

Review Article

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A review of rutting in asphalt concrete pavement

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Abstract: Undoubtedly, rutting in asphalt concrete pavement is considered a major dilemma in terms of pavement performance and safety faced by road users as well as the road authorities. Rutting is a bowl-shaped depression in the wheel paths that develop gradually with the increasing number of load applications. Heavy axle loadings besides the high pavement summer temperature enhance the problem of rutting. According to the AASHTO design equation for flexible pavements, a 1.1 in rut depth will reduce the present serviceability index of relatively new pavement, having no other distress, from 4.2 to 2.5. With this amount of drop in serviceability, the entire life of the pavement in effect has been lost. Therefore, it is crucial to look at the mechanism, possible reasons, as well as techniques, to reduce the rutting in order to offer long service life and safe roadways. To this end, the need has been arising for this research which deals mainly with a thorough review of the existing literature to highlight some key points for the researchers and pavement engineers related to rutting mechanism, measurement, and criteria, both intrinsic (mixture variables) and extrinsic (traffic and temperature) contributory factors to rutting, material characterization, test methods, and prediction methodologies, as well as possible ways to minimize the rutting distress in asphalt concrete pavement. So far, this research attempts to bridge the gap in the literature that frequently only addresses a single aspect of rutting by providing an in-depth review of rutting in asphalt concrete and thereby offers a complete comprehensive understanding of this major distress type.

Keywords: rutting, permanent deformation, axle loading, temperature, dynamic loading, creep

1 Introduction

The function of pavement is to carry traffic safely, smoothly, and economically from one location to another [1]. However, various factors such as material properties, construction quality control, traffic loading, and the environment collectively act over time to reduce the original smoothness of the pavement. In flexible pavements, this reduction in pavement smoothness or serviceability will ultimately lead to failure or an intolerable level of roughness. The most common forms of load associated distresses leading to a reduction in serviceability of flexible pavements are permanent deformation (rutting) and fatigue cracking. According to the AASHTO design equation for flexible pavements, a 1.1 in rut depth will reduce the present serviceability index (PSI) of relatively new pavement, having no other distress, from 4.2 to 2.5 [2].

Rutting in flexible pavements develops gradually with an increase in the number of load applications, typically manifesting as longitudinal depressions in the wheel paths and minor upheavals to the sides, as seen in Figure 1.

It is caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation and can occur in any one or more of the pavement layers as well as in the subgrade. Although the rutting problem must be addressed for structural and economic reasons, the concern for permanent deformation may also be related to traffic safety. Pavement rutting can cause operating hazards such as loss of vehicle control during lane changes and hydroplaning due to the accumulation of water in the wheel path.

In Iraq, within about 1 year after construction, rutting distress was observed at several locations on the highways due to the high axle loading coupled with the relentless high summer temperatures [3]. For instance, in Baghdad city (the capital of Iraq) the ambient air temperature for nearly 3 months can reach 50°C (and pavement surface temperature can reach up to 60°C), which enhances the rutting problem in local roads.

Traditionally, flexible pavement design considers the permanent deformation problem indirectly using the maximum level of rutting allowed for the entire pavement structure. This is made based on the assumption of the

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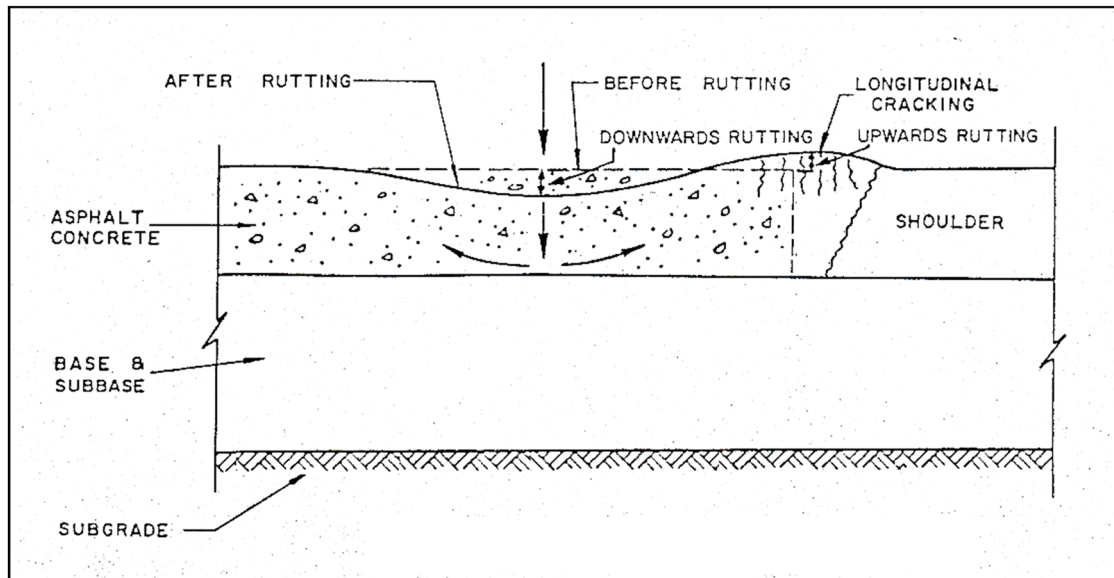


Figure 1: Rutting in flexible pavement [4].

allowable magnitude of compressive strain at the top of the subgrade rather than predicting its actual magnitude within the pavement layers. In order to achieve a reliable estimate of the pavement rutting, one must consider loading, material, and environmental variables when developing the law at which permanent deformation accumulates to ascertain pavement layer on the basis of laboratory works. One of the basic requirements for this law is to test the material in the lab under conditions that satisfactorily simulate the field conditions. Although, the characterization of a material's permanent deformation potential in the laboratory under repeated loads is central to its contribution in rutting appearing at the surface of the pavement structure, the variability in the traffic as well as the environmental conditions in the field make their simulation in the laboratory somewhat difficult.

Although there is an agreement among the researchers that the rutting in asphalt concrete pavement is a major distress type, so far most of the previous research focused on one of the following: (1) single aspect or synergic effect of some contributory factors that cause rutting, (2) common permanent deformation test methods, and (3) prediction of rutting in asphalt concrete. Therefore, there is a distinct lack of an in-depth review of rutting in asphalt concrete that provides a complete comprehensive understanding for this major distress type. In view of the above preface, this research would serve as a practical guide that could help the pavement construction community by covering the findings of research studies in terms of causes, measurement, both intrinsic and extrinsic affecting factors, material characterization, and test methods, and the prediction methodology for rutting in asphalt concrete pavement.

2 Rutting: types, mechanism, and distribution with depth

Historically, the term “permanent deformation” was used to describe any distortion of the pavement surface, including shoving and pushing due to mix instability [5]. Today, however, this form of distress refers to longitudinal depression or “ruts” that form in the wheel paths due to “consolidation and/or lateral movement in one or more of the component pavement layers due to repeated, transient load applications.” Because rutting appears only as a change in transverse surface profile, it was often erroneously blamed on surface instability. Investigations at the AASHO road test in 1959, however, revealed that permanent deformation occurred in all layers of the pavement system, as illustrated in Figure 2. From 51 sections trenched in 1960, the total permanent deformation was distributed among the component layers in the following average proportions [6]:

Component layer	Percentage of permanent deformation
AC surface	32
Base	14
Subbase	45
Subgrade	9

Other studies have indicated that as much as 19% of the permanent deformation may be attributed to the subgrade, while others have shown that for 6 in thick

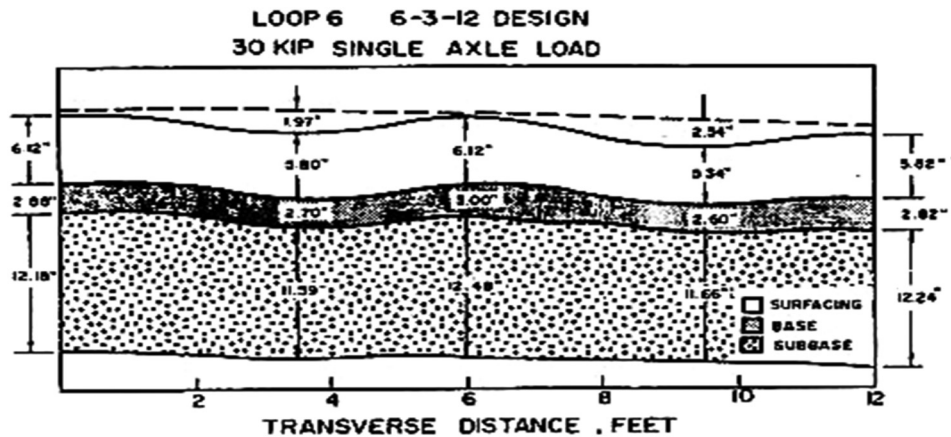


Figure 2: Typical transverse profile, 1959 AASHO trench study [6].

bituminous pavements, rutting was entirely due to deformation within the asphalt concrete [7,8].

In 2002, National Cooperative Highway Research Program [9] classified rutting as shown in Figure 3.

Wear rutting, which is due to the progressive loss of coated aggregate particles from the pavement surface, is caused by combined environmental and traffic influences.

Structural rutting, which is due to the permanent vertical deformation of the pavement structure under repeated traffic loads, is essentially a reflection of the permanent deformation within the subgrade.

Instability rutting is due to the densification (decrease in volume and, hence, increase in density) and lateral displacement (shear deformation) of material within the pavement asphaltic concrete layers. Dawley et al. [10] state that the majority of hot mix asphalt (HMA) rutting is primarily due to instability rutting. This research deals with this type of rutting.

Undoubtedly, the mechanical responses of the HMA layer to various loading conditions are the result of a series of complex internal activities. For years, researchers tried to relate these microscopic functions to the macroscopic rutting phenomenon. Some researchers have hypothesized that the relative movements of aggregate particles result in different arrangements of the particles in order to satisfy equilibrium conditions. It is further hypothesized that this process is not a reversible one, and upon the removal of the loads, equilibrium is achieved through a recovery process that involves some permanent deformations [11]. Others have taken the above theory one step further at the microscopic level and offered explanations of the mechanisms involved in particle reorientation and the collapse of the void network. They have suggested that the rheology (the word rheology is derived from the Greek word rheo, which translates literally as "to flow" and is used to illustrate the dependency of the stress-strain relationship of asphaltic

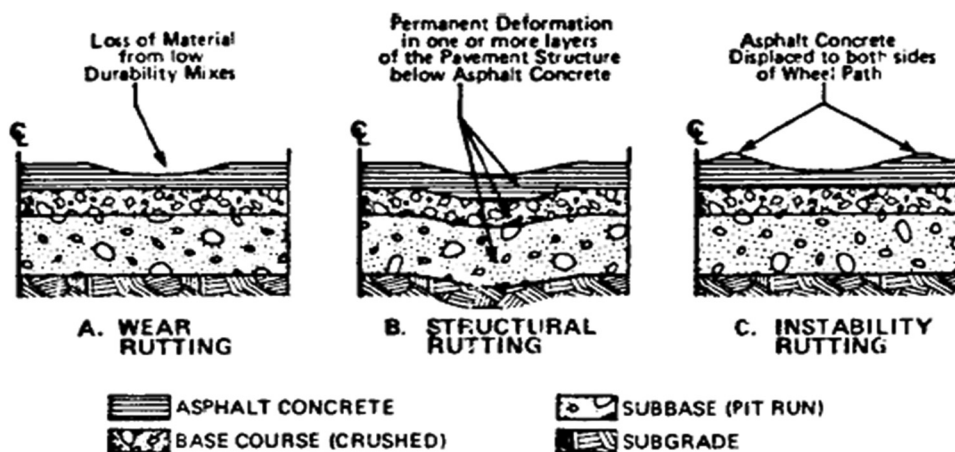


Figure 3: Description of rutting categories [9].

material on time) of asphalt concrete and its “flow like” behavior stem from the viscous flow of the asphalt binder itself. The flow of asphalt cement into the voids and the reduction in the thickness of aggregate coating result in a reduction in the relative distances between aggregate particles. Hence, particle reorientation is caused by the flow of asphalt cement into the voids [12,13]. As a result of this re-orientation of aggregate particles which is enhanced by the temperature effect liquefies asphalt cement and makes the sliding of aggregate particles against each other easy. Rutting in asphalt concrete is appearing due to the repetition of traffic axle loads [14].

There are contradictions between the researchers with respect to the distribution of rutting with depth. Hofstra and Klopman [7] found that the deformation throughout the asphalt layer was greatest near the load and gradually decreased with depth. This distribution of permanent strain with depth seems reasonable as there should be more resistance to plastic flow with the increase in depth below the wheel loading, as well as due to the high temperature and vertical stress near the surface.

Repeated load tests by McLean [15] indicated that the greatest amount of permanent deformation occurs at a depth of about 2 in (5.08 cm) below the surface, as illustrated by the data presented in Figure 4, i.e., at the point of occurrence of the largest value of stress difference. Researcher at the University of Waterloo suggests that nearly all of the permanent deformation in the bituminous layer occurs in the lower half of the layer as a result

of the lateral tensile stresses [6]. This conclusion is in contrast with the observations of Hofstra and Klopman [7] and the predictions of McLean [15].

3 Rutting measurement and criteria

Rut depth is defined as the vertical distance between the valley and the crest of the ruts. Rut depth is measured by placing 1.2 m (or 3.6 m) metal straightedge across the wheel path to establish a horizontal reference line and measuring the vertical distance between the straightedge and pavement surface by 0.3 m (12 in) ruler (as shown in Figure 5). This measurement is repeated for each 6 m interval (in traffic direction) in both wheel paths and the results are averaged to give the mean rut depth.

