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OVERVIEW OF ENVIRONMENTAL CONSIDERATIONS IN AASHTO PAVEMENT DESIGN GUIDES

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ABSTRACT

This paper presents an overview of the effects of environmental factors, namely moisture and temperature, on the material properties of flexible pavement road structure considered in the design guides of the American Association of State Highway and Transportation Officials (AASHTO). It considers the historical development of AASHTO design guides and the new Mechanistic-Empirical Pavement Design Guide (M-EPDG). The study showed the shift in emphasis from total reliance on an empirical method to a combination of mechanistic and empirical methods in the new design guide. Further, moisture and temperature were indirectly considered in the current guide whereas these parameters are accounted for in the new design guide through the resilient modulus and the complex modulus. The sensitivity analyses of environmental consideration using the new design guide software are presented in this paper.

INTRODUCTION

When studying the performance of flexible pavement, it is necessary to understand the effects of temperature and moisture changes over a wide range, on a daily and a seasonal basis. Seasonal changes in moisture content and temperature and freeze-thaw cycles would significantly affect the life and performance of pavements.

In seasonally and perennially frozen areas, in the northern states of the USA and most of the Canada provinces, pavements are affected by frost and their strength and load bearing capacity change with season. Pavements are subjected to ruts (long deep tracks produced by repeated passage of vehicles) and cracking due to thermal stresses and traffic loading. Road construction in cold regions differs from that in warm regions in that, the former is constrained by daylight, weather, short construction season and long distances in remote areas. In general the pavements in frost-affected regions also require more maintenance.

Pavement deterioration in cold region is caused by three factors: thermal contraction and fracture in the bound layer, volume changes caused by frost heave and unbound material strength loss due to thaw during the spring season (Dore, G., 2002).

Road designers expect roads to perform without any major distresses over wide ranges of temperature and moisture content. To improve the performance, the effects of environmental, operating and service conditions as well as traffic loading have to be identified and understood. Currently, pavement analysis, including the new Mechanistic-Empirical Pavement Design Guide (M-EPDG) (NCHRP 2004) model, is based primarily on multilayered linear elastic analysis. Mechanistic characterization techniques of road materials represent one of the major improvements introduced in the new M-EPDG model. Pavement design relies heavily on the temperature, which has been used to specify the performance grades for asphalt binders. Load limits during the spring season and the frost-free base thickness are the most basic pieces of information for modeling pavement performance and design.

Pavements is made of complex structural materials that have different properties. Flexible pavement design procedures were empirical, which recommended the use of the strength of the sub-grade to determine the thickness of the base, sub-base and surface layers. The soil strength parameters expressed in terms of California Bearing Ratio test (CBR), Hveem value (R) and Soil

Support Value (SSV), are often used in pavement design. All these parameters are derived from the results of laboratory tests on soil specimens.

Flexible pavements rarely fail by sub-grade failures during their design life (Huang, Y.H., 1993). Failures occur by either excessive rutting of the supporting pavement layers or cracking of the asphalt surface, as a result of fatigue due to environmental changes (Barksdale, R. D., 1972; Brown, S.F., 1974, 1996).The concept of soil resilient modulus, M_R was introduced as a measure of the mechanical property of the soil recognizing its permanent deformation to repetitive dynamic loading (AASHTO, 1993). The total pavement thickness requirements were assumed to be a function of the sub-grade resilient modulus (M_R), determined by the AASHTO test method (AASHTO, 1992). This was the first attempt at implementing a mechanistic property in pavement design. It should be noted that the AASHTO guide empirical model (AASHTO, 1993) is sensitive to the variation in the resilient modulus. It is recommended by the AASHTO design guide (AASHTO, 1993) that the resilient test be performed in the laboratory using site condition stress levels and the corresponding moisture conditions. It is common practice that in the case of lack of availability of testing facilities to determine M_R, to use some empirical correlation with other soil properties such as CBR and/or R values.

