular test track and two test pits for repeated loading studies. According to the guidelines of the research program, the circular test track had two main purposes (Corro et al. 1972):

- controlling the parameters evaluated in the experiment, using a set number of load repetitions with a known magnitude, and changing some characteristics of the pavement sections constructed in the circular test track to obtain statistically significant conclusions; and
- solving specific problems, such as evaluating specified parameters in standards to assess their suitability and analyzing new materials.

The facility was designed to test full-scale pavements placed over various types of subgrades and embankments up to failure, and the facility has been in operation since February 1971. To avoid uncontrolled effects due to environmental conditions, the test track is within a laboratory that is 17.5 m wide, 34.40 m long and 6.50 m high. The majority of tests were performed during the day within an eight-hour period to decrease temperature gradients; the temperature inside the laboratory varies from 18 to 24 °C. The following section describes the main features of the circular test track.

2.1 Test Pit of Circular Test Track

The pavement test sections are constructed in a concrete tank that confines the bottom and sides of the sections. To control the humidity in the unbound layers and the drainage conditions, a very rigid concrete pit was built that is sufficiently wide to construct a road lane and the side slope of an embankment.

According to Corro et al. (1972), to define the geometry of the pit, technical and economic aspects were considered. Too large of dimensions would increase the cost of constructing the sections to be tested; in addition, aspects that would influence on the test section performance such as the construction process and the boundary conditions were also considered. Through the analysis of the pressure distribution using the Boussinesq theory, the researchers concluded that the influence of boundary conditions on the outer wall and the floor of the test pit were negligible (Corro et al. 1972).

The pit has a 14 m outside diameter, and the central ring has a 3.20 m outside diameter. The walls and floor slab are 0.5 m thick. The depth of the gap between the two rings is 1.50 m and is the area where the experimental sections are

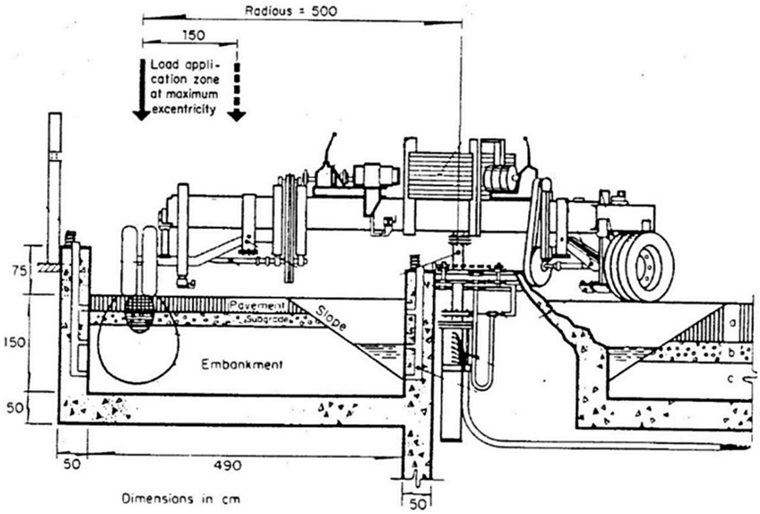

Fig. 1 Cross section of the circular test track

constructed (Fig. 1). The central ring is 4.0 m deep and contains a tunnel that is 1.5 m wide and 2.0 m high for access to the control area. The pit is used to confine the experimental sections, accommodate instrumentation devices, place anchors to build load frames, saturate the material to the water table depth, and support the eccentricity mechanism, which allows planetary motion of the loading frame.

2.2 *Load Frame*

For the load frame design (Corro et al. 1972) the following characteristics were considered: continuous operate, loads applied within a certain range of the surface of the pavement sections, independent suspension of the different sets of wheels, and planetary motion to reproduce the load distribution histogram in the pavement cross section.