The occurrence of permanent deformation or rutting is one of the major problems affecting the performance of pavement structure [16]. It is considered as a serious safety problem encountered by the vehicles for two reasons:

1. Loss of vehicle control during lane changing, ruts tend to pull a vehicle toward the rut path as it is steered across the rut.
2. If the rut depth is greater than 12.5 mm for pavement with crown slopes on the order of 2%, this rut depth is sufficient for the accumulation of water (pounding)

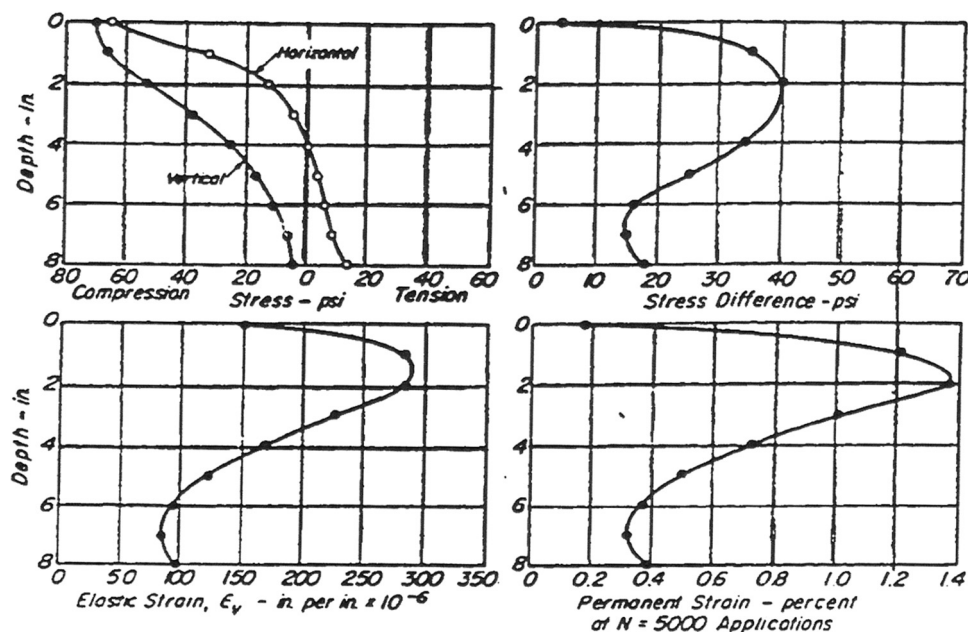


Figure 4: Stress and strain distributions in 8 in thick asphalt concrete pavement subjected to 1,500 lb wheel load with 70 PSI contact pressure [15].

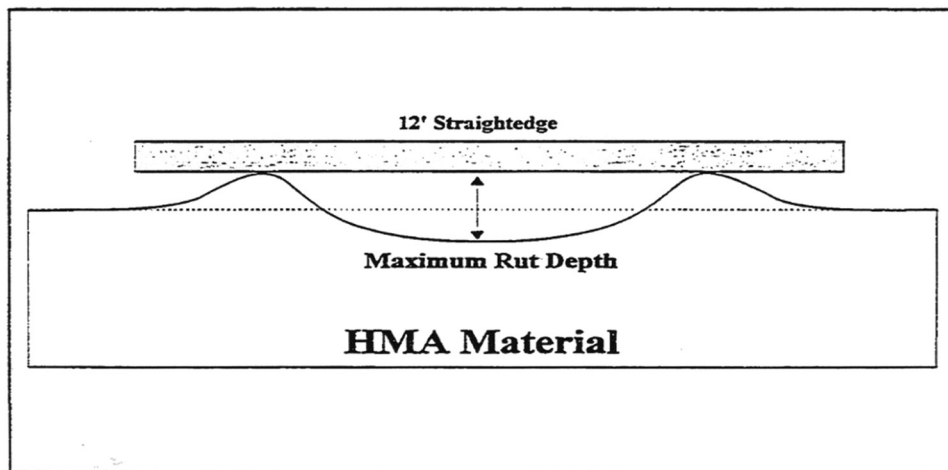


Figure 5: Schematic of rut depth measurement with straightedge [25].

and possibly causing vehicles traveling at a speed of 80 km/h or more to hydroplane.

Based on the AASHTO guide [17], rutting is classified according to severity level as exhibited in Table 1.

4 Factors affecting rutting

The AASHTO Joint Task Force on rutting [2] expressed the opinion that there are many factors that can influence HMA rutting. Traffic and environmental (temperature) factors were identified as the major causes of HMA rutting. Unfortunately, the highway agencies have little control over these two factors. However, there are also important factors that have contributed to the HMA rutting problem that is within the control of highway agencies [2]. Highway engineers have focused attention on these factors rather than the traffic and environment. With proper control of asphalt cement, aggregate quality and gradation, asphalt content, and construction, the HMA rutting problem can be greatly minimized. The subcommittee on materials of the Western Association of Highway and Transportation Officials, WASHTO, has also made recommendations on the selection of materials to minimize the HMA rutting [18].

Table 1: Rut depth criteria according to AASHTO (1993)

Mean rut depth (mm)	Severity level
6–13	Low
13–25	Medium
>25	High

4.1 Traffic characteristics

Traffic characteristics is one of the most important factors affecting rutting, it includes tire contact pressure, vehicle speed, and the number of load repetitions (traffic volume).

The shape of the contact area between a tire and the road surface is approximately circular when the load applied is small relative to the recommended maximum for the tire, but it becomes increasingly elongated as the wheel load is increased at constant inflation pressure, this is shown in Figure 6, where the highest load considered is 50% above the tire manufacturer's rating [19]. In calculating pavement stresses resulting from the passage of the traffic, it is usual to assume that the load carried by the wheel is uniformly distributed over a circular area and the radius of loading is calculated from the wheel load and the tire pressure [1], this is because it is assumed that the tire pressure is equal to the contact pressure (no effect for tire wall).

Higher tire pressures and weights of trucks since the AASHTO road testing have resulted in higher HMA rutting [18]. Responses to the 1987 AASHTO survey on the HMA rutting problem showed that 93% of those responding expressed that heavy truck tire pressure was a major cause of HMA rutting [2]. While the current 1993 AASHTO guide [17] for the design of pavement structure [17] is based on 18 kip loads and tire contact pressure of 75–80 PSI, recent studies [20,21] have shown that truck tire inflation pressure have increased and are now averaging around 100 PSI. Some researchers [20,22,23] reported truck tire pressures to be as high as 140 PSI. Chen et al. [24] stated in their field study using the Texas Load Simulator that such an increase in tire inflation pressure from 80 to 100 PSI leads to an increase in rut depth of about

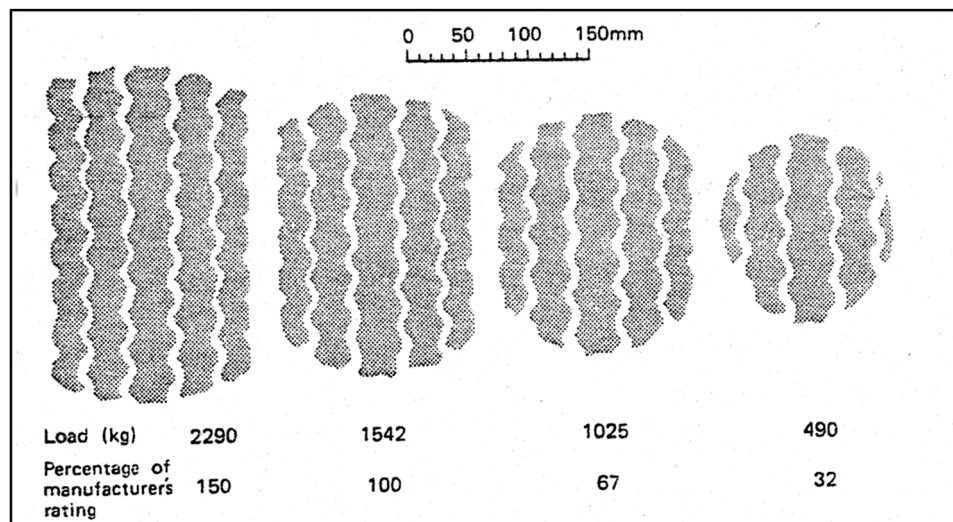


Figure 6: Tire prints for different loadings [19].

43% after 1,600,000 axle load repetitions. In Dubai [26], after extensive laboratory and field studies, it was determined that the mixture and pavement had originally been well-designed according to existing methodologies. But the accelerated rutting (after 10 months of trafficking) appeared due to heavier than expected loads (up to 80,000 lb axle loads as compared to the 18,000 lb axle loads used for design) and higher tire pressures. Abbas et al. [27], in their study of the rutting in the oil tanks road located west of Baghdad, indicate that the increase in the tandem axle load by 61% leads to an increase in rut depth by 82%.

Another factor related to the traffic that significantly affects the rutting of asphalt concrete layers is the speed of traveling vehicles. When the viscoelastic approach is used to calculate the pavement response to the applied wheel load, speed is directly related to the duration of loading. If the elastic approach is used in the pavement response calculation, the elastic modulus of asphaltic concrete layers should be determined in commensurate with the vehicle speed. Generally, the greater the speed, the larger the modulus, and the lesser the deformation in the pavement [1]. Pereira et al. [28] investigated the effect of truck speed on the accumulation of permanent deformation; measurements of the development of actual rut depth were recorded as a function of truck speed (which decreased as the trucks climbed a steep hill) for the three sites in Portugal. The investigated roads pass through hilly terrain where long stretches of highways are on inclines and trucks frequently slow down to about 20 km/h. Schematic diagram for the location of highway and rutting severity is shown in Figure 7.

Pereira stated that the rut depth at the end of the upward direction lane with 5% grade and 25 km/h average truck speed is 20 mm, while at the beginning of the grade, the rut depth is 10 mm. Also, Fwa and Tan [29] stated in their rutting survey on Singapore roads that rutting is commonly found in the slow lanes of major highways and in the approaches to the traffic-light junction. He also stated that this is an indication of the association of this problem with the slow-moving vehicles. Albayati and Saadi [30] in their research on some of the important rural highways connecting Baghdad with other governorates agreed with the above observation. They also found that all the observed highways suffer from rutting particularly on the slow-moving vehicle lane (right lane), which carries the bulk volume of the commercial vehicles.

The third component of the traffic that affect rutting is load repetition. In general, as the load repetition increases, the rutting increase. Specifically, the trend of

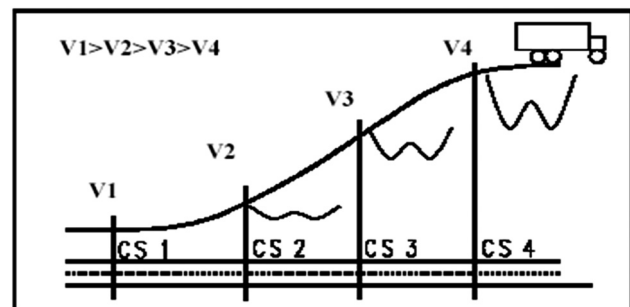


Figure 7: Schematic diagram showing the effect of vehicle speed along the grade on the rut depth [28].

this relationship is a function of several factors, such as temperature, loading conditions, and mixture parameters. Researchers [31,32] show that in most cases it follows the linear trend when plotted in log scale. Eisenmann and Hilmer [33], on the basis of wheel tracking test results, suggest the following relationship between the rut depth (Rd) and the number of load repetitions (N):

$$Rd = a + b(N)^{0.5}, \quad (1)$$

where a and b are laboratory determined parameters.

From the preceding discussion, it is apparent that the increased tire inflation pressure has placed the HMA mixture near the surface under high stresses, through increase in the probability of rutting. Therefore, more attention should be given to the selection of high-quality materials in designing the asphalt mixture and to quality control during the construction of the surface course of flexible pavement in order to minimize rutting.

4.2 Temperature

Rutting is more prevalent in hot climate areas because the viscosity of the asphalt binder which is inversely related to rutting is significantly reduced with the increase in temperature resulting in a more rut susceptible HMA mix. Figure 8 shows the effect of temperature on log asphalt viscosity for a wide range of asphalt cement grades [34]. From the Figure, it is obvious that the viscosity of asphalts varies from less than one Poise to more than one trillion Poises. Within such an extreme viscosity range, asphalts are transformed from low viscosity Newtonian liquids to materials exhibiting shear-dependent visco-elastic behavior, where with decreasing temperature, the elastic component tends to be predominant. Thus, the gradually changing curvature of plots in Figure 8 indicates that the viscosity of asphalt tends to change more rapidly at low temperatures, and such change becomes far less pronounced at higher temperatures when the viscous behavior is predominant.

Hofstra and Klopman [7] showed from test wheel track measurements that rutting is significantly increased when testing temperature varies from 20 to 60°C. The obtained result is shown in Figure 9. The presented data indicate that the rut depth increases by a factor of 250 when the temperature increases from 20 to 60°C (from 68 to 140°F), this is consistent with Linden and Van der Heide [35] who reported a significant increase in rutting in Europe during the very hot summers of 1975 and 1976.

Célaré [36], when testing cylindrical specimens (100 mm diameter × 200 mm height) in dynamic creep test, stated that

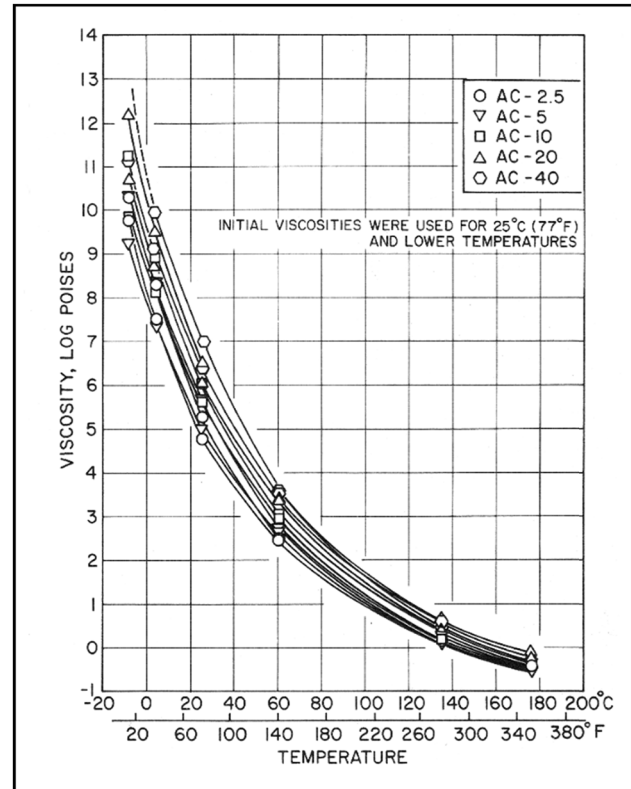


Figure 8: Relationship between viscosity and temperature for asphalt cements [34].

the creep rate (percent deformation per million cycles) is increased by a factor of 2.5 when testing temperature changes from 25 to 35°C, under loading condition of 10 cycles per second and 70 PSI deviator stress.