M_R (in MPa) for a CBR test with saturated fine grained soils of 10 or less (Heukelom, W., Klomp, A. J. G., 1964), is given by:

$$\mathrm{M_R} = 10.3 \times \mathrm{CBR} \tag{1}$$

For other types of soil, correlations were established to estimate the resilient modulus (Van Til *et al.*, 1972). However, those correlations are not used by designers because they produce inconsistent results. Several researchers (Salgado, R.; Yoon, S., 2003; Amini, F., 2003), have developed relationship between the stiffness of subgrades and bases and measured dynamic cone penetration (DCP).

The strength of unbound road materials (resilient modulus) is greatly affected by the moisture content and one single value of resilient modulus will not be representative for the material. Seasonal variations in volumetric water content and temperature were explored and a formula for estimating these variations as a function of the time of the year was established (Heydinger, A. G., 2003). Typically an increase in sub-grade water content results in a decreased resilient modulus that leads to increased deflections in the pavement, resulting in to a decrease in pavement design life. Guidelines for estimating the decrease in sub-grade resilient modulus with a known increase in the degree of saturation and water content has been proposed (Drumm *et al.*, 1997) .

For existing roads, Choubane and McNamara (2000) proposed the use of the back calculation method to estimate the stiffness of sub-grades and base and sub-base materials using deflection measurements of Falling Weight Deflectometer (FWD) for pavement design. The relationships between modulus, loads and deflection are given by equation 2.

$$E_{FWD} = 0.00147 \times \left(\frac{P}{d_r}\right) \qquad (2)$$

Where; E_{FWD} = Subgrade modulus, MPa, P = applied load in N and d_r = deflection in m, measured at a radial distance, r, of 0.9 m.

The temperature gradient of the road structure has a big impact on the resilient properties of unbound materials including gravel, sand, and clay and has great effect on the asphalt concrete surface layer. Mechanical properties of asphalt materials are often measured at room temperature, as required by the AASHTO design guide (AASHTO, 1993). However, asphalt concrete experiences a wide range of thermal regimes during the spring, summer, fall and winter seasons. It is well known that asphalt concrete becomes brittle and stiffer at temperatures below -5^{o}C. High temperature on the other hand, causes flow and fluidity of the asphalt binder, which makes the asphalt concrete soft and produce high permanent deformation, leading to rutting when subjected to stresses from traffic loadings. These stresses are generally small compared to the ultimate strength of the asphalt concrete material and are within its elastic limit. Plastic deformation is related to temperature and the number of loading applications (Wright, B.; Zheng, L., 1994).

The current design guide and its predecessors were largely based on design equations derived empirically from the observations made during road performance tests completed in 1959-60. Several transportation experts (Hajek, J.J., 1994), have criticized the empirical data thus derived as outdated and inadequate for today's highway and urban road systems. In March 1994, a USDOT Office of Inspector General report concluded that the design guide was outdated and that pavement design information in this guide could not be supported and validated with systematic comparisons to actual results of pavement response.

Two mix design methods are common in current practice, including the traditional Marshall mix design and the superpave mix design. Superpave suggests the establishment of sustainable aggregate gradation and performance-based binder specifications (Asphalt institute, 1991), to produce a durable Hot Mix Asphalt (HMA) product. The method was designed to replace the conventional Marshal and Haveem methods.

Performance grading specifications were developed as a part of the Strategic Highway Research Program (SHRP) and are a major component of superpave. Binders are specified on the basis of the climate and design pavement temperatures.

The most commonly used binder is performance grade PG 58-28. The first number (58) represents the average 7-day maximum pavement design temperature in degrees Celsius. This establishes the upper temperature limit for the binder to retain adequate rigidity to resist rutting. The second number (-28) represents the minimum pavement design temperature in degrees Celsius. The minimum temperature establishes the lower limit for the binder to retain sufficient flexibility to resist thermal cracking. Physical properties of the binders are measured at various temperatures both before and after laboratory aging. The laboratory aging is conducted to simulate field conditions imposed during the HMA production process as well as from long-term environmental exposure.

Historically, empirical properties were used to correlate to performance, has been used. Superpave was developed to use engineering properties to predict performance. The Performance-Grade of binder specification, "PG ", is adopted by the new design guide.