The result of the points described above was a rotating device with three metal arms with dual wheels on the ends used to apply loads; the load level can be adjusted between 80 and 100 kN per set of dual wheels. The radius between the wheel center and the center of rotation is 5.0 m (Fig. 1). The arms are spaced at 120° apart. A plate system regulates the ballast loads. Using an eccentric device, the rotation axis of the loading frame describes a planetary motion to simulate the histogram of load applications on a road, covering an adjustable strip of pavement from 0 to 1.50 m. The device has a ball joint and bearing, which allows rocking the frame without vertical reactions in the axis of rotation. The velocity can be varied between 4 and 40 km/h by three 30 kW variable velocity AC motors with 40 HP coupled to five-speed gearboxes. Each 62 revolutions of the frame generate a full cycle of wheel movement on the complete pavement surface.

The instrumentation of the study sections initially consisted of electrical strain gauges, linear variable differential transformers (LVDT), pressure cells and other transducers to determine the dynamic deflections, pressure, water content, and temperature.

3 Pavement Research by the Engineering Institute

In 1961, the Ministry of Public Works (now the Secretariat of Communications and Transport, SCT) launched a research program for low traffic volume roads through the Engineering Institute of the Autonomous University of Mexico (UNAM). Its main objective was to develop best practices for the design, construction and maintenance of roads with low traffic volumes in Mexico considering the characteristics of materials, traffic, weather, regional conditions, conservation practices, specifications, construction procedures, safety factors and investment programs. Since the inception of the research program, the Institute of Engineering has developed various projects related to the study of pavements in Mexico.

The research was based on three complementary areas: performance assessment of three test roads located in two different regions; studies on the behavior of several test sections on the national road network; and full-scale laboratory tests using the circular test track (Corro and Prado 1974). The main results of this research program are mentioned.

3.1 Research on the Behavior of the Test Roads

To meet this objective, a limited number of experimental sections were designed and built in 1964, located on roads that were under construction, taking advantage of the construction equipment available. Three experimental sections located in two climatic zones were defined. Road test A was located in a climate transition zone between tropical and subtropical, and the traffic circulating on this road was low. Sections B and C were built on the same road separated only by a transition section. The objective was to compare the behavior of the same pavement structure for two sections on embankments with different characteristics (exceeding the specification parameters for road C and below these parameters for road B). The traffic was medium volume, and the climate zone was the cold steppes. The details for the sections are given elsewhere (Corro and Prado 1974; Corro 1978, 1982).

The three test roads were divided into 80 sections, each 30 m long. These sections were designed factorially to distinguish the main variables that influence performance. The specifications and procedures of the time were used, and rigorous control was maintained to guarantee the uniformity of the characteristics for the materials used in the pavement and earthworks.

The main objective of this study was to establish typical tendencies in the behavior of the pavements tested under critical conditions of differing maintenance (Corro and Prado 1974). A sealing coat was applied to roads B and C in 1967, and no other maintenance work was undertaken until 1978. Test road A received a sealing coat in 1972 due to routine maintenance in that zone, without any sign of distress in the test section. In 1978, section B reached failure conditions, after 14 years of actual service and a cumulative number of standard axles close to one million; the average terminal serviceability was 2.5. Test section C, along the same road, had an average terminal serviceability of 2.8 for the same traffic and years of service.

The differences between the performance of test section B, with earthworks below specification, and test section C, with high quality earthworks, was not significant because the geotechnical, climatic and traffic conditions were the same; furthermore, the materials of the surface dressing, road base and sub-base courses were the same quality. Consequently, the long-term analysis of pavements with the same design but constructed upon radically different earthworks was possible. Destructive testing of sections B and C was performed in 1978. Test section A continued as part of the study; after 18 years of service, it had a serviceability level of 2.8 and less accumulated traffic. Test sections B and C were reconstructed in 1979 to study typical maintenance practices for low traffic volume roads and to analyze the performance of two types of road mixes for overlays.