Based on wheel tracking tests to evaluate some of the pavement mixtures conventionally used in Singapore, Fwa and Tan [29] state the following “after 10,800 passes of load, at 35 and 60°C test temperatures, the corresponding rut depth is 3.89 and 12.95 mm, respectively, i.e., 70% of rut depth was developed at 60°C.”

Tayebali et al. [37] carried out 36 repeated axial creep tests to evaluate the applicability of this test and some other tests in the assessment of rutting potential for a mixture containing modified binders. They found that the average plastic strain increased by a factor of 1.5 when the testing temperature increased from 40 to 60°C. This was observed at 20 PSI axial stress and 0.1s load duration (60 cycles per minute).

Yassoub [3] stated that the time required to achieve 10 mm rut depth in asphalt concrete at 50°C is 72% shorter than that required at 40°C. Bonnot [38] selected a test temperature of 60°C for wearing-course asphalt concrete and 50°C for base courses. These temperatures were chosen to be relatively high to reproduce the most

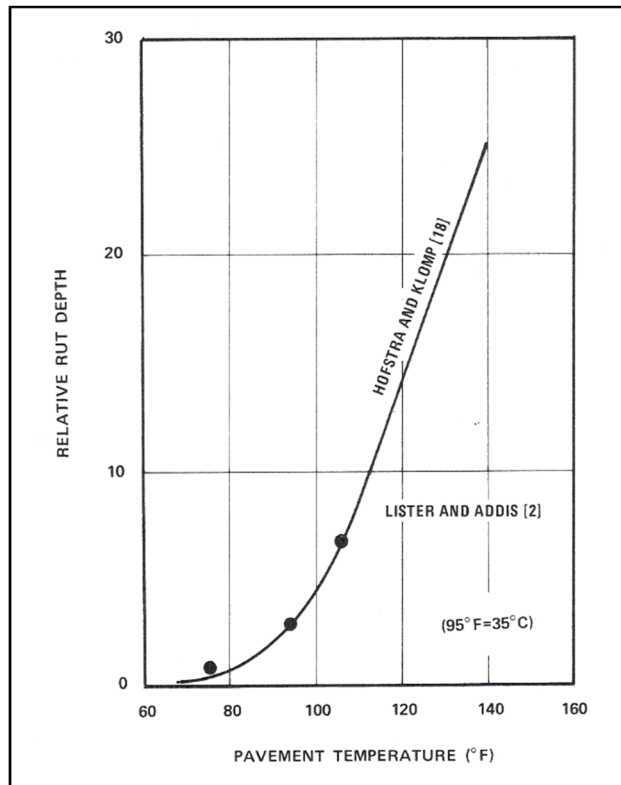


Figure 9: Effect of pavement temperature on rut depth [7].

unfavorable conditions expected in France. Similarly, Mahboub [39] conservatively selected the hottest pavement profile to represent critical conditions. Based on the above, it can be concluded that the researchers have recognized the need to conduct laboratory tests at temperatures within the high-temperature range encountered in the field.

4.3 Asphalt concrete mixture components and properties

Speer [40] investigated the effect of different asphalt penetration grades on the rutting potential of asphalt concrete. His investigation was based on the laboratory test track and traffic simulator machine which have the capability for applying different tire pressures (30, 50, 70, and 90 PSI). Based on his experiments, he stated that asphalt cement with a softer grade (90) resulted in a rut depth more than that of penetration grade (40) by a factor of 1.5 at the end of one million repetitions of 90 PSI tire pressure. The comprehensive results of Speer are shown in Figure 10. However, Speer cautioned about the construction problems associated with the use of hard-grade

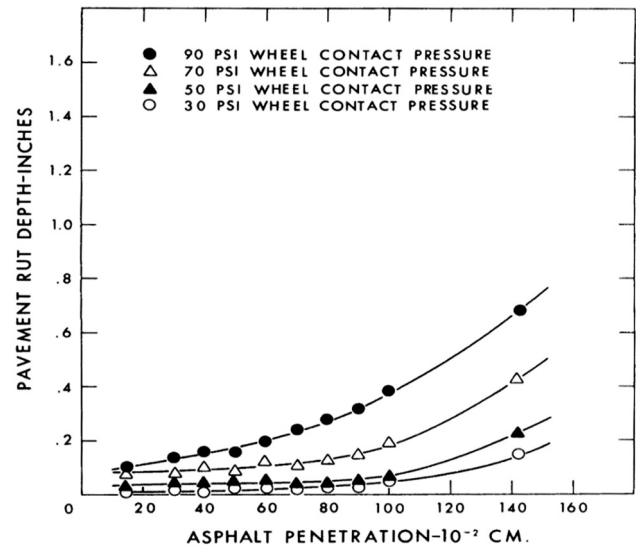


Figure 10: Effect of asphalt cement penetration grade on rutting [40].

asphalt due to the difficulty of mixing operation and pavement laydown process.

Leahy and Witczak [41] compared the performance of an AC-5 and AC-20 as related to the accumulated plastic strain in the repeated load test. They found that the plastic strain introduced to the asphalt mix by using AC-5 is 20% higher than that introduced by using AC-20 under the same loading and environmental conditions. On the basis of uniaxial static creep tests (1 h. loading time, 20°C testing temperature, and 14.5 PSI stress level), Mahboub [39], when investigating the performance of three types of asphalt cement (AC-5, AC-10, and AC-20), concluded that less viscous asphalts make the mixture less stiff and therefore more susceptible to irrecoverable deformation, i.e., rutting. Monismith et al. [42] made similar observations and recommended the use of harder (more viscous) asphalt cement on thicker pavements and hotter climates. Also, Decker and Goodrich [43] found that at a given temperature and loading rate, a high viscosity asphalt cement resulted in a stiffer mix which provides better rutting resistance, but they state such grade may cause low temperature cracking problems. Therefore, as they stated, a balance between the requirements of asphalt viscosity should always be maintained to ensure good performance of asphalt mixture during hot and cold ambient conditions. Hughes and Maupin [44] compared the performance of an AC-20 and AC-30 to prevent rutting. The researchers reported that the binder type was not as important as the aggregate gradation in minimizing early rutting. Keyser and Ruth [45] reported in a field study of pavements in Quebec, Canada that

there was no good correlation between asphalt cement viscosity and rutting susceptibility. This conclusion, which is in contrast with that observed by the abovementioned researchers, may be attributed to the low ambient temperature encountered within this area which vanishes the effect of asphalt viscosity (mean annual temperature is -7.2°C , as listed in the World Index program [46]). Several researchers have tried to improve the rutting performance by using modifiers (polymers, micro fillers, etc.) to increase the viscosity of the asphalt cement at high temperatures without adverse effects at low temperatures. For example, Monismith and Tayebali [47] investigated the relative behavior of mixtures containing AR2000, AR8000 (AR refers to Aged Residue viscosity) and AR2000 modified by carbon black as micro filler. Based on both creep tests and repeated load triaxial tests, the latter two mixtures resulted in better resistance to permanent deformation at high temperatures than the mixture containing the AR2000 asphalt cement.

There is much in the literature on the relationship between asphalt cement content and asphalt concrete rutting susceptibility. Arabia [48] compared the results of cores from both good-performing and rutted areas of seven pavements in Saudi Arabia to identify the mix and material properties that caused rutting susceptibility. The author reported that the rutted areas had higher asphalt cement contents than the good-performing areas. Higher asphalt content is defined by the author as that produced air voids in a mix of less than 3%. Brown et al. [49] stated on the basis of laboratory test track that the addition of 0.5% asphalt beyond the optimum content increases the permanent deformation by approximately 50%. Mahboub and Little [50] indicated that higher asphalt cement contents which produce lower air voids increased rutting potential. They suggested that the reduction in air voids as a consequence of increased asphalt content is attributed to the fill of void space with asphalt. As a result, the increase in asphalt content is equivalent to the introduction of lubricants between aggregate particles otherwise separated by a very tight network of air voids. This phenomenon causes the mixture containing higher asphalt content to be more susceptible to permanent deformation induced by the viscous flow of asphalt between aggregate particles.

El-Basyouny and Mamlouk [51] studied the effect of aggregate gradations and asphalt contents on rutting potential using a cyclic creep test. The obtained results of tests were recorded as α and μ for use as input to the VESYS3AM program for the purpose of rut depth calculation. The obtained results indicate that the optimum asphalt content (4.5%, for 19 mm aggregate maximum

size) yields the minimum rut depth (10 mm) after six million standard axle load repetitions. This conclusion may provide further evidence to the earlier mentioned conclusion that an increase in asphalt content beyond optimum is equivalent to the introduction of lubricants between the aggregate particles with the consequence of increasing mix susceptibility to permanent deformation.

There have been numerous laboratory and field studies on the effect of aggregate characteristics (surface texture, shape, max size, and gradation) on the HMA rutting. Aggregate with rough surface texture provides higher internal friction and a stronger bond with the asphalt cement to provide better mix stability and rut resistance. Parker and Brown [52] investigated 13 pavements and rutting data from Alabama Highway Department road condition database to determine the aggregate properties that relate to rutting susceptibility. The authors concluded that the pavements with more angular, crushed particles experienced less rutting than pavements with more rounded aggregates.

Perdomo and Button [53] conducted a study to evaluate the effects of natural sands on permanent deformation and to quantify the influence on resistance to plastic deformation when natural sand is replaced with crushed fine aggregate. The study showed that the total deformation and rate of deformation increased as the percentage of natural sand increased. The shape and texture of the fine aggregate were major factors controlling plastic deformation in asphalt concrete mixtures. The authors recommended replacing natural sand with manufactured sand to increase the resistance of the asphalt concrete pavement to permanent deformation. Kalcheff and Tunnicliff [54] conducted a laboratory study to determine the effects of crushed aggregate size and shape on the properties of asphalt concrete mixtures. They specifically evaluated the effect of coarse aggregate gradations and the shape effects of fine aggregates. The laboratory specimens were produced with Marshall and Hveem methods using an aggregate blend composed of natural and manufactured sands. The authors reported that asphalt mixes having a higher percentage of coarse aggregate have less deformation; also, the authors found that asphalt concrete mixtures containing crushed fine aggregate were more resistant to permanent deformation from repeated loadings than comparable mixtures containing natural sand. The behavior of the asphalt concrete mixture was improved when manufactured sands replaced natural sands.

Brown et al. [55] reported that increasing the maximum aggregate size generally results in a tougher mix. Kandhal [56] and Brown and Bassett [57] believed that

the use of larger aggregate size in asphalt mixes can minimize or eliminate rutting in HMA pavements. Dawley et al. [10] reported the results of a laboratory creep study which showed that mixes with larger max size, more crushed coarse aggregate, and less natural sand provide more resistance to permanent deformation than mixes with smaller max sized gravel and natural sands. Monismith et al. [42] reported that dense aggregate gradations are desired to mitigate the effects of rutting. Dense gradation (close to the 0.45 power curve) mixes tend to have higher stiffness and thus higher resistance to rutting. Moore and Welke [58] conducted numerous asphalt mix designs to determine the effect of fine aggregate on the Marshall stability. They stated that the asphalt concrete mixture gradation and aggregate angularity were very significant in increasing the stability of mixtures. They reported that as the mixture gradation approached the 0.45 curve for maximum density, the Marshall stability increased. They also stated that the more angular the fine aggregate, the higher the stability. The study concluded that rounded fine aggregate (natural sand) produced lower stabilities than the crushed fine aggregate.

Marker [59] and Crawford [60] concluded that particle shape and the amount of material passing the No. 4 sieve were major factors contributing to the tenderness of an asphalt concrete mixture. They showed that most tender pavements have an excess of middle-sized sand particles (No. 8 to No. 100) in the aggregate gradation. This excess of mid-sized sand particles is revealed as a hump in the curve when the gradation is plotted as percent passing vs the sieve size raised to the 0.45 power. Tenderness is generally most critical when this hump is near No. 30 sieve. This condition is generally combined by a relatively low amount of filler. The authors also stated that rounded, uncrushed aggregates are more likely to contribute to tender mixes, especially as the amount of uncrushed material passing the No. 4 sieve increases. Brown and Cross [61] conducted a study to evaluate aggregate properties that affect pavement rutting. Samples from 42 pavements that had rutted in less than 5 years or been in service for more than 5 years without rutting were tested to determine aggregate and mixture properties. The authors concluded that aggregate properties do not significantly affect the rutting potential when in-place air voids are below 2.5% since the mixtures tend to rut regardless of aggregate properties. They stated that the percentage of fractured faces of the coarse aggregate affected the rate of rutting. The rate of rutting increased as the percentage of crushed faces decreased. They concluded that higher percentages of crushed coarse aggregate and crushed fine aggregate reduced the potential for

rutting. The effect of aggregate characteristics on rutting has also been demonstrated from field studies of the following researchers: Miller et al. [62], Huber and Heiman [63], Grau [64], and Carpenter [65], all of these authors reported less rutting occurred in HMA pavements with more crushed coarse aggregate and manufactured fine aggregate than that in HMA pavements constructed using rounded aggregate and natural sand.