There are three levels of superpave mix design. Level 1 does not contain performance-based properties. Volumetric properties (air voids, asphalt content, etc.) and aggregate properties (crushed faces, fine aggregate sharpness, etc.) are the basis of Level 1. In some ways, Level 1 mix design is similar to Marshall mix design, but in superpave Level 1 the method of compaction using the gyratory compactor determines how strong the aggregate skeleton is inside the mix. It produces specimens stronger than that produced using the Marshall hammer. Both Level 2 and Level 3 mix design use the performance-based properties of the various components to predict performance. Level 3 is a more detailed analysis than Level 2. A superpave shear tester is used to measure the engineering properties.

Moisture content and the temperature of the various structural layers of the road necessitates that many municipalities of North America enforce weight restriction during the thawing seasons in the spring of each year. While the decision of imposing load restrictions is not due solely to higher stresses imposed on the unbound layers of the road, it reflects the lack of understanding of the changing environmental conditions of the road layers.

REVIEW OF AASHTO FLEXIBLE PAVEMENT DESIGN GUIDES

AASHTO Design Guide 1961-1972

The AASHTO pavement design method has passed through frequent developments. Upon completion of the AASHTO Road Test in late 1950s and early 1960s in Ottawa, Illinois, the AASHTO interim guide for the design of rigid and flexible pavement was developed and circulated (AASHTO, 1961). Based on the test results, pavement design criteria and design procedures were developed. After several years, the AASHTO interim guide for the design of pavement structures was published (AASHTO, 1972).

Design Principles:

The function of any road is to safely and smoothly carry vehicular traffic. In order to quantify this, two main concepts were introduced in AASHTO guide, serviceability, and performance. Serviceability defined as the ability of a pavement to serve the traffic for which it was designed. Performance was defined as the ability of the pavement to serve traffic over a period of time. From these definitions, performance could be interpreted as the trend of serviceability over time. For the AASHTO Road Test, performance was determined by the serviceability at the time of construction as well as at different times after construction. Ratings from 0 to 5 of serviceability were obtained by taking the mean ratings determined by a group of people. 0 rating indicates poor pavement, while 5 indicates excellent pavement. Present Serviceability Rating (PSR) was introduced as a measurement of serviceability (Van Til *et al*, 1972). Van Til *et al*, (1972) also statistically correlated PSR to various physical measurements of the pavement and it is referred to as Present Serviceability Index.

The basic equations developed from the AASHTO Road Test for flexible pavements design was:

$$\log W_{t18} = 9.36 \left(\log\log \frac{1}{R} + 1 \right) - 0.2 + \frac{\log\left[(4.2 - p_t) / (2.7) \right]}{0.4 + \left[1094 / (SN+1)^{5.19} \right]} \tag{3}$$

Where; W_{t18} is the number of 18-kip single axle load applications over time t; p_t = serviceability at end of time t; SN = Structural Number of pavement

Equation 3, however, was not applicable for different climatic conditions and various types of soils. So it was modified to relate the number of 18-kip single-axle repetitions (W_{t18}) required to reach a predefined terminal serviceability level (p_t) for any given pavement structure (SN), climatic condition (R), and Sub-grade soil (S_i). These modifications are included in Equation 4

$$\log W_{t18} = 9.36 \log(SN+1) - 0.2 + \frac{\log\left[{(4.2-pt)}/{(2.7)}\right]}{0.4+\left[{1094}/{(SN+1)^{5.19}}\right]} + \log\frac{1}{R} + 0.372(S_i-3) \qquad (4)$$

Design Input Parameters:

The following input parameters were used in the AASHTO Design as seen in equation 4 above.

Terminal Serviceability (p_t): This is period before resurfacing. It is the lowest serviceability that will be tolerated on the road at the end of the traffic analysis.

Equivalent Wheel Load Repetitions (W_{t18}): Traffic could be equated for daily 18- kip load applications if a common 20-year traffic analysis period is selected, or it can be expressed as the total 18-kip load applications within the traffic analysis period.

Regional Factor (R): Represents the climatic environment effect.

Structural Number (SN): Is defined as an index number derived from an analysis of traffic, roadbed soil condition, and regional factor. SN can be converted to thickness of various layers of flexible pavement using suitable coefficients related to the type of material being used in each layer. SN is given by equation 5:

$$SN=a_1D_1+a_2D_2+a_3D_3 \tag{5}$$

Where; D_i is the thickness of the *ith* layer, and a_1, a_2, a_3 represents the coefficients of the surface, base, and sub-base respectively.