It was considered that the experimental sections were representative of a high percentage of roads in Mexico, in terms of materials, specifications, construction procedures, design, weather and traffic. The measurements obtained on the experimental stages showed a linear relationship between the damage accumulated and the logarithm of the number of load applications. In addition, the results were significant and constituted an adequate estimation of the behavior of pavements in road tests within a period equivalent to the life of the project, as long as they were properly preserved.

Based on the behavior of the experimental sections, it was concluded that the charts for pavement design used at that time were not adequate because for low traffic volume roads, pavements were over-designed and for high traffic volume roads, pavements were under-designed. Among the recommendations from the research program, the most important are the following: use unified test procedures for characterizing materials and zoning the different climatic zones of the country; adopt the concept of equivalent traffic; and adopt the new chart developed for thicknesses design, which was developed based on the behavior observed in the road test.

3.2 Assessment of the Highway Network Performance

Planning to define this stage began in 1965 with the aim of analyzing the trends of the general behavior of the roads in Mexico and defining the most significant variables for the experiment. The main variables were climate, subgrade quality, bearing capacity of the structure, traffic volume and years of service.

Climate was included at three levels, following the Köppen-Geiger classification system: A, tropical; B, steppe and C, sub-tropical. All the other variables were considered at two levels: high and low. The factorial combination of the variables suggested an experiment with 96 test sections (Corro and Prado 1974). All the sections were 500 m long and one lane wide and were located in typical roads.

From 1972 to 1979, a program to systematically evaluate the 96 sections was carried out. The evaluation surveys were performed once or twice a year to detect seasonal changes. To avoid problems related to traffic operation and taking into account budget limitations, in most cases, the studies were limited to non-destructive testing of the road sections. The main problems found in these surveys were lack of reliable construction and maintenance records for the specific lengths of road within the experimental sections. Additionally, the wide scatter of collection data made it necessary to perform a large number of tests along each section.

The typical data obtained in each experimental section were serviceability ratings, May's roughness charts, photographs of the road and details of the type of prevailing distress, 80 kN Benkelman beam and Dynaflect deflection basins, and rut-depth measurements.

The information collected in this phase qualitatively verified the trends observed in the test sections and the circular track. Among the experimental data of greatest interest were the dynamic measurements of the resistance of the bearing capacity of the road, where it was noted that seasonal variations in maximum deflections registered with a Dynaflect device had little importance. Because it does not show the shape of the basin of deflections, no significant correlation was found between the maximum elastic deformations in the pavement surface and the resistance of the bearing capacity of the pavement.

3.3 Tests Carried Out in the Circular Test Track

Tests performed on the circular track of the Engineering Institute have been fundamental in the research, development and validation of different phases of the pavement design methods used in Mexico since it began operation in 1971. There have been 40 tests conducted on this device; to maximize the number of variables analyzed, each ring has three sections for different pavements that are 9 m long with 1.5 m long transitions, as measured along the axis of wheel movement; therefore, approximately 120 pavement structures have been tested to date.

All of the tests have used simple dual axis wheels with 100 kN of weight, 540 kPa of inflation pressure in the tires, and a velocity of 10 km/h. Through experimentation, the damage factors were obtained for converting the load applications of the circular track into equivalent single-axle loads of 80 kN: the number of applications on the track are divided by 2.3 to obtain the number of equivalent single-axle loads. Next, the most significant trials conducted in the circular test track over four decades of research are described.

The first experimental stage of the circular track was from 1971 to 1973 and tested 6 rings to structural failure, representing 18 different pavement structures. One of the objectives of this first stage was to verify the operation of the test track and determine the times required for the construction of each ring, load application, data acquisition and construction of a new ring in the test track. According to the results obtained in this first stage, a full study of a ring, to the failure of the section or by the application of one million equivalent single axle loads (ESALs) of 80 kN, was conducted in three months, including the construction of a new ring.

The main purpose of this stage was to evaluate the influence of the thickness and quality of the subgrade layer on the pavement behavior with a surface treatment. In this stage, 18 structural sections were tested (six test rings) with pavements comprising a base layer with a surface treatment on subgrades and earthwork of the same clayey-loam material. However, the sections had different strength characteristics, obtained by varying the compaction degree and test conditions, such as the construction procedures: sections were made impermeable or saturated, flooding the slope zone to establish the water table at a depth of 0.6 m beneath the ring surface.