A portion of the mineral filler (particles greater than asphalt film thickness) contributes to the interlocking of the aggregate. The other portion of the filler (particles less than asphalt film thickness) is suspended in the asphalt cement and acts as part of the binder in the mix. The resulting filler-asphalt binder can increase the stiffness by more than 100 times depending on the types and sizes of the mineral filler [66,67]. Dukatz and Anderson [68] reported that creep compliance is greatly increased by the stiffening of the filler. Brown et al. [55] reported that there is evidence that the optimum amount of filler content is between 4 and 8% for well-graded asphalt concrete to improve its resistance to permanent deformation.

Asphalt mixture volumetric properties (air voids, voids in mineral aggregate [VMA], and voids filled with asphalt [VFA]) have an essential role in the rutting susceptibility of HMA mixes [69]. The importance of air voids in HMA mixes is well documented in the literature. The Federal Highway Administration (FHWA) Technical Advisory on Asphalt Concrete Mix Design and Field Control [70] recommended that pavements have an in-place air voids content of 3–5% after densification by traffic. To achieve this air void content, the Technical Advisory recommends that asphalt mixes be designed with 3–5% voids at optimum asphalt content. This requirement is adopted by the Iraqi specification for HMA concrete [71].

Ford and Ford [72] studied the relationship between in-place air voids and rutting. Thirty-eight pavement sites were selected to represent various types of HMA pavements in the state of Arkansas. The pavement structure age ranged from 0.5 year to 22.7 years and the number of total accumulated 18 kip equivalent single axle loads ranged from 130,000 to 3,100,000. The rut depth of each pavement was measured before taking three inside wheel path cores using a 101.6 mm (4 in) core machine. The author stated that rutting is more severe for pavements with air voids significantly less than 3% [72].

Brown and Cross [73] observed low voids in their prematurely rutted pavements and they observed in other studies [61] that when the in-place voids were below 3%, the probability of having premature rutting was much higher than if the voids were above 3%. Huber and

Heiman (1986) found no direct correlation between voids and rutting; however, they reported that 4% voids appeared to be a threshold value with unacceptable rut depths occurring as voids fell below 4%. The relationship between voids and rutting was not well defined by Kandhal et al. [74]. However, they did report that pavements that rutted prematurely had lower in-place voids than pavements that did not rut prematurely.

Several researchers related the importance of the mix design void content to an unacceptable rate of rutting. The U.S. Army Corps of Engineers recognized the importance of voids when they developed their specifications for the Marshall mix design method. The original requirements [75] specified that the HMA should have between 3 and 5% voids at optimum asphalt content, which is still recommended today by SCRB [71]. Dawley et al. [10] concluded that HMA should be designed at 4% voids to prevent low voids in-place and hence an unacceptable rate of rutting. Miller et al. [62] concluded that the mix design void content should be raised from 2.5 to 4% to prevent premature rutting in Illinois. Ford and Hensley [76] concluded that premature rutting in Arkansas pavements was related to low mix design air void contents. Kandhal et al. [77] reported that Pennsylvania HMA with higher mix design voids experienced lower rates of rutting.

Several researchers reported good correlations between VFA and rutting susceptibility. Huber and Heiman [63] reported that the in-place VFA should be a maximum of 70% to minimize rutting; however, they qualified their statement for VFA as being lower than usually suggested and recommended further study. Ford and Ford [72] found a relationship between VFA and rutting susceptibility which showed that higher VFA lead to an increased rate of rutting. The US Army of Corps of Engineers [75] recommended that VFA be between 75 and 80% for 50 blow mixes, and 70–80%, for 75 blow mixes, based on laboratory and field studies. However, neither the FHWA [70] nor SCRB [71] gives recommendations for voids filled with asphalt cement.

The volume contained between aggregate particles in a compacted paving mix is termed the VMA. It is composed of air voids and effective asphalt volume [78]. For asphalt concrete with an aggregate maximum size of 19 mm, the SCRB specifications recommended 14% as a minimum [71]. Pradhan [79] presented data related to VMA for permanent deformation of asphalt concrete mixes, he stated that as VMA decreased, the resistance to permanent deformation increased. Huber and Heiman [80] found that HMA pavements with high VMA have higher rutting than pavements with low VMA and reported a VMA of 13.5% for mixes with an aggregate top size of 16 and 18 mm.

5 Permanent deformation characterization

5.1 Laboratory test methods

The overall objective of materials testing should be to reproduce as closely as practical *in situ* pavement conditions, including the general stress state (stress magnitude and duration), temperature, and general condition of the material. Laboratory tests usually used to characterize the permanent deformation response of asphalt concrete are typically categorized as uniaxial, triaxial, or diametral. Within those three general categories, loading may be static (creep), repeated, or dynamic [81].

Before the discussion about the properties of each test and how much it can simulate the field conditions, it is necessary to highlight the stress condition (magnitude and duration) within the pavement under the effect of moving loads. The stress condition within the asphalt concrete surface layer is varying according to the location with respect to both the axis of loading and the neutral axis. For an element away from the axis of loading symmetry, the element is subjected to three normal stresses in the direction of x , y , and z , also there are three tangential shear stresses acting on the surfaces of the equilateral element. Under these three-dimensional states of stress, unfortunately, no testing equipment is currently available which can simulate these stress conditions. Therefore, some simplification is required, if an element on the axis of load symmetry is being considered, then two simplifications will bring the stress conditions in line with those occurring in the triaxial test. The principal stresses will become vertical and horizontal (no shear stresses) and the two stresses acting horizontally in the direction of x and y will be equal. Further, along the axis of load symmetry, the state of stress varies according to the location with respect to the neutral axis, as shown in Figure 11. Also, from the same Figure, it can be shown that the vertical stress remains in a compressive state, while the horizontal stress varies from the compression above the neutral axis to tension below the neutral axis.

Application of tensile stresses to reproduce the theoretical stress condition in the bottom of the layer is quite difficult and not suitable for use in a routine design method for characterizing the permanent deformation [82]. Also, when an element of asphalt concrete in the tensile zone starts to deform laterally in the direction of the tensile stress, passive resistance would be encountered due to the presence of surrounding materials; therefore, the lateral tensile stress developed in the field would

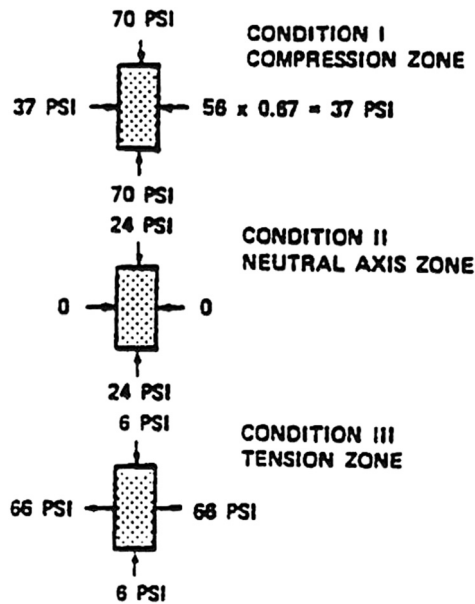


Figure 11: Average theoretical stress state for 26.67 cm (10.5 in) thick full-depth asphalt concrete pavement under the axis of loading [90].

be less than that calculated by the layered theory [82]. Near the center of the asphalt concrete at the neutral axis, the lateral stress is zero and an axial compressive state exists similar to that in the unconfined compression test [82].

The existence of a simple unconfined compressive stress state near the center of the layer suggests that such a condition can be reasonably close to the average of the tensile and compressive stress state within the entire asphalt concrete layer. This can be a practical alternative to using considerably more complicated stress states involving both tension and compression which require more sophisticated test equipment with a possibly high cost that makes attaining them by most testing laboratories difficult [81]. For the above reason, the uniaxial load test may be more practical than that of the triaxial test in characterizing the permanent deformation of the asphalt concrete.

On the other hand, the diametral test can also be used for characterizing permanent deformation, but its use does not seem promising for two major reasons:

The state of stress is nonuniform and strongly dependent on the shape of the specimen [83]. At high temperatures or high loads, permanent deformation produces changes in the specimen shape that significantly affect both the state of stress and test measurements.

Its use is restricted to relatively low testing temperatures (less than 40°C) and for low-stress levels (less than 20 PSI) [84]. Accordingly, the diametral test may be better suited to the repeated load testing associated with modulus

measurements than to the longer time periods associated with the permanent deformation characterization [84].

Although researchers agree that the non-recoverable deformation of an asphalt concrete layer in a pavement structure can be best characterized by the axial compression test, they differ on the type of loading that should be used in this test. In order to best simulate the moving wheel loads, most of the researchers prefer the use of a repetitive loads test rather than the static creep test for permanent deformation characterization, others prefer the latter due to the simplicity of the testing device. Shell researchers [13,85] who pioneered the use of the static creep test have developed their creep and rutting criteria based on the static compressive creep. Others have presented their rutting prediction models based on the repetitive load test. The VESYS model [86] and the modified ILLIPAVE model [87] are two examples of predictive models which require repetitive load testing. Researchers at the Australian Road Research Board investigated both the static creep and repetitive load tests [88]. They showed that although the magnitude of plastic deformation will be different depending on the type of loading, the irrecoverable deformation trends are similar. This conclusion is in agreement with that made by Van Der Poel [89] who describes the dynamic and static responses of bitumen. Barksdale and Miller [90] reported that a repeated load test is more sensitive to mixture variables than the creep tests. On the basis of shell creep tests, they showed that the increase in the asphalt content of a particular mixture from 4.5 to 5.5 does not have any significant effect on the rut depth. However, the results of the repeated load tests on the same mixture indicated that such an increase in asphalt content could increase the rut depth by 16% (Figure 12). When comparing his results with laboratory test track data, McLean [15] found that his creep test results under-predicted permanent deformation by a factor on the order of 25.

Some creep testing was also undertaken by Snaith [91] using repeated load tests. The applied vertical stresses and temperatures were similar to those used in the repeated load tests. The objective was to determine if the relatively simple creep test could be used to predict permanent deformation under the more complex repeated load situation. At low stresses, he found that the static and repeated load test results were similar. However, at a higher stress level, he observed that a static stress of about 65% of the repeated stress value would be required to produce the same strain at a particular time. When plotting log strain vs either log time (static creep test) or log cycle (repeated load test), Snaith found that the slope factor was the same for similar test conditions. He

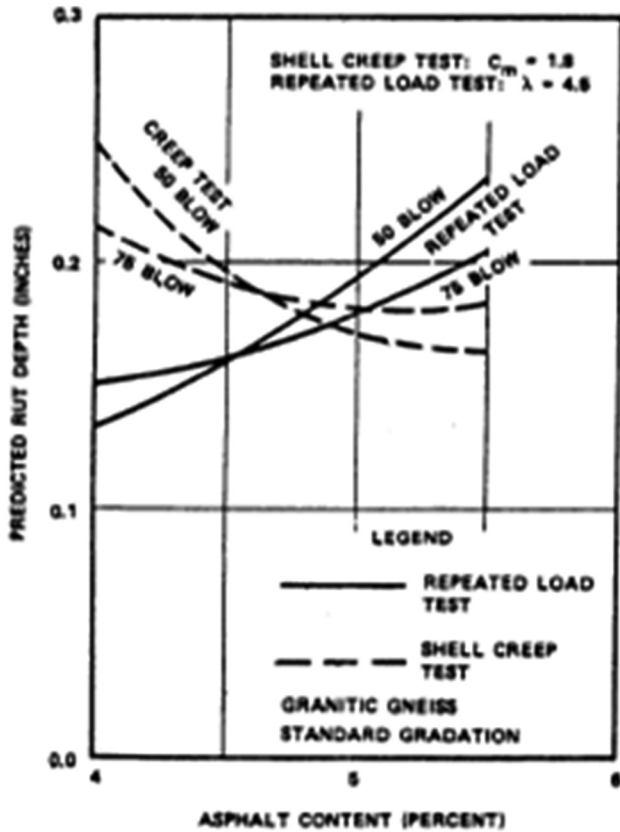


Figure 12: Comparison of rut depth predictions from repeated load and creep tests [90].

concluded that any difference in the strain behavior due to the manner of loading would be shown in the intercept value alone. He related the intercept values for the two types of tests by the equation shown below:

$$a = 1 - 0.087a_s + 0.229a_s^2, \quad (2)$$

where a = intercept value for repeated load test and a_s = intercept value for static creep test.

Chen et al. [24] indicated that the repetitive compressive test gives a more reasonable estimate for the field rutting than the creep test. He attributed this conclusion to the better simulation of the repetitive loading test to the field condition than that of the creep test, also he recommended the use of pulse time as close as possible to that occurring in the field. For laboratory testing, the shape of the load-time trace is commonly one of three forms [92]: sine, square, or triangular. Using elastic finite element theory to evaluate the shape and duration of the stress pulse, Barksdale [93] found that the vertical compressive stress pulse varies from an approximately sinusoidal one at the surface to a more nearly triangular pulse for elements near the subgrade. More specifically, for conventional pavements with surfaces up to a thickness

of about (12.5 cm), a sinusoidal stress pulse should be applied. For thicker, deep-strength, or full-depth pavements, a sinusoidal stress pulse should be used for the upper parts of the pavement. At the middle and bottom, a triangular-shaped pulse more nearly approximates the actual shape. Figure 13 shows the variation in vertical stress pulse with vehicle velocity and depth. Additionally, some of the techniques used to define the time of loading are shown in Table 2.

Finally, the researchers of SHRP [78] summarized the tests that were used to characterize the permanent deformation as presented in Table 3.

5.2 Predictive models

Numerous studies have been made to characterize the permanent deformation response of asphalt concrete materials due to repeated load applications. The studies used the repeated compressive load test to investigate the variables that influence the relationship between the number of load applications (N), and the permanent strain (ϵ_p). Rather than reviewing each in detail, the more recent research efforts are presented in tabular form (Table 4) to facilitate ease of revisions.