Soil Support Value (S): Represents the soil sub-grade condition.

AASHTO Design Guide 1983-1993:

In 1983, an evaluation of the Guide was made to incorporate information developed since 1972. Based on research completed during the 20 years after the Road Test, several changes were introduced in the revised version of the AASHTO Guide (AASHTO, 1993). The soil support value (S) was been replaced with the resilient modulus (M_R), a material property to be incorporated in the design method. However, M_R serves only the unbound material properties and neglects the asphalt concrete surface layer properties. Accordingly, the design equations 3 and 4 for flexible pavement were modified. The new formula generated is:

$$\log W_{t18}=Z_R\times S_o+9.36\log(SN+1)-0.2+\frac{\log\left[\left(\Delta PSI/2.7\right)\right]}{0.4+\left[1094/(SN+1)^{5.19}\right]}+2.32\times\log M_R-8.07 \tag{6}$$

Where; W_{18} = Predicted number of 18-kip equivalent single axle load applications; Z_R = Standard normal deviate; S_o = Combined standard error of the traffic prediction and performance prediction; ΔPSI = Difference between the initial design serviceability index, p_o, and the design terminal serviceability index, p_t; M_R = Resilient modulus (psi); SN is the structural number indicative of the total pavement thickness.

The modified equations are predictors of the amount of traffic that can be sustained before the road deteriorates to some terminal level of serviceability.

In the AASHTO (1993) design procedure, the required structural thickness is determined based on their effective resilient modulus of native soils determined using the AASHTO (1992) procedure. It is common practice to use estimated values of M_R using some empirical correlation with other soil properties such as CBR and/or R values. Eq. (1) was used to estimate the M_R measured in MPa for a CBR test with saturated fine grained soils of 10 or less (Heukelom, W.; Klomp, A.J.G., 1964), this equation is adopted by the AASHTO design guide (1993).

To take account of the influence of moisture variation on the resilient modulus, the current ASSHTO design guide (AASHTO, 1993) recommends dividing the year into 12 or 24 periods, where each period is assigned a resilient modulus value based on the expected water content, which is then used to determine a relative damage or reduction factor. Eq. (7) is used to estimate the relative damage corresponding to each periods, then sum all seasons damage and divide it by number of periods. The mean of the relative damage factor is then used in the same Eq. (7) to obtain a single value for the resilient modulus, known as the "effective roadbed soil resilient modulus". It is noted that the AASHTO design guide (AASHTO, 1993), relies on physical properties to characterize pavement structure materials except the native soil (sub grade soil).

$$u_f = 9.488\times10^{16}\times M_R^{-2.32} \qquad (7)$$

Where; M_R = Resilient modulus, MPa.

A drainage coefficient was added to determine the layer coefficients representing the various unbound layer materials related to the resilient modulus. The bound material may be tested by procedures described in ASTM standard D4123 (ASTM, 1999). By knowing the elastic modulus at 25^{o} C, the asphalt structural layer coefficient (a_1) can be determined from the chart used by the AASHTO design guide, (AASHTO, 1993). The coefficient of the materials base (a_2) and sub-base (a_3) can be determined using the following correlations given by equations (8):

$$a_i = C_1\left(\log_{10} M_R\right) - C_2 \quad (8)$$

When i = 2, C_1 and C_2 are 0.481 and 0.977 respectively and when i = 3, C_1 and C_2 are 0.478 and 0.839 respectively. M_R = Resilient modulus, MPa

It's clear from Eq. (8) that the test results of the laboratory resilient modulus can significantly influence the predicted layer coefficient. The AASHTO design guide (AASHTO, 1993) expresses the relationship between structural layer coefficients, which is a measure of the relative ability of the material to function as a structural element of the pavement, structural number (SN), thickness (D) and drainage coefficient for the layer (m). These relationships describing the concept of layer thickness are depicted in Fig. 1. The 1993 AASHTO design guide relied heavily on characterizing materials using elastic modulus.