Another important stage of experimentation that was carried out in the circular track was assessing the behavior of thin, cold in-place asphalt mixes. To evaluate their performance, tests were performed on rings 21 through 23 between the years of 1980 and 1982. The variables analyzed in the asphalt mixes were type of aggregate (crushed basalt and river aggregate) and grading of the asphalt mix (coarse, dense and fine). Based on the specifications of the time, the first tests at elevated temperature were performed (45–50 °C) compared with the temperatures commonly performed (18–24 °C). The system used to control the heating of the circular track sections consisted of infrared spotlights, which were lit according to a predetermined cycle to control the temperature within the specified range; this system had a capacity to heat the pavement to 60 °C.

Among the general recommendations of this stage of experimentation, it was proposed to amend the upper limit of the grading zone because the asphalt mixes with fine graduation had better performance in the test sections. Another recommendation was to review the design criteria of asphalt mixtures with the aim to perform tests that represent the mechanical behavior of asphalt mixtures.

The study of fatigue cracking in flexible pavements began in 1984, with testing of ring 24. In this experiment, a hot-mix asphalt (HMA) produced by a plant near the Engineering Institute was used. The main variable to evaluate was the thickness of the HMA layer in pavement structures with similar maximum deflections to maintain the tensile strain at the bottom of the HMA layer at similar levels. Because strain gauges were not used in pavements sections, the tensile strain at the bottom of

Fig. 2 Pavement section after the test at the circular track

the HMA layer was estimated indirectly through surface deflections by layer elastic analysis.

The sections of ring 24 were composed of three layers (HMA, granular base and embankment of clayey-loam material); the HMA thicknesses were 30, 60 and 90 mm. The sections were designed for the pavement to fail within a short period of load applications and with a predominant damage of fatigue cracking.

The test of the sections was performed at an average laboratory temperature of 21 °C (with ranges of ±3 °C). The initial cracking was observed simultaneously in the three sections for a transit of 10,000 ESALs of 80 kN, showing a scattered fine crack pattern. The test continued until 100,000 ESALs were applied, when the cracking pattern was dense and dominated by fine and intermediate cracks. The section that experienced more damage was the HMA layer 60 mm thick, and the section with 90 mm thick HMA was the best performing. Figure 2a shows fatigue cracking after the test, and Fig. 2b shows a cut of the section.

Extensive research was conducted continuously in the laboratory to characterize the fatigue behavior of HMA used in the study, and diametral compression tests were performed with cyclic loading on laboratory-compacted samples and cores extracted from the layer placed on the circular track. At the time of the study, there was no fatigue failure criterion for flexible pavements in Mexico, so the results of the study showed the need to develop more rational criteria for the characterization of materials and models to estimate fatigue damage in asphalt pavements.

The study of fatigue cracking continued until 1994, when ring 32 was tested. The main objective was to verify the design method for asphalt pavements. These three sections were designed for one million ESALs of 80 kN. A confidence level was not applied to obtain structural failure at the end of the application of loads; therefore, the confidence level was 0.5. According to the design, it was expected for the sections to present fatigue failure at the finished load application. The pavement structures were composed of HMA, granular base, sub-base and subgrade; the materials of each of the layers complied with the specifications and standards. The HMA thicknesses were 30, 60 and 90 mm, those of the base were 200 and 150 m, and those of the subbase were 390, 380 and 320 mm.

During the time of the study, different tests were performed to evaluate performance under loads, including measuring the rut depth, measuring the deflections with a Benkelman beam and Dynaflect device, and measuring the tensile strains in the HMA using strain gauges.

Parallel testing was conducted of the dynamic modulus (ASTM D3497), the unconfined compression under sinusoidal cyclic loading to evaluate the permanent deformation, and indirect tensile stress under sinusoidal cyclic loading to assess fatigue. At the end of the test, cores were extracted in sections to assess the actual thickness and mechanical properties of the materials.