6 Rut depth prediction methods

With increases in axle loads, load repetitions, tire pressures, and asphalt-concrete thicknesses, a need has

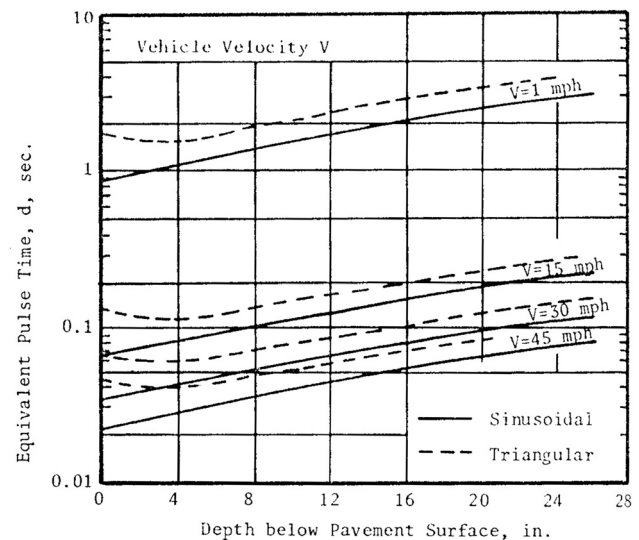


Figure 13: Speed-loading time relationship [93].

Table 2: Speed–duration relationship

Reference	Relationship
Célaré [36]	$f = \frac{s_p}{1.8}$, where f = loading frequency, and s_p = vehicle speed (km/h)
Ullidtz [94]	$t_w = \frac{(2a+h)}{s_p}$, where a = tire contact radius (m), h = asphalt layer thickness (m), and s_p = vehicle speed (m/s)
Huang [1]	$t_w = \frac{12a_r}{s_p}$, where t_w = load duration (s), a_r = tire contact radius (m), and s_p = vehicle speed (m/s)
Pereira et al. [28]	$t_w = \frac{8}{s_p}$, where s_p = vehicle speed (km/h)
Yassoub [3]	$\log(t_w) = 5 \times 10^{-4} \times h_{\text{asph}} - 0.2 - 0.94\log(s_p)$, where h_{asph} = the thickness of asphalt layer (mm), and s_p = vehicle speed (km/h)

developed for a methodology to predict rut depths in advance of construction to mitigate potential safety problems, e.g., hydroplaning [78]. Concomitant with the development of analysis procedures that permit estimates of stresses, strains, and deformations resulting from traffic

loads, pavement design systems have evolved which include provisions for rutting considerations. These have been referred to as analytically based, mechanistic, or mechanistic-empirical procedures [78]. A number of these procedures include criteria for limiting values of subgrade strain to levels that preclude

Table 3: Comparison of various test methods for permanent deformation evaluation [15]

Test method	Specimen shape	Measured characteristics	Advantage and disadvantage
Uniaxial static (creep)	Cylindrical, 4 in diameter, 8 in height	Creep modulus vs time Strain vs time	Wide spread, well known Easy to implement, equipment generally available in labs State of stress constant shear Components in the Mohr-Coulomb representation More technical information
Uniaxial repeated		Resilient modulus Permanent deformation vs cycles Poison's ratio	Better expresses traffic conditions Equipment is more complex
Uniaxial dynamic		Dynamic modulus Damping ratio Poison's ratio Permanent deformation vs cycles	Capability of determining the damping as a function of frequency for different temperatures
Triaxial static (creep confined)	Cylindrical, 4 in diameter, 8 in height	Creep modulus vs time Strain vs time	More states of stress can be obtained State of stress contains shear components in Mohr-Coulomb representation
Triaxial repeated		Resilient modulus Permanent deformation vs cycles Poison's ratio	Better expresses traffic conditions Equipment is more complex
Triaxial dynamic		Dynamic modulus Damping ratio Poison's ratio Permanent deformation vs cycles	Requires a triaxial chamber Capability of determining damping as a function of frequency for different temperatures
Test tracks	Slab	Rut profile vs number of passages In-depth strain/stress profile	State of stress duplicate field conditions Fundamental material properties cannot be obtained Good method for verification of predictive models Requires special equipment that can be costly

Table 4: Summarized overview of the permanent deformation models

Author	Permanent deformation equation	Variables	Laboratory test
Kirwan et al. [95]	$\varepsilon_n = A\Delta^b$	ε_n = induced axial permanent strain after an elapsed time N A = function of elapsed time and material b = constant for the material Δ = applied axial compression stress	Uniaxial compression dynamic loading creep test
Monismith et al. [96]	$\varepsilon_z^p = [\delta(T)N^\alpha (\bar{\sigma})^{\alpha-1} t]$ $\left[\sigma_z - \frac{1}{2}(\sigma_x + \sigma_y) \right]$	ε_z^p = vertical permanent deformation $\delta(T)$ = function of temperature α = coefficient determined experimentally N = number of stress repetitions $\bar{\sigma}$ = equivalent stress defined as a function of σ_1 , σ_2 , and σ_3 t = loading time	Repeated load triaxial compression test
Brown and Bell [97]	$\varepsilon_p = \left(\frac{q}{a}\right)^b (N)$	ε_p = permanent shear strain q = deviator stress a, b = constants N = number of load applications	Axial repeated load tests
Meyer and Haas [98]	$\varepsilon_p = F(\sigma_1, \sigma_3, T, AV, N) \pm E$	ε_p = axial permanent deformation σ_1 = vertical stress σ_3 = lateral stress T = temperature AV = air voids N = number of load applications E = error of estimate	Repeated load triaxial test
Kenis [99]	$\varepsilon_p(N) = e\mu N^{-\alpha}$	$\varepsilon_p(N)$ = permanent strain per pulse $\alpha = 1 - S$ S = slope of the line on a log-log plot of permanent strain vs N e = peak haversine load strain for a load pulse of duration (d) $\mu = IS/e$ I = intercept	Uniaxial repeated load tests
Thrower [100]	$\dot{\varepsilon}_{ij} = \frac{\sigma_{ij}}{2\eta} i + j$ $\dot{\varepsilon}_{ij} = \frac{\sigma_m}{3\chi} + \frac{(9\sigma_{ij} - \sigma_m)}{18\eta}$	$\dot{\varepsilon}_{ij}$ = rate of deformation σ_{ij} = state of stress σ_m = isotropic mean stress χ = coefficient of “volume viscosity” η = coefficient of shear velocity	
Huschek [101]	$\varepsilon_{irr} = c \cdot \sigma t^A$ $\varepsilon_{irr}(T, \Delta t_1, t) = \frac{\sigma \Delta t_1}{[\eta(T, t)]}$ $\eta(T, t) = \frac{t^{1-A}}{(c \cdot A)}$	ε_{irr} = permanent deformation c = constant A = consolidation characteristic σ = stress level η = viscosity T = temperature t = total time of loading Δt_1 = time of loading	Uniaxial creep tests, cyclic load creep test
Khedr [102]	$\frac{\varepsilon_p}{N} = A_a N^{-m}$	ε_p = permanent strain N = number of load cycles A_a = material property functions of resilient modulus and applied stress m = material parameter	Multi-step dynamic tests
Battiatto et al. [103]	$J(t) = J_1 t^\alpha$ $u_{ik}^{perm} = \frac{1}{\eta_s} g_{ik}(y, z)$	$J(t)$ = creep compliance function t = time J_1 = shear creep parameters	Uniaxial creep tests

(Continued)

Table 4: Continued

Author	Permanent deformation equation	Variables	Laboratory test
Van de Loo [108]	$\varepsilon_p = c\sigma N^a$	α = slope of line on a log-log between $J(t)$ and time u_{ik}^{perm} = permanent deformation η_s = shear viscosity of the Maxwell element in series $g_{ik}(y, z)$ = tensor function ε_p = axial permanent deformation c = constant σ = axial stress level (15 PSI) N = number of load applications a = constant	Axial creep test
Uzan [31]	$\varepsilon_p(N) = e_r \mu N^{-\alpha}$	$\varepsilon_p(N)$ = permanent strain for Nth repetition e_r = resilient strain N = number of repetitions α, μ = characteristics of materials based on intercept and slope coefficients	Repeated load testing
Leahy [92]	Statistically derived predictive models for permanent strain, ε_p $\varepsilon_p = f(T, \sigma_d, V_{air}, N, \eta_{asp}, P'_{Wasp})$	ε_p = plastic strain T = temperature σ_d = deviator stress V_{air} = volume of air η_{asp} = asphalt viscosity P'_{Wasp} = effective asphalt content	Repeated load and creep, axial testing
AASHTO [109]	$\frac{\varepsilon_p}{\varepsilon_r} = 10^{k_1 T^{k_2} N^{k_3}}$	N = number of repetitions ε_p = plastic strain ε_r = resilient strain T = temperature k_1, k_2, k_3 = regression parameters	Repeated load testing
Abed [110]	$\log \varepsilon_p = -9.473 + 0.532 \log N +$ $1.798 \log T + 0.838 \log \sigma$ $-0.672 \log \eta + 0.448 \log AC$	ε_p = permanent plastic strain N = number of load repetition T = temperature σ = stress level, psi η = viscosity, Pa s Ac = asphalt content, %	Repeated axial load test

rutting at the pavement surface. Examples include the Shell procedure [85]; the Asphalt Institute procedure [104]; and the State of Kentucky methodology [105]. Some have recommended limitations on vertical subgrade stress (rather than strain), e.g., Barksdale and Miller [90]. Others have utilized statistically based rut depth prediction equations. For example, Saraf et al. [106] presented such an equation that incorporated surface deflection as computed from elastic layered analysis. Design limitations on strain or stress are based on the assumption that if the maximum vertical compressive strain or stress at the surface of the subgrade is less than a critical value, then rutting will be limited to a tolerable level for a specified number of load applications. Unfortunately, such methodology does not necessarily preclude rutting which might occur in the

asphalt-bound layer. The Shell method [85] exemplifies a procedure that attempts to improve the above process by including additional analysis to estimate the amount of rutting occurring in the asphalt-bound layer.

This predictive methodology is an example of one of the two analytical procedures which have evolved to estimate the amount of rutting. The procedure makes use of layered system elastic analysis and represents one of a number of such procedures termed layer-strain. In this approach repeated load tests or creep tests are used to characterize the permanent deformation behavior of asphalt concrete. The second approach makes use of closed-form viscoelastic analyses to represent pavement structure with permanent deformation characterization by means of a creep test [107].

6.1 Layer-strain procedure

The layer-strain approach uses either linear or nonlinear elastic theory to analyze the pavement structure and estimate rut depths using permanent deformation features identified from laboratory studies. The basic idea behind this approach was first put forth by Barksdale [111] and Romain [112]. Although nonlinear elastic theory should produce more accurate findings [97], it has not been applied widely because of its extra complexity. Each pavement structure layer is divided into several sublayers, and the stress state is calculated at the center of each sublayer immediately beneath the wheel load using elastic analysis (Figure 14). This allows for predicting the amount of permanent deformation that would occur after a specific number of wheel load applications. Results of laboratory experiments can be used to determine the axial plastic strain associated with the average stress state at the center of each sublayer. The average plastic strain that occurs in the center of each sublayer and the corresponding sublayer thickness are added together to provide the overall rut depth for a specified number of load repetitions.

$$\Delta p = \sum_{i=1}^n [(\epsilon_{pi})(\Delta z_i)], \quad (3)$$

where Δp is the total rut depth, ϵ_{pi} is the average plastic strain in the center of the i th sublayer, Δz_i is the thickness of the i th sublayer, and n is the total number of sublayers. This approach has been adopted in various forms by many researchers and, as noted above, the Shell design methodology represents a practical example of the use of this procedure, also, the VESYS elastic approach represents another example of this method. The layer-strain method is considered a simplified engineering approach for predicting rut depth which permits the flexibility of using either linear or nonlinear elastic analysis. The following sections provide a description of the Shell and the approach used in the VESYS program.

6.1.1 Shell method

Shell researchers [14,108] have developed a practical procedure, utilizing layer-strain concepts, to predict rutting in the asphalt-bound layer. These concepts are used in a pavement design procedure to determine the plastic strain which is input to equation (6). This procedure requires (1) detailed information on mixture components, traffic, and the pavement environment; (2) a layered elastic analysis; and (3)

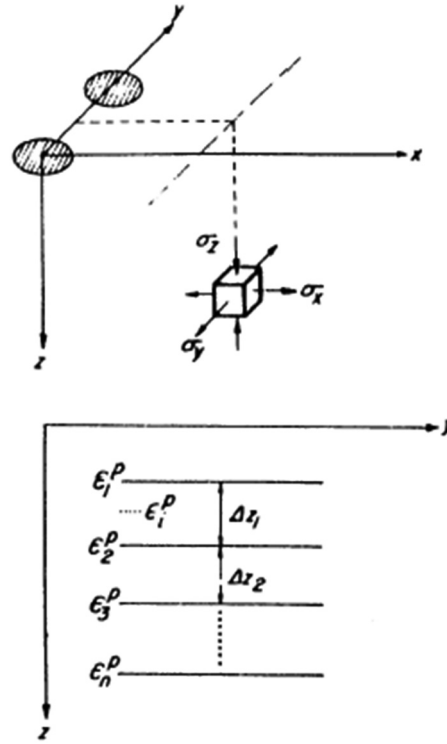


Figure 14: Diagram of pavement system used to estimate permanent deformation [78].