AASHTO Design Guide 2004:

The new design guide (NCHRP, 2004) has adopted two new material characterization techniques as design parameters. One of them is the Resilient Modulus to characterize the mechanistic response of the unbound granular materials, and the other one is the complex modulus, creep compliance and tensile strength to characterize the mechanistic response of asphalt concrete materials. This approach is expected to improve the road design processes. The advanced design level recommends using actual laboratory test data of the dynamic and resilient modulus determined under simulated environmental and traffic loading conditions.

The 1993 AASHTO design guide was based on mechanics theory and used the Young's modulus "E" to characterize pavement structures, assuming the pavement behaved as an elastic material. However, this is not true since asphalt concrete materials don't behave purely in elastic manner, but they are visco-ealstic. To estimate the behavior of such materials, it is important to account for their visco-elastic characteristics and the new design guide is considering this behavior by adopting the complex modulus for asphalt concrete materials characterization.

To properly define the response of pavement materials properly, one must consider the following service conditions: stress state (associated with loading), environmental condition (temperature), and construction condition (binder content). The stiffness characteristics of asphalt mixtures are dependent on the time of loading and temperature. At temperatures above 25^{o} C it is most likely that the stress has an influence on the stiffness characteristics as the binder becomes less stiff. At temperatures above 40^{o} C mixtures can no longer be treated as linear visco-elastic, (Monismith, C.L., 1992). At low temperatures, the behavior of asphalt concrete is considered the combination of both elastic and linear visco-elastic behavior. This behavior can be considered purely elastic and visco-elastic at low strain amplitude measurement (Benedetto and La Roche, 1998).

The new design guide (NCHRP, 2004) provides 3 levels of input depending on the importance of the project, the sensitivity of the pavement performance to a given input accuracy, the resources available to the designer, and the availability of input information at the time of the design.

Level 1is the highest accuracy level and requires physical testing for hot mix asphalt (dynamic modulus, creep compliance and indirect tensile strength) and unbound materials (resilient modulus).

Level 2 is considered intermediate accuracy. The required inputs are determined using established correlations in the model. For example, the dynamic modulus could be estimated based on results of tests performed on binders, aggregate gradation and mix properties.

Level 3 has the lowest accuracy level. Inputs are typically national or regional default values, such as the physical properties and type of binder used to characterize the asphalt concrete mixes.

Mechanistic parameters

Road engineers and practitioners anticipated the release of the new version of the design guide (NCHRP, 2004) to incorporate the mechanistic approach to the experimental approach M-EPDG model. The efforts of calibrating the design guide are not yet completed**.** Level 1 analysis of unbound materials in the M-EPDG model involves measuring the resilient modulus of the unbound granular materials, complex modulus, creep compliance and indirect tensile strength for hot mix asphalt.

Resilient Modulus

The resilient modulus parameter was adopted for the characterization of unbound materials in the new design guide (NCHRP, 2004). The resilient modulus along with the Poisson’s ratio is used in the pavement response model to quantify the stress dependent stiffness of unbound material layers. This resilient modulus is determined from laboratory testing of representative material samples. Two standard test methods are recommended in the guide (NCHRP, 1997; AASHTO 2003c). Results of the laboratory test are used to determine the non-linear elastic coefficients and exponents of the classical universal model in Eq. (9), but unfortunately the nonlinear part of the new design guide is not working so the design is still linear in the case of unbound materials (Uzan, J., 1985).

$$M_R = k_1 \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \quad (9)$$

Where; $\theta = \sigma_1 + \sigma_2 + \sigma_3$ (kPa); $\sigma_d = \sigma_1 - \sigma_3$ (kPa); p_a = atmospheric pressure (kPa); k_i = i = 1 to 3 (Regression constant)

Therefore, the mechanistic properties of materials used in the different pavement layers are needed to develop effective material models for road structures. Furthermore, environmental factors such as temperature and moisture influence these properties and must be considered in the material model and, hence, its strength, durability and load carrying capacity. The quality of construction also has an impact on the mechanistic response of construction materials and should be accounted for in modeling them. In-service conditions associated with aging (asphalt concrete surface) or densification (unbound aggregate layers) also affect the structural response of a pavement. In-service conditions may also include cracking, where an unfavorable response to external loading in the form of crack propagation may occur. The Design Guide incorporated the Enhanced Integrated Climatic Model (EICM) to simulate changes in the behavior and characteristics of pavements and sub-grade materials that occur with climatic conditions over the design period.