The three sections behaved in accordance with the estimates from the developed design method. At the end of the test, it was observed that the depth of the rut was equal or inferior to the permissible depth (12 mm, in 20 % of the section). During the study, there was no fatigue cracking, although the tensile strain exceeded the tensile strain estimated in design. During the study, no other structural defects were observed. These results confirmed the suitability of the developed design method, which had a theoretical and experimental basis.

The latest study on the circular track was in the year 2007, related to the use of special concrete that included fragments of shredded tire rubber. The aim of the study was to evaluate the behavior of this type of concrete for residential areas, lowering the cost of concrete and solving ecological problems by using shredded old tires (Corro and Rangel 2008). Nine sections were built in the circular track and subjected to one million ESALs of 80 kN. The main variable analyzed was the type of concrete used in the slabs: three sections of normal concrete, three sections with small pieces of crushed rubber and three sections with medium fragments of crushed rubber were used. All of the sections had a slab 150 mm thick. At the end of the scheduled number of load repetitions, good behavior was observed in all of the sections evaluated, without providing evidence of any damage in the slab sections. Figure 3 shows the sections of concrete in the circular test track.

Fig. 3 Image of the slabs with crushed tire rubber in the circular track

3.4 Asphalt Pavement Design Method

The first pavement design guide (currently DISPAV-5) was presented in 1974 by the Institute of Engineering, which was based on an experimental-theoretical criterion for the design of flexible pavements. The experimentation carried out in road tests, the evaluation of existing highways and testing in the circular test track during 1965–1973 were the foundation for this first design guide.

The proposed design method consisted of a series of design charts that considered variables, such as the damage coefficients for the axis type or type of vehicle, equivalent cumulative traffic, and structural design of flexible pavements for different types of roads (primary and secondary). It was recommended that these variables were evaluated within a general framework to reach economic solutions. In addition, the method proposed the standardization of procedures for laboratory tests for characterizing materials.

The method employs the concept of bearing capacity in cohesive soil and Boussinesq's theory of the distribution of vertical stress (σ_z) (deduced for a circular, static flexible plate uniformly supported at the surface of an elastic, homogeneous, isotropic medium) in the particular case of a multilayered structure of uniform relative strength, subjected to repeated loads of an equivalent single axle with a defined static weight of 80 kN and with a constant impact coefficient (I). It is further assumed that the California bearing ratio at the site (CBR_z) is a good indicator of the bearing capacity of the different layers (Corro 1978).

Failure in a layer at the surface of the highway is analyzed in light of the hypothesis that there is a linear relation between the logarithm of resistance (log CBR_z) and the logarithm of the cumulative number of equivalent 80 kN single axle loads (log ΣL). For any layer of depth z, the concept is generalized, multiplying the resistance at the surface (log $CBR_{z=0}$) by Boussinesq's coefficient of influence (F_z), assuming by definition a structure of constant relative strength.

Analyzing the data referencing this hypotheses, based on experimental evidence, made it possible to establish the equations of the design charts for different degrees of reliability for the minimum strength required in any layer so that the structure might support a determined number of equivalent applications (ΣL) before surface deterioration reached the level defined as functional failure of the highway.

The design charts presented are limited to the typical case of the structures employed in Mexico, where the thickness of the asphaltic concrete surface rarely exceeds 75 mm and where the others layers of the structure consist of granular materials or fine soils mechanically stabilized by compaction. In the case of thick asphalt pavements, the design hypothesis would vary, and it would be necessary to take into account the radial stress that can cause failures due to fatigue in the HMA.

From 1994 to 1999, the DISPAV-5 design method underwent major upgrades that established the current design method. In 1994, it was expanded to consider fatigue cracking in the asphalt layers and thus consider the damage that appeared on the roads of Mexico. In 1996, it developed an interactive tool programmed in an MS-DOS operating system, which incorporated all the information on pavement design developed so far. In 1997, the method was updated to consider the maximum legal loads for trucks transport in Mexico.