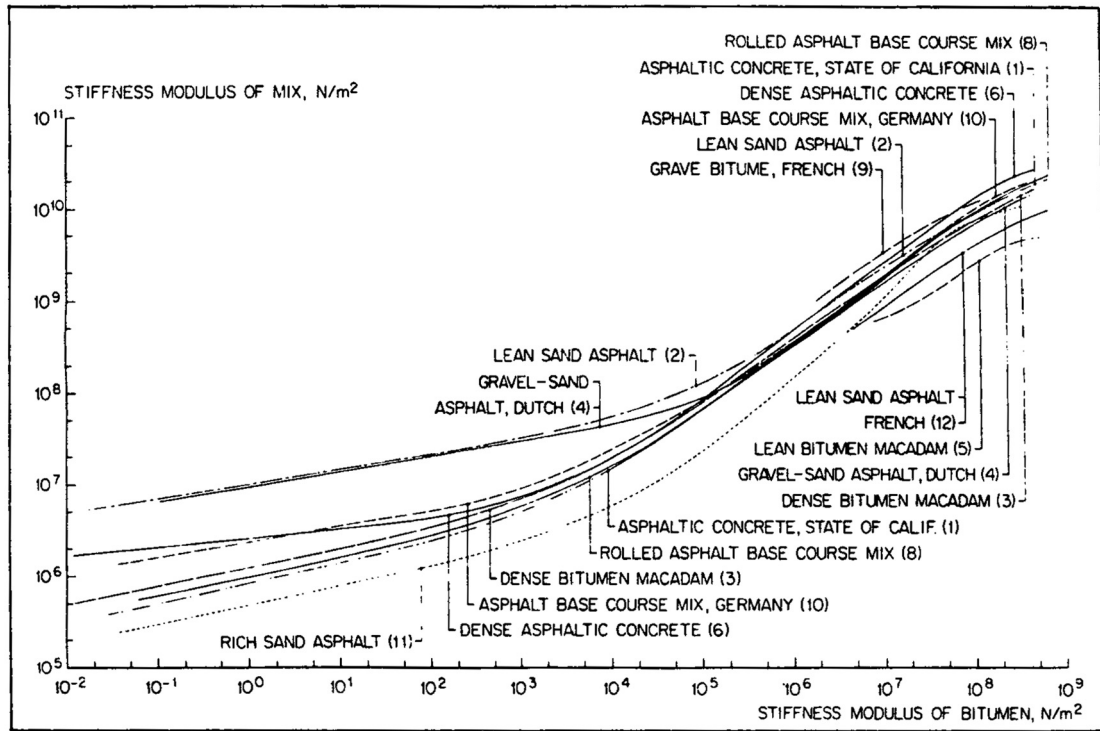
data from a simple uniaxial creep test on a specimen representative of the mixture. The basic premise is that the development of deformation in an asphalt pavement is related to that occurring in a laboratory creep test [11]. The Shell researchers have presented the results of creep tests in the form shown in Figure 15 and have demonstrated that mixture stiffness (S_{mix}) and bitumen stiffness (S_{bit}) are uniquely related, regardless of the temperature, since S_{bit} is a function of both time of loading and temperature. If a value of S_{bit} can be found corresponding to the field conditions under which the deformation occurs, the resulting S_{mix} can be found from the test curve (like those shown in Figure 15).

In this methodology, it is argued [14] that the required bitumen stiffness is the viscous component of the total stiffness, $(S_{bit})_{vis}$, which can be determined as follows:

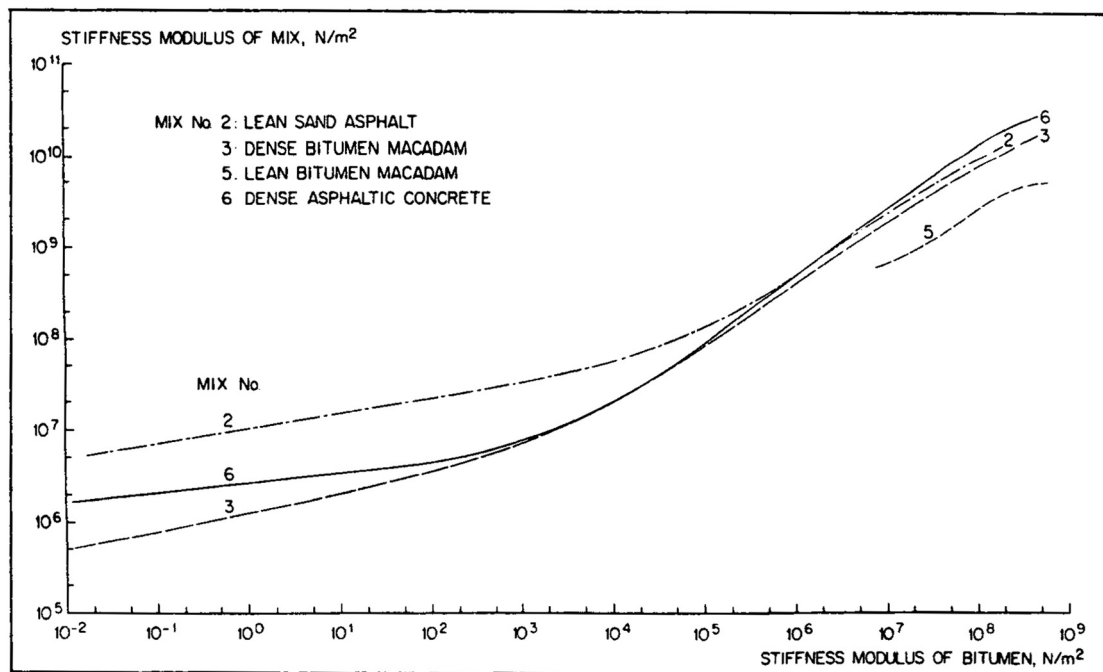
$$(S_{bit})_{vis} = \frac{3\eta}{Nt_w}, \quad (4)$$

where N is the total number of load applications, t_w is the loading time for one load application (s), and η is the viscosity of bitumen ($N\ s/m^2$).

A nomograph is provided by Shell for estimating the viscosity which requires as input the pavement temperature together with the penetration index and the



a.



b.

Figure 15: Stiffness characteristics of mixture [85]. (a) Range of mixtures. (b) Representative mixtures.

temperature corresponding to 800 pen. for the asphalt. To estimate permanent deformation in the asphalt-bound layer, the following variation in equation (3) is used:

$$\Delta h = C_m h \left(\frac{\sigma_{av}}{S_{mix}} \right), \quad (5)$$

where σ_{av} is the average stress in the bituminous layer and determined from $\sigma_{av} = Z\sigma_o$; h is the thickness of the bituminous layer; Δh is the change in thickness of the bituminous layer; S_{mix} is the value of the mixture stiffness for S_{bit} determined from equation (4) and obtained from a curve like that shown in Figure 15; C_m is a correction factor; Z is a coefficient determined using layered elastic analysis; and σ_o is the contact stress between tire and pavement.

The procedure for using equation (5) [85] requires that σ_{av} is determined by applying a “Z” factor (determined using the BISAR program for computation of stresses and strains in a multilayer elastic system) to σ_o , the contact stress between tire and pavement. Also, the method divides the bituminous layer(s) into three sublayers ($h_1 = 4$ cm, $h_2 = 4$ cm, and $h_3 =$ total asphalt thickness = 8 cm) and calculates the deformation in each, requiring appropriate S_{mix} and σ_{av} values for each of the sublayers.

As emphasized by Claessen et al. [85], a considerable error could result if an inappropriate S_{mix} vs S_{bit} curve is used. The S_{mix} vs S_{bit} should be determined from a creep test on a core of material, or by correlations between laboratory specimens and field cores. In the event that such data are not available, the Shell researchers have presented three creep curves representative of different mixture types, the selection of one of these curves for the analysis depends on the judgment of the designer. Mahboub [39] stated that there are two major drawbacks associated with the Shell prediction equation, these are as follows:

1. The stiffness parameter, S_{mix} , is a pseudo-elastic parameter, and it is used in a Hook’s law format as follows:

$$\text{Strain} = \frac{\text{Stress } (Z\sigma_o)}{\text{Stiffness } (S_{mix})}. \quad (6)$$

It is extremely important to remember that the above format only holds true for elastic (recoverable) deformations. As a result, using the total stiffness parameter, S_{mix} , which represents the combination of elastic, plastic, viscoelastic, and viscoplastic responses in a Hook’s law format for rutting prediction, is not valid [39].

2. Another serious consequence of using a Hookean constitutive relationship for permanent deformation characterization is the assumption of linearity. Mahboub

[39] states that the accumulation of permanent strains is not linearly proportional to the stress level, further he states that this relationship is of log-linear form.

6.1.2 VESYS method

The FHWA, Austin Research Engineers, and Massachusetts University of Technology all contributed to the ongoing development of VESYS, a probabilistic and mechanistic flexible pavement analysis system [1]. Primary response, general response, damage, and performance model are the four main interaction models that are included. The basic response model uses either the elastic approach (material characterized by resilient modulus and Poisson’s ratio) or the viscoelastic method to determine the layered system response (stress, strain, and deflection) (material characterized by creep compliance). The damage model includes three sub-models for the prediction of cracking, rut depth, and roughness under static loading, which incorporates the influence of moving load using Boltzmann’s principles. To determine how the PSI will change over the analysis period, the calculated values for these distresses are used as input for the performance model [1]. The VESYS system is a computer software; VESYS 5, is the most recent version. The layer and system rutting options are available in this version’s rut depth predictive sub-model. The system rutting option takes into consideration subgrade rutting. It uses the total deflection in the pavement surface to determine the total rut depth for the entire system, as opposed to the layer rutting option, which calculates the rut depth for each layer in the pavement structure [113].

Based on the power relationship of ϵ_p - N of the asphalt concrete shown in equation (7), below

$$\epsilon_p = aN^b, \quad (7)$$

where ϵ_p = permanent strain, N = number of stress applications, a = intercept coefficient, b = slope coefficient,

the permanent strain for the N th repetition can be calculated as follows [92]:

$$\epsilon_p(N) = \epsilon_t(N) - \epsilon_r(N) = \epsilon_r N^{-a}, \quad (8)$$

where $\epsilon_p(N)$ = permanent strain for N th repetition, $\epsilon_t(N)$ = total strain for N th repetition, $\epsilon_r(N)$ = resilient strain for N th repetition (assumed to be independent of N).

Assuming linear stress–strain behavior during the loading and unloading cycles with $E_{loading} \neq E_{unloading}$, the total and resilient strain can be written as follows:

$$\epsilon_{tz} = \frac{1}{E_{lo}(N)} [\sigma_z - \gamma (\sigma_x + \sigma_y)] = \frac{\sigma'_z}{E_{lo}(N)}, \quad (9)$$

$$\varepsilon_{tz} = \frac{1}{E_{un}(N)} [\sigma_z - \gamma (\sigma_x + \sigma_y)] = \frac{\sigma'_z}{E_{un}(N)}, \quad (10)$$

where ε_{tz} = total axial strain for N th repetition, ε_{tz} = resilient axial strain for N th repetition, σ_z = axial stress, σ_x and σ_y = radial stresses, $E_{lo}(N)$ = modulus during loading cycle for N th repetition, E_{un} = modulus during unloading cycle, γ = Poisson's ratio, and σ'_z = resultant axial stress.

By substitution of equations (9) and (10) in equation (8), we get

$$\sigma'_z \left(\frac{1}{E_{lo}(N)} - \frac{1}{E_{un}} \right) = \left(\frac{\sigma'_z}{E_{un}} \right) \mu N^{-\alpha}. \quad (11)$$

By solving equation (11) for $E_{lo}(N)$ yields the following:

$$E_{lo}(N) = \frac{E_{un}}{1 + \mu N^{-\alpha}}. \quad (12)$$

The main assumptions included in the program are:

1. Poisson's ratio is constant for both loading and unloading conditions.
2. ε_r , and consequently E_{un} , is independent of the number of load repetitions.

The model of equation (12) is used to evaluate rutting in the asphalt concrete layer as follows:

1. Determine the value of resilient modulus, E_{un} .
2. For a specific value of N , determine the value of $E_{lo}(N)$.
3. Using $E_{lo}(N)$ in a multilayer elastic solution, compute the deflections due to loading ($\delta_{lo}(N)$) and unloading (δ_{un}).
4. Compute the rut depth for the N th load repetition, $Rd(N) = \delta_{lo}(N) - \delta_{un}$.
5. Repeat steps 2 through 4 for the specific value of N .
6. Compute the total rut depth for N repetitions as follows:

$$Rd = \int_{i=1}^N Rd(N) dN. \quad (13)$$

Omer [114] states that the use of the VESYS sub-model for rut depth prediction of full depth asphalt concrete over silty clay subgrade yield results that are compared favorably with the measured rut depth, as shown in Figure 16.

6.2 Viscoelastic approach

In this approach, moving wheel loads can be considered in conjunction with time-dependent material properties to define the states of stress and strain at particular points in the pavement structure. Material properties can be defined either in terms of models consisting of finite numbers of Maxwell and/or Kelvin elements in various arrangements or in terms of generalized compliance relationships. An important advantage of this approach is that moving wheel loads can be considered directly. This results in the correct time rate of loading to be applied to each material element and permits estimates to be made of the lateral plastic flow of material from beneath the moving wheel. While non-linear viscoelastic response characteristics may provide a more realistic estimate of pavement response, the associated mathematical complexities have limited past analyses to linear characterizations [115,116]. In this approach, material properties within a given layer are assumed to be the same throughout the layer regardless of whether the material is in tension or compression. Another example of this methodology is embodied in the VESYS procedure [99]. If a viscoelastic analysis is used, a generalized linear viscoelastic response is tractable, and several authors have used or proposed this method [117]. The calculations tend to be time-consuming; however, the assumption of linearity itself is questionable [100]. A nonlinear viscoelastic model seems even more prohibitive, in terms of both computational effort and the scale of laboratory work necessary to establish appropriate nonlinear, time-dependent constitutive equations. A viscoplastic theory, coupled with the use of

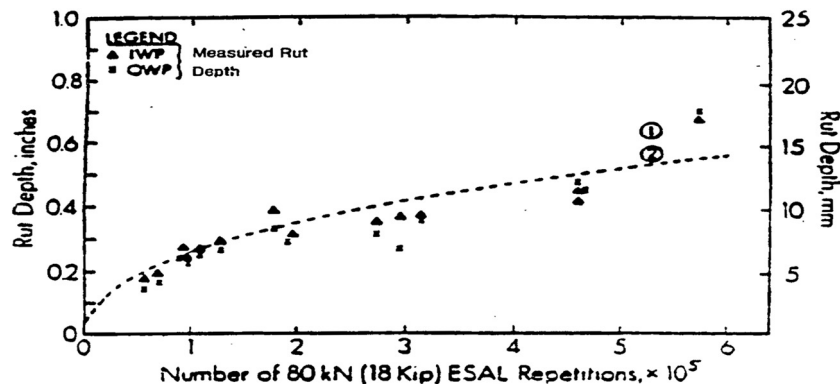


Figure 16: Rut depth prediction [114].

finite-element methods [100] seems to have the same drawbacks. More recently, Thrower et al. [118] and Nunn [119] have suggested that using estimates of the accumulation of permanent deformation on viscous properties of asphalt concrete has the potential to provide reasonable estimates of rutting.