Complex modulus

The behavior of an asphalt concrete mixture, similar to its binder, depends on temperature and load frequency. Viscoelastic properties of asphalt materials are generally determined within the linear viscoelastic domain where the material is subjected to sinusoidal loading at different frequencies at small values of strain to keep it within the linear zone. The modulus value of asphalt concrete materials can rise during the cold winter months by a factor of 20 compared to its value during the hot summer months (Clyne *et al*., 2003).

The dynamic modulus, the true component of the complex modulus, has been adopted as the stiffness property in the M-EPDG model and is determined following AASHTO procedure TP62 (AASHTO, 2003a) test specifications. Since the pavement material response depends on mix composition, type of material and aging characteristic, asphalt concrete temperature, and rate of loading. It is also influenced by prevailing unique local conditions such as that the performance models incorporated in the new design guide (NCHRP, 2004) also require calibration. The recommended test series consists of five test temperatures (-10, 0, 20, 30, and 40° C) and six loading frequencies (0.1, 0.3, 1.0, 5, 10, and 20 Hz.) Each specimen should be tested for the 30 combinations of temperature and frequency starting with the lowest temperature and proceeding to the highest. Testing at a given temperature should begin with the highest frequency of loading and proceed to the lowest.

The complex modulus testing approach focuses on capturing the viscoelastic response of asphalt concrete materials where traffic loading is simulated in the laboratory with a sinusoidal load has been reported. The response of the material is also sinusoidal in nature but with a phase lag (Sayegh, G., 1967). The dynamic modulus is the only component of complex modulus that has been implemented in the proposed new design guide (NCHRP, 2004). The structural response model of the guide is based on linear elasticity and hence, the phase angle is not being considered in the analysis. Further development in mechanics may make it possible to incorporate the effect of the phase angle in the structural response model. Due to the complexity of the response, direct measurement in the laboratory remains the most accurate method for determining the dynamic modulus. Most users, however, don't yet have the necessary laboratory testing capabilities, due to the high cost and complexity of laboratory testing and the lack of personnel trained to conduct the test. This has hampered material development and the establishment of an effective laboratory characterization technique and has led to the use of predictive equations adopted by new design guide (NCHRP, 2004), known as levels 2 and 3. Most important models developed since 1967 have been summarized and it has been reported that all have several limitations (Witczak, M.W.; Fonseca, O.A, 1996). Both proposed a new predictive equation for estimating the dynamic modulus of asphalt concrete materials based on a statistical study conducted on data consisting of 1429 points from 49 separate asphalt concrete mixes. The equations developed appear to be better than the previous models because it accounts for the aging effect for both short and long term loading conditions and extreme temperature conditions. The Witczak and Fonseca (1996) predictive model is considered the latest and most accurate and has been adopted by the new design guide (NCHRP, 2004).

Indirect tension tests

In the new design guide, creep compliance and tensile strength tests are considered the most promising for predicting the low-temperature performance of asphalt concrete mixtures. The creep compliance is determined by applying a static compressive load of fixed magnitude along the diametric axis of a specimen for a duration of 100 seconds. The measured horizontal and vertical deformations are used to calculate the creep compliance. The recommended test series consists of three test temperatures -20, -10 and 0^{o} C. The indirect tensile strength is measured by applying load on the HMA specimen along its diametric axis at constant rate until failure. The test is always performed at a temperature of -10^{o} C (AASHTO, 2003b).

This type of pavement failure is the result of tensile stress that is caused by sudden temperature drops in combination with the embrittlement of asphalt concrete at low temperature. Thermal cracking continues to be a prevalent cause of permanent deterioration in asphalt pavement throughout the world. Thermal cracking can develop early in pavement life thereby contributing to loss of pavement serviceability. If left untreated thermal cracks permit the ingress of water into underlying layers, causing additional pavement deterioration.