Among the improvements made with respect to the original method, published in 1974, was incorporating a mechanistic model to determine the tensile horizontal strain that generates fatigue damage in asphalt mixtures based on experimental studies on asphalt mixtures from 1985 to 1999. A new model was developed to design structures of high-standard expressways (high traffic), considering a mechanistic-empirical approach for the two main modes of pavement failures, which include permanent deformation of the unbound pavement layers and fatigue cracking of the asphalt-bound layers (DISPAV-5 version 2.0). Additional information about this update can be found elsewhere (Corro and Prado 1997).

The last update was in 2012; the scope was defined in the source code migration to a JAVA environment to run the program independently of the operating system. The model created in the DISPAV-5 version 2.0 was maintained, but the interface and presentation of the results were modernized. One of the improvements in the new version (DISPAV-5 version 3.0) was updating the weights and dimensions of heavy trucks (Corro et al. 2014).

4 Main Factors Affecting the Performance of Pavements in Mexico

The DISPAV-5 pavement design method is the most commonly used design tool in Mexico. Currently, a large number of newly built pavements and most road reconstructions are designed using this method. However, according to the brief description of the method presented earlier, the models incorporated in DISPAV-5, have a number of limitations in representing the current condition of the pavements. Therefore, this chapter describes the main factors influencing the performance of flexible pavements, and the prevailing conditions in Mexico are particularly described.

4.1 Traffic

One of the most significant improvements offered in the M-E Design Guide is the methodology to account for highway traffic volumes and loads. This enhancement proposes replacing the number of equivalent single axle loads (ESALs) by actual axle load distributions per axle type per vehicle class. These distributions are often referred to as axle load spectra. Traffic is indeed one of the most critical pavement design inputs, determining how a pavement will perform and how long it will last. Traditionally, traffic data are associated with a high level of uncertainty (Prozzi et al. 2008).

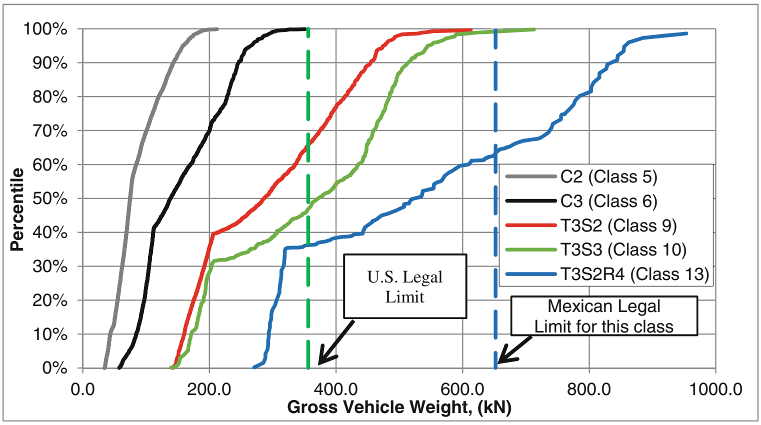

Fig. 4 Gross vehicle weight from Las Rajas, México State (Central Zone)

In Mexico, the uncertainty is even greater because there is a high percentage of truck vehicles with overload. The percentage of overload that exists on the roads of Mexico can be observed in a study published by the Mexican Institute of Transport (Mayoral et al. 2014). The study focuses on four main roads to Mexico City, and the report shows the percentage by vehicle type and the percentage of overload for each type of vehicle. The vehicles with the highest percentage of overload on the maximum weight allowed were trucks such as T3S3 (six axis) and T3S2R4 (nine axes); the percentage of overload for the second vehicle was between 27.6 and 50.7 %.