6.3 Artificial neural network approach

An artificial neural network is a parallel information processing system that has certain performance characteristics similar to biological neural networks. A neural net consists of a large number of simple processing elements called neurons. Each neuron is connected to other neurons by means of directed links, each directed link has a weight associated with it. The weights acquired through the training process represent abstracted information from the dataset, which is used by the net to solve a particular problem. In order to construct a neural network for solving a particular problem, three key components need to be determined first. They are (1) architecture, (2) learning method, and (3) neuron activation function [120,121].

According to Oh and Barham [122], an efficient method for capturing the non-linear modeling functions to predict the rutting of asphalt materials is the artificial neural network backpropagation algorithm. In their study [123], Mirabdolazimi and Shafabakhsh found that their constructed artificial neural network model for the prediction of rut depth corroborated the experimental findings quite well. The pavement condition index was modeled by Amin and Amador-Jimenez [124] using the backpropagation neural network technique. According to Shafabakhsh et al. [125], rutting for asphalt mixtures containing nano-additives can be predicted using the backpropagation algorithm. A permanent deformation model was created by Haddad et al. [126] using data taken from the LTPP database and a deep neural network. When compared to models found in the current literature, the results showed that the extended model had improved predictive power.

7 Minimizing rutting in asphalt concrete pavement

Valuable and many efforts have been made by researchers in the past years to reduce the rutting mode of distress in

asphalt concrete mixtures, and they have varied in nature from controlling the components of the asphalt concrete mixture to the use of additives, as well as the use of new types of sustainable asphalt concrete mixtures. Results of the laboratory investigation conducted by Button et al. [127] showed that the chief mixture deficiencies contributing to rutting were excessive asphalt content, excessive fine aggregate (sand-size particles), and the round shape and smooth texture of the natural (uncrushed) aggregate particles. The researchers suggested increasing voids in mineral aggregate requirements (14–15% minimum), replacing most or all natural sands with manufactured particles, increasing minimum allowable air voids in the laboratory-compacted mix to 4%, and limiting the filler-to-bitumen ratio to about 1.2. On the bases of natural sand, Albayati and Abdulsattar [128] recommended that the highway-specifying agencies should consider limiting the natural (uncrushed) particle content of asphalt mixes in high-volume pavement facilities to about 10–15%, depending on other characteristics of the mixture.

Other researchers [129] focused on the enhancement of the rheological properties of asphalt cement to mitigate the rutting in asphalt concrete since the asphalt binder characteristics account for around 40% of the performance of asphalt pavements with regard to permanent deformation [130].

Hamid et al. [131] indicated that the addition of 8% glass fiber (GF) to the neat binder enhanced the rutting resistance of the asphalt mixture, which reduced the rut depth by 55%. The combination of the styrene butadiene styrene (SBS) and GF (2% SBS + 8% GF) reduced the rut depth to 82% as compared to the control mix with neat asphalt cement. Other types of polymers were also tried by researchers and show distinct results, Bulatovic et al. [132] used ethylene copolymer. Epoxy resin showed excellent resistance to permanent deformation [133]. High-modulus modifiers exhibited better resistance to rutting as compared to the control mix [134].

Also, hydrated lime which has been categorized as a major additive in asphalt pavement because of its wide availability and relatively cheap cost, when implemented in a dosage of 2.5% by weight of aggregate has shown premium resistance to rutting [135]. The same additive when used in the nanoscale at a dosage of 1.5% enhanced the resistance for rutting [136]. Other nanomaterials were also tried by researchers and showed promising results. Aljbouri and Albayati [137] investigated the use of nanomaterial, including nano silica (NS), nano carbonate calcium (NCC), nano clay (NC), and nanoplatelet hydroxyapatite (NP), the results revealed that nanomaterials significantly improved the resistance of rutting.

The Enrobés à Module Elevé or simply high-modulus asphalt which was developed in France as a high-performance mixture for use in heavy-duty pavements also exhibits premium resistance to permanent deformation as compared to conventional dense graded asphalt concrete mixture [138]. Also, some studies have shown that stone mastic asphalt (SMA) mixture has high resistance to deformation with high coarse aggregate content interlocked to form a stone skeleton that is more durable and rutting resistant than the conventional asphalt mixtures [139–141]. Sustainable warm mix asphalt (WMA) is currently gaining popularity due to increasing material prices coupled with more acute environmental awareness and the implementation of regulation which has driven a strong movement toward the adoption of sustainable material. According to many investigations, the permanent deformation resistance of WMA was frequently greater than that of the control HMA mixture due to the lower mixing temperature and shorter binder aging times [69,142,143]. The improvement in the rutting resistance of WMA was influenced by the type of warm additive, mixes having additives such as Asphamin® and Evotherm® revealed comparable rutting resistance to the control mixture.

8 Conclusion

Rutting in asphalt concrete occurs in one of the following types: wear rutting which is due to the progressive loss of coated aggregate particles from the pavement surface, structural rutting due to permanent deformation in the subgrade, and instability rutting in asphalt concrete layers. The mechanism of instability rutting is the densification (decrease in volume and, hence, increase in density) and lateral displacement (shear deformation) of material within the pavement asphaltic concrete layers. According to the AASHTO guide [17], rutting is classified based on the severity level to low (6–13 mm), medium (13–25 mm), and high (more than 25 mm). The increased tire inflation pressure has placed the HMA mixture near the surface under high stresses, through increase in the probability of rutting. Rutting is more prevalent in hot climate areas because the viscosity of the asphalt binder which is inversely related to rutting is significantly reduced with the increase in temperature, the rut depth increases by a factor of 250 when the temperature increases from 20 to 60°C (from 68 to 140°F). Asphalt concrete mixture components, asphalt cement, aggregate quality and gradation, and asphalt content have a great effect on HMA rutting problem. The laboratory tests usually used to characterize the permanent deformation response of asphalt

concrete are typically categorized as uniaxial, triaxial, or diametral, within those three general categories loading may be static (creep), repeated, or dynamic. Also, the wheel track test is usually used to evaluate the rut depth in asphalt concrete mixtures, this type of test is gaining popularity as it is best to simulate the traffic condition.

Many efforts have been made to employ a variety of methodologies to create a rutting prediction model that takes into account a variety of effective factors. Mainly, a power permanent strain law showed a promising result when employed in the framework of elastic layer-strain procedure. Also, another approach makes use of closed-form viscoelastic analyses to represent pavement structure with permanent deformation characterization by means of creep test. A computer program, for instance, VESYS, also could be served as a good tool to predict rut depth using the elastic layered-strain procedure and the asphalt concrete characterized by Alpha and Mu. Recently, Artificial Neural Network Approach is used to predict the rutting in asphalt concrete mixtures.

Finally, a series of proposals and recommendations were explored to improve the rutting resistance of asphalt concrete pavements based on the findings of the available literature. The use of different kinds of polymers, hydrated lime with regular size or nano size, nanomaterials like NS, NCC, NC, and NP could minimize the rutting in asphalt concrete mixtures. Also, the high-modulus asphalt concrete, SMA as well as the sustainable warm mix frequently showed better resistance to rutting in comparison with the conventional HMA asphalt.

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References

- [1] Huang YH. Pavement analysis and design. Upper Saddle River, NJ: Pearson Prentice Hall; 2004.
- [2] AASHTO. Report of the AASHTO joint task force on rutting. American Association of State Highway and Transportation Officials; 1989.
- [3] Yassoub N. Prediction model of rutting potential in flexible pavements. Ph. D thesis, Civil Engineering, University of Baghdad; 2005.
- [4] Albayati A. Permanent deformation prediction of asphalt concrete under repeated loading. Iraq: University of Baghdad; 2006. p. 129.
- [5] Goetz WH, McLaughlin JF, Wood LE. Load deformation characteristics of bituminous mixtures under various conditions of loading. USA: Association of Asphalt Paving Technologists (AAPT); 1957.
- [6] Morris J. The prediction of permanent deformation in asphalt concrete pavements. USA: The Transport Group; 1973.

- [7] Hofstra A, Klop A, editors. Permanent deformation of flexible pavements under simulated road traffic conditions. Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept 11–15, 1972; 1972.
- [8] Majidzadeh K, Bayomy F, Khedr S. Rutting evaluation of subgrade soils in Ohio. *Transp Res Rec.* 1978;671:75–84.
- [9] White TD. Contributions of pavement structural layers to rutting of hot mix asphalt pavements. Washington, DC, USA: Transportation Research Board; 2002.
- [10] Dawley C, Hogewiede B, Anderson K. Mitigation of instability rutting of asphalt concrete pavements in Lethbridge, Alberta, Canada (with discussion and closure). *J Assoc Asph Paving Technologists.* 1990;59.
- [11] Hills J. Creep of asphalt mixes. *J Inst Pet.* 1973;59(570):247–62.
- [12] Davis RL. Relationship between the rheological properties of asphalt and the rheological properties of mixtures and pavements. USA: ASTM International; 1987.
- [13] Van de Loo P, editor. Creep testing, a simple tool to judge asphalt mix stability. USA: Association of Asphalt Paving Technologists Proc; 1974.
- [14] Van de Loo P, editor. Creep test: A key tool in asphalt mix design and in the prediction of pavement rutting. USA: Association of Asphalt Paving Technologists Proc; 1978.
- [15] McLean DB. Permanent deformation characteristics of asphalt concrete. Berkeley: University of California; 1974.
- [16] Bissada AF. Compactibility of asphalt paving mixtures and relation to permanent deformation. *Transp Res Rec.* 1983;911:1–10.
- [17] Officials T. AASHTO Guide for Design of Pavement Structures, 1993. Aashto; 1993.
- [18] Betenson W, Hanson D, Jones W, Mayruth J, Rask R, Tea R, et al. Asphalt Pavement Rutting-Western States; (No. FHWA-TS-84-211 Final Rpt.), USA; 1984.
- [19] Croney D, Croney P. The design and performance of road pavements. 2nd ed. UK: McGraw-Hill, Inc.; 1991.
- [20] Middleton DR, Roberts FL, Chira-Chavala T. Measurement and analysis of truck tire pressures on Texas highways. *Transp Res Rec.* 1986;1070:1–8.
- [21] Thompson MR, editor. Analytical methods for considering tire pressure effects in pavement design. Proceedings, AASHTO Symposium/Workshop on High Pressure Truck Tires, Austin, TX; 1987.
- [22] Hudson SW, Seeds SB. Evaluation of increased pavement loading and tire pressures. *Transp Res Rec.* 1988;1207.
- [23] Al-Mosawe H, Thom N, Airey G, Al-Bayati A. Predicting asphalt mechanical properties as a function of aggregate packing. USA: TRB 95th Annual Meeting; 2016.
- [24] Chen DH, Lin HH, Hugo F. Application of VESYS3AM in characterization of permanent deformation. *Int J Pavement Eng.* 2000;1(3):171–92.
- [25] Ahlrich RC. Influence of aggregate gradation and particle shape/texture on permanent deformation of hot mix asphalt pavements. USA: Auburn University; 1995.
- [26] Vallerger BA, Tayebali AA, Monismith CL. Early rutting of asphalt concrete pavement under heavy axle loads in hot desert environment: case history. *Transp Res Rec.* 1995;1473(10):25.
- [27] Abbas AS, Albayati AH, Alani H. The transition to a PG grading system for asphalt cement in Iraq. *J Eng.* 2010;16(4):5911–31.
- [28] Pereira PA, Pais JC, Sousa JB. Modeling the effect of truck speed on permanent deformation of asphalt concrete mixes. USA: TRB 78th Annual Meeting; 1999.
- [29] Fwa TF, Tan SA. Laboratory evaluation of rutting potential of asphalt mixtures. USA: ASTM International; 1992.
- [30] Albayati AK, Saadi A, editors. Influence of axle overload on the performance of local flexible pavement. 7th Scientific Engineering and 1st International Conference “Recent Trends in Engineering Sciences and Sustainability”; 2017.
- [31] Uzan J, editor. Prediction of rut depth performance in flexible highway pavements. Association of Asphalt Paving Technologists Proceedings; 1983.
- [32] Al-Juraiban S, Jimenez RA. Rutting properties of a dune-sand paving mixture. USA: TRB; 1983.
- [33] Eisenmann J, Hilmer A, editors. Influence of wheel load and inflation pressure on the rutting effect at asphalt-pavements: experiments and theoretical investigations. International Conference on the Structural Design; 1987.
- [34] Albayati AH. Influence of temperature upon permanent deformation parameters of asphalt concrete mixes. *J Eng.* 2017;23(7):14–32.
- [35] Linden F, Van Der Heide J, editors. Some aspects of the compaction of asphalt mixes and its influence on mix properties (with discussion). Association of Asphalt Paving Technologists Proc; 1987.
- [36] Célaré B, editor. Esso road design technology. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [37] Tayebali AA, Goodrich JL, Sousa JB, Monismith CL. Relationships between modified asphalt binders rheology and binder-aggregate mixture permanent deformation response (with discussion). *J Assoc Asph Paving Technologists.* 1991;60.
- [38] Bonnot J. Asphalt aggregate mixtures. *Transp Res Rec.* 1986;1096:42–51.
- [39] Mahboub K. Rutting characterization in an improved asphalt concrete mix design procedure for the state of Texas. USA: Texas A&M University; 1988.
- [40] Speer T, editor. Laboratory Traffic Tests of Miniature Asphalt Highways. Proceedings; 1962.
- [41] Leahy RB, Witczak MW. The influence of test conditions and asphalt concrete mix parameters on permanent deformation coefficients alpha and mu (with discussion). *J Assoc Asph Paving Technologists.* 1991;60.
- [42] Monismith C, Epps J, Finn F, editors. Improved asphalt mix design (with discussion). Association of Asphalt Paving Technologists Proc; 1985.
- [43] Decker DS, Goodrich JL, editors. Asphalt cement properties related to pavement performance. Association of Asphalt Paving Technologists Proc; 1989.
- [44] Hughes C, Maupin G, editors. Experimental bituminous mixes to minimize pavement rutting. Association of Asphalt Paving Technologists Proceedings Technical Sessions, 1987, Reno, Nevada, USA; 1987.
- [45] Keyser JH, Ruth BE. Analysis of asphalt concrete test road sections in the province of Quebec, Canada. *Transp Res Rec.* 1984;968.