CONCLUSIONS

Based on the literature review of the flexible pavement design guides in this study, the following is the summary of the findings of the literature review of flexible pavement design guides:

1. Empirical nature

- The current structural design approach to flexible pavement is empirical and based on the results of a limited experimental study conducted more than fifty years ago. The experimental results of the previously discussed Illinois study were used to produce design equations for pavement structures to reflect the observed loss of serviceability to tested pavement thickness and traffic impact.
- Most of the current design methods focus on load repetitions (frequency) to account for the impact of traffic volume on performance. These equivalent load factors mask weight

characteristics of different trucks. A simple load factor associated with the design truck does not cover the wide variation in factors such as number of axles and tire contact area.

2. Environmental consideration

- Temperature is a significant factor in influencing the performance of a pavement, especially in the case of asphalt concrete. The stiffness of AC is less at higher temperature making it susceptible to deformations. Low temperatures make the AC layer extremely brittle and the surface becomes susceptible to cracking. Additionally, the prevailing temperature condition is a significant factor that influences the rate of accumulation of damage in asphalt concrete pavements. However, none of the design standards have considered temperature as a design input.

- Moisture variation was discussed as influencing the resilient modulus. The current AASHTO design guide (AASHTO, 1993) uses an equation to estimate the resilient modulus based on the relative damage corresponding to each season. It is noted that the AASHTO design guide (AASHTO, 1993) relies on physical properties to characterize pavement structure materials except the native soil (sub grade soil).

3. AASHTO road test

The AASHTO design equations were developed using the specific conditions of road tests. The limitations of these tests and equations can be attributed to:

- The duration of the accelerated test was only two years, rather than the specified expected in-service life of the designed pavement.

- The maximum load used was less than what is experienced in field conditions.

- The distributions of axle load and configuration were simple and did not represent the actual vehicles used today.

- The materials used and construction practice was limited to the 1950 standard.

- It was limited to one climatic condition only.

4. Mechanistic Empirical design

- The 2004 AASHTO design guide (NCHRP, 2004) was aimed at bridging the limitations resulting from the absence of a link between the design and analysis tools and the material properties required for characterization.
- The design guide incorporated the Enhanced Integrated Climatic Model (EICM) to simulate changes in the behaviour and characteristics of pavement and sub-grade materials that concur with climatic conditions over the design period.
  - The continuous development of materials and demands of the road structure have far exceeded the capabilities of the empirical equations.
  - The current AASHTO design practice does not accurately account for the speed of the passing traffic. Traffic volume and development of cities across North America resulted in slower traffic speed and stoppage during rush hours. These conditions resulted in high occurrence of rutting damage, more specific during periods of high temperature. This damage can also be the result of using inadequate mix design and roadway usages such as at intersections and bus stops, where greater rutting damage

An instrumentation system designed and installed to monitor the behavior of pavements under different environmental conditions and the results of measurements from actual road performance will be presented in a future paper.

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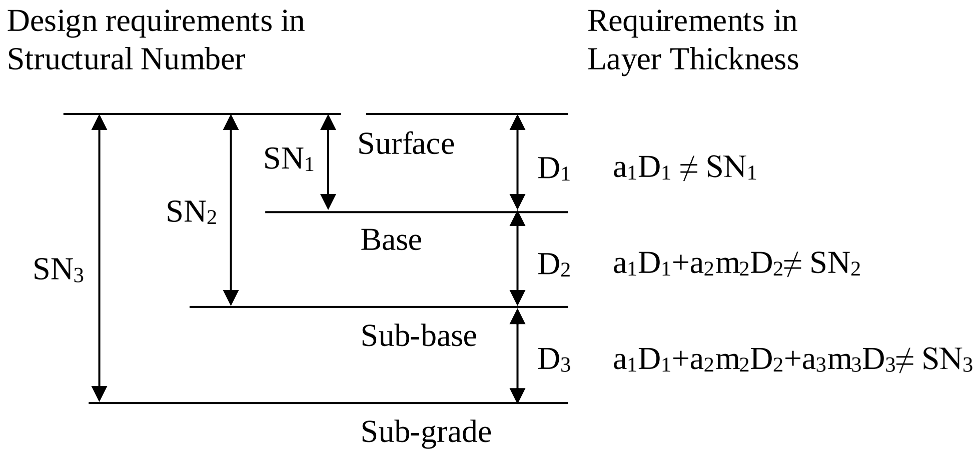

Fig 1. The concept of layer analysis