Figure 4 shows the gross vehicle weight obtained from “Las Rajas” weigh-in-motion (WIN) station located in Mexico State. The articulated vehicle average weight (more than five axles) exceeds 300 kN. An interesting case is the T3S2R4 truck, which is similar to the USA class 13. This Mexican truck has an average weight of 540 kN, which is more than 40 % over the Mexican legal load limit. To show the percentage overload, the dotted green line shows the legal load limit in the USA (363 kN) for all freight vehicles.

Garnica and Hernández (2013) recently published representative axle load spectra from the Mexican Federal road network. All of these data were obtained from different WIM stations from different regions in Mexico. They defined four types of axle load spectra based on the observed overload level. However, it is necessary to extend this study to define load spectra based on other factors and not just based on the percentage of overload observed. One example is the methodology defined by Lu and Harvey (2009), evaluating road characteristics (number of lanes, functional classification, etc.) and socioeconomic factors (population density, land use, etc.).

4.2 Climate

Environmental conditions have significant impact on pavement design and performance. These conditions are represented as the effects of weather and climate on the strength, durability and load bearing capacity of the pavement. In flexible pavement, the surface layer is usually made of hot-mix asphalt (HMA), which is a viscoelastic material, and its behavior is highly related to its temperature, i.e., HMA responds similar to an elastic solid under low temperature and strain conditions; conversely, it also acts as a viscous material at high temperature in the sense that the deformation due to traffic loading cannot be fully recovered within a finite time period under the unloading condition. Thus, an accurate prediction of the temperature profile in the HMA layer is desired when selecting the asphalt binder and predicting asphalt pavement responses under traffic and environmental loadings (Wang 2010).

According to the National Institute of History and Geography (INEGI), Mexico has a variety of climates: arid territory in the north, warm and sub-humid in the south and southeast, and cold or temperate climates in the mountain geographic regions. Because of this large variety of climates, it is important to consider the influence of climate on the behavior of materials both for their selection (in the case of asphalt grade PG) and pavement design as well as considering their variation during different seasons in the structural design of the pavement.

In Mexico, there is little or no research on this subject; one of the main constraints is the lack of climate information to develop models to estimate the variation of the temperature or humidity in the layers of the pavement structure. However, a recent study by Schwartz et al. (2015) presented new sources of climate data henceforth unknown to pavement engineers. This data source, the Modern-Era Retrospective Analysis for Research and Applications (MERRA), developed by the National Aeronautics and Space Administration (NASA) for its own in-house modeling needs, provides continuous hourly weather data starting in 1979 on a relatively fine-grained uniform grid. MERRA is based on a reanalysis model that combines computed model fields (e.g., atmospheric temperatures) with ground-, ocean-, atmospheric-, and satellite-based observations that are distributed irregularly in space and time. The result is a uniformly gridded dataset of meteorological data derived from a consistent modeling and analysis system over the entire data history. MERRA data are provided at an hourly temporal resolution and at 0.5 degrees latitude by 0.67 degrees longitude (approximately 55 km by 73 km at mid-latitudes) spatial resolution over the entire globe (Schwartz et al. 2015).

With this database and the information generated by the National Water Commission (CONAGUA), the models developed in other countries such as the Enhanced Integrated Climate Model (EICM) can be calibrated and models for Mexico can be developed to estimate the variation of climatic conditions in pavement materials.

4.3 Pavement Materials

The characteristics of the materials is one of the most important input parameters during pavement design. Within the extensive research conducted at the Institute of Engineering, great efforts have been made to incorporate the mechanical properties of the materials forming the flexible pavements; however, these practices were never adopted as common practice during the design process. In particular, the evaluation of the mechanical properties for the design of asphalt mixtures is a procedure that has become widespread since 2008, due to implementing the design methodology of high performance asphalt mixtures called "AMAAC protocol," based on the superior performing asphalt pavements (Superpave) system developed by the Strategic Highway Research Program (SHRP).

Four levels are defined in this protocol, according to the traffic level. The first level has the same Superpave requirements; in the next levels, performance tests are specified: Hamburg Wheel Tracking is specified for the second level, stiffness tests (Dynamic modulus, |E*|) are specified for the third level, and fatigue tests (four-point bending beam) are specified for the fourth level.

Although there is some experience in this type of testing, so far, this procedure is limited to the design of the asphalt mix, i.e., to determine the proportions of its components without using the mechanical properties evaluated in the design of pavements. This limitation is mainly due to the lack of a method in which to incorporate these features. It is also important to calibrate or develop predictive models of the mechanical properties of the materials to be used in projects that are not feasible for laboratory tests.

4.4 Performance Prediction Models

Performance prediction models developed in the research conducted by the Institute of Engineering were successful in their time and were the basis of the DISPAV-5 design method. The level of service demanded by users currently requires large investments to maintain the road network under suitable conditions, so performance models that adequately simulate real pavement performance are indispensable. This required level of reliability is not achieved by the models included in the DISPAV-5 because technological development has generated a greater variety of materials (for example, modified asphalts) and construction procedures (for example, mixtures with RAP) with behavior that cannot be estimated from these models. Furthermore, due to the age and lack of durability of roads,, the rehabilitation or reconstruction of pavements in the road network has become increasingly common, a function for which this method was not developed.

With the development and publication of the MEPDG guide, the way pavements are designed is changing and is directed toward the development of mechanistic-empirical pavement design methodologies. To take advantage of research conducted in this area, the proposal is to evaluate emerging performance prediction models in different design methods recently established to determine which is more feasible to be used for the conditions of Mexico considering the influence of the variables mentioned above.

In the second stage, the evaluation of the models considered more convenient should be accompanied by experimentation in the circular test track to verify their applicability to road conditions in Mexico.

5 Future Directions

Currently, the pavements lab at the Engineering Institute is undergoing a transition, as it renews the research staff and garners increasing interest from graduate students to conduct pavement research. Currently, the Institute is defining the future directions to be followed, giving more importance to the current problems in order to generate solutions to these problems. The areas of current research focus are as follows:

- characterization of asphalt used in road construction, including modified and conventional asphalts through rheological properties and parameters representing service behavior to validate the performance-based specifications that are currently in use;
- study of the mechanical properties of asphalt mixtures (dynamic modulus and fatigue) and calibration and development of predictive models of these properties according to the materials used;
- characterization of granular materials and soil to incorporate their properties into design and quality control of these materials in the performance of the pavement;
- evaluation of new technologies such as mixtures with RAP, warm mix, and use of construction residues to verify their feasibility in road construction;
- development of a new pavement design method that considers the current condition of the roads in Mexico; and
- modernization and instrumentation of the circular test track for use in pavement investigation.

Linking projects with highway agencies and the private sector is an important step for carrying out the points above because without their financial support, performing the research is more difficult. Furthermore, these groups can implement the obtained results.

6 Conclusions

For four decades, research by the Institute of Engineering has contributed to the development of pavements in Mexico; this research has generated important products that even now contribute to pavement practices in Mexico. One of the main objectives of the project that began in 1961 was the design and construction of a device that would allow the laboratory testing of full-scale pavement sections. The result was the circular test track, which began operation in 1971 and is currently still in service. In this device, approximately 120 sections of pavement have been tested and approximately 45 million equivalent axes of 80 kN have been applied.

The main outcome of the research was to develop a method of structural design for flexible pavement known as DISPAV-5; this method has been updated at different times to incorporate the road conditions in pavement design throughout these four decades. It is currently the most widely used method of design in Mexico for new pavements and the rehabilitation of existing pavement.

The latest update of the performance models of DISPAV-5 took place more than 15 years ago, decreasing the reliability of the results obtained with this method. Differences in traffic loads and materials currently used increases the uncertainty in the results obtained with DISPAV-5 in the pavements design process, so it is urgent to develop a comprehensive update of this method.

Clearly, this update cannot be conducted in the short term; therefore, the future directions to be followed in the pavement lab must be the foundation for an upgrade or development of a method for more reliable pavement design. A very important aspect of the proposed projects is linking the research with the road agencies and the private sector.

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