- [46] Weeks W, MELLOR M, editors. US army cold regions research and engineering laboratory, Hanover, NH 03755, USA. Iceberg Utilization. Proceedings of the First International Conference and Workshops on Iceberg Utilization for Fresh Water Production, Weather Modification and Other Applications Held at Iowa State University, Ames, Iowa, USA, October 2–6, 1977; 2013. Elsevier.
- [47] Monismith CL, Tayebali A, editors. Permanent deformation (rutting) considerations in asphalt concrete pavement sections (with discussion and closure). Association of Asphalt Paving Technologists Proc; 1988.
- [48] Arabia BJ. Laboratory and field study of pavement rutting in Saudi Arabia. *Transp Res Rec.* 1990;1259:79.
- [49] Brown E, Prowell B, Cooley A, Zhang J, Powell R. Evaluation of rutting performance on the 2000 NCAT test track (with discussion). *J Assoc Asph Paving Technologists.* 2004;73.
- [50] Mahboub K, Little D. Improved asphalt concrete design procedure. *Research Rep 474-1F*; 1988.
- [51] El-Basyouny M, Mamlouk M, editors. Effect of aggregate gradation on rutting potential of Superpave mixes. In *The 8th Annual Meeting of the Transportation Research Board.* Washington, DC: Transportation Research Board; 1999.
- [52] Parker F, Brown ER. Effects of aggregate properties on flexible pavement rutting in Alabama. USA: ASTM International; 1992.
- [53] Perdomo D, Button J. Identifying and correcting rut-susceptible asphalt mixtures. *Final Report*; 1991.
- [54] Kalcheff I, Tunnicliff D, editors. Effects of crushed stone aggregate size and shape on properties of asphalt concrete (with discussion). Association of Asphalt Paving Technologists Proceedings; 1982.
- [55] Brown ER, Crawley A, McRae J. Effect of aggregates on performance of bituminous concrete. USA: ASTM International; 1989.
- [56] Kandhal PS. Design of large stone asphalt mixes to minimize Rutting. *NCAT Report No. 90-1*, USA; 1990.
- [57] Brown E, Bassett CE. Effects of maximum aggregate size on rutting potential and other properties of asphalt-aggregate mixtures. *Transp Res Rec.* 1990;1259:107–19.
- [58] Moore R, Welke R. Effects of fine aggregate on stability of bituminous mixes. Michigan Department of State Highways and Transportation. *Res Rep.* 1979;78.
- [59] Marker V. Tender mixes: the causes and the Cures. USA: Asphalt Institute; 1977.
- [60] Crawford C. Tender mixes: probable causes, possible remedies (Revised And Reprinted); 1989.
- [61] Brown ER, Cross SA. Comparison of laboratory and field density of asphalt mixtures. Auburn, AL, USA: National Center for Asphalt Technology; 1991.
- [62] Miller JW, Monroney H, Traylor M, editors. Illinois develops stable mixes. Association of Asphalt Paving Technologists Proc; 1988.
- [63] Huber G, Heiman G. Effect of asphalt concrete parameters on rutting performance: a field investigation. Canada: Transportation Association of Canada (TAC); 1986.
- [64] Grau RW. Utilization of marginal construction materials For LOC: US Army Engineer Waterways Experiment Station; 1979.
- [65] S. Carpenter TF. An analytical study of bituminous mixtures used as overlays on concrete pavements. U.S.: FHWA, Department of Transportation, FHWA; 1984.
- [66] Kallas B, Puzinauskas V, Krieger H. Mineral fillers in asphalt paving mixtures. *Highw Res Board Bull.* 1962;329.
- [67] Anderson DA, Goetz WH Mechanical behavior and reinforcement of mineral filler-asphalt mixtures. USA: Joint Highway Research Project, prude university; 1973.
- [68] Dukatz EL, Anderson DA, editors. The effect of various fillers on the mechanical behavior of asphalt and asphalt concrete. Association of Asphalt Paving Technologists Proceedings; 1980.
- [69] Albayati A, Wang Y, Wang Y, Haynes J. A sustainable pavement concrete using warm mix asphalt and hydrated lime treated recycled concrete aggregates. *Sustain Mater Technol.* 2018;18:e00081.
- [70] Heinz R. Asphalt concrete mix design and field control. *Fed Highw Administration FHWA Technical Advisory.* 1988;5040:27.
- [71] SCRB/R9. General Specification for Roads and Bridges, Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges, Ministry of Housing and Construction, Republic of Iraq; 2003.
- [72] Ford Jr M. Pavement densification related to asphalt mix characteristics. USA: Transportation research record; 1988.
- [73] Brown E, Cross S. A study of in-place rutting of asphalt pavements. USA: National Center for Asphalt Technology. Vol. 58; 1989.
- [74] Kandhal P, Cross S, Brown E. Evaluation of bituminous pavements for high pressure truck tires. *Final Report*; 1990.
- [75] McFadden G, Ricketts WC, editors. Design and control of asphalt paving mixtures for military installations. Proceedings, The Association of Asphalt Paving Technologists; 1948.
- [76] Ford Jr M, Hensley M, editors. Asphalt mixture characteristics and related pavement performance (with discussion). Association of Asphalt Paving Technologists Proc; 1988.
- [77] Kandhal PS, Cross SA, Brown E. Evaluation of bituminous pavements for high pressure truck tires. Auburn University; 1990.
- [78] Sousa J, Craus J, Monismith C. Summary report on permanent deformation in asphalt concrete. Strategic Highway Research Program. National Research Council (US), Washington, DC; 1991.
- [79] Pradhan MM. Permanent deformation characteristics of asphalt-aggregate mixtures using varied materials and molding procedures with Marshall method. USA: Montana State University; 1995.
- [80] Huber G, Heiman G, editors. Effect of asphalt concrete parameters on rutting performance: a field investigation (with discussion). Association of Asphalt Paving Technologists Proc; 1987.
- [81] Leahy R, McGennis R. Asphalt mixes: Materials, design and characterization. *J Assoc Asph Paving Technologists.* 1999;68:70–127.
- [82] Barksdale RD, editor. Practical application of fatigue and rutting tests on bituminous base mixes. Association of Asphalt Paving Technologists Proc; 1978.
- [83] Sousa JB, Craus J, Monismith CL. Summary report on permanent deformation in asphalt concrete. Washington, D.C.: SHRP; 1991.

- [84] Law TL. Resilient modulus of asphalt concrete mixtures. M.Sc. Thesis, University of Manitoba, Canada; 2004.
- [85] Claessen A, Edwards J, Sommer P, Uge P, editors. Asphalt pavement design-the shell method. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [86] Kenis WJ. Predictive design procedures, VESYS users manual: An interim design method for flexible pavements using the VESYS structural subsystem. United States: Federal Highway Administration; 1978.
- [87] Tseng KH, Lytton RL. Prediction of permanent deformation in flexible pavement materials. *Implic Aggreg Design, Constr Perform Flex Pavements ASTM STP*. 1989;1016:154–72.
- [88] Kinder D. A study of both the viscoelastic and permanent deformation properties of a New South Wales Asphalt, 13th Australian Road Research Board. New South Wales, Australia; 1986.
- [89] Van Poel CD. A general system describing the visco-elastic properties of bitumens and its relation to routine test data. *J Appl Chem*. 1954;4(5):221–36.
- [90] Barksdale RD, Miller J, II. Development of equipment and techniques for evaluating fatigue and rutting characteristics of asphalt concrete mixes. USA: GDOT Research Project 7305; 1977.
- [91] Snaith MS. Deformation characteristics of dense bitumen macadam subjected to dynamic loading. UK: University of Nottingham; 1973.
- [92] Leahy RB. Permanent deformation characteristics of asphalt concrete. College Park: University of Maryland; 1989.
- [93] Barksdale RD. Compressive stress pulse times in flexible pavements for use in dynamic testing. *Highw Res Rec*. 1971;345(4):32–44.
- [94] Ullidtz P, editor. A fundamental method for prediction of roughness, rutting and cracking of pavements. *Association of Asphalt Paving Technologists Proceedings*; 1979.
- [95] Kirwan R, Snaith M, Glynn T, editors. A computer based subsystem for the prediction of pavement deformation. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [96] Monismith C, Inkabi K, Freeme C, McLean D, editors. A subsystem to predict rutting in asphalt concrete pavement structures. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [97] Brown S, Bell C, editors. The prediction of permanent deformation in asphalt pavements. *Association of Asphalt Paving Technologists Proceedings*; 1979.
- [98] Meyer F, Haas R, editors. A working design subsystem for permanent deformation in asphalt pavement. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [99] Kenis WJ, editor. Predictive design procedures – A design method for flexible pavements using the VESYS structural subsystem. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [100] Thrower E, editor. Methods of predicting deformation in road pavements. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [101] Huscsek S, editor. Evaluation of rutting due to viscous flow in asphalt pavements. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [102] Khedr SA. Deformation mechanism in asphaltic concrete. *J Transp Eng*. 1986;112(1):29–45.
- [103] Battiatto G, Ronca G, Verga C, editors. Moving loads on a viscoelastic double layer: Prediction of recoverable and permanent deformations. Volume I of Proceedings of 4th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 22–26, 1977; 1977.
- [104] Shook J, editor. Thickness design of asphalt pavements-the Asphalt Institute method. *Proc 5th Int Conf on the Structural Design of Asphalt Pavement*; 1982.
- [105] Southgate HF, Deen RC, Havens JH, Drake WB. Kentucky research: A flexible pavement design and management system. *Proceedings, Fourth International Conference on Structural Design of Asphalt Pavements, Vol. II, the University of Michigan, Ann Arbor, Michigan, USA*; 1976.
- [106] Saraf C, Smith W, Finn F. Rut depth perception. *Transp Res Rec*. 1976;616.
- [107] Monismith C. Rutting prediction in asphalt concrete pavements. *Transp Res Rec*. 1976;616.
- [108] Van de Loo P. Practical approach to the prediction of rutting in asphalt pavements: the Shell method. *Transp Res Rec*. 1976;616.
- [109] Officials T. Mechanistic-empirical pavement design guide: A manual of practice. Washington, DC, USA: AASHTO; 2008.
- [110] Abed AH. Required criteria for Implementation of the Superpave System in Local Pavement Design. Ph. D. Thesis. Civil Engineering department, Collage of Engineering. Baghdad, Iraq; 2010.
- [111] Barksdale RD, editor. Laboratory evaluation of rutting in base course materials. Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept 11–15, 1972; 1972.
- [112] Romain J, editor. Rut depth prediction in asphalt pavements. Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept 11–15, 1972; 1972.
- [113] Kenis W, Wang W, editors. Calibrating mechanistic flexible pavement rutting models from full scale accelerated tests. *Eighth International Conference on Asphalt Pavements Federal Highway Administration*; 1997.
- [114] Omer MS. Prediction of performance of flexible pavements using VESYS IIIA structural subsystem. USA: North Carolina State University; 1984.
- [115] Barksdale RD, Leonards G, editors. Predicting performance of bituminous surfaced pavements. *Intl Conf Struct Design Asphalt Pvmnts*; 1967.
- [116] Elliott J, Moavenzadeh F. Analysis of stresses and displacements in three-layer viscoelastic systems. *Highw Res Rec*. 1971;345.

- [117] Moavenzadeh F, Elliott J, editors. A stochastic approach to analysis and design of highway pavements. Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept 11–15, 1972; 1972.
- [118] Thrower E, Mortazavi S, Dougill J. Methods for predicting permanent deformation in flexible pavements; 1986. Report No. 0266–7045
- [119] Nunn M. Prediction of permanent deformation in Bituminous Pavement Layers; UK: Transport and Road Research Laboratory (TRRL); 1986.
- [120] Hilal MM. Prediction of permanent deformation models for asphalt pavements in hot climates. Iraq: University of Baghdad; 2011.
- [121] Khalifah R, Souliman MI, Bajusair MBM. Development of prediction model for rutting depth using artificial neural network. *Civ Eng*. 2023;4(1):174–84.
- [122] Oh I, Barham W. The application of artificial neural network for the prediction of the deformation performance of hot-mix asphalt. *Comput Civ Eng*. 2011;2011:227–33.
- [123] Mirabdolazimi S, Shafabakhsh G. Rutting depth prediction of hot mix asphalts modified with forta fiber using artificial neural networks and genetic programming technique. *Constr Build Mater*. 2017;148:666–74.
- [124] Amin SR, Amador-Jiménez LE. Backpropagation Neural Network to estimate pavement performance: dealing with measurement errors. *Road Mater Pavement Des*. 2017;18(5):1218–38.
- [125] Shafabakhsh G, Ani OJ, Talebsafa M. Artificial neural network modeling (ANN) for predicting rutting performance of nano-modified hot-mix asphalt mixtures containing steel slag aggregates. *Constr Build Mater*. 2015;85:136–43.
- [126] Haddad AJ, Chehab GR, Saad GA. The use of deep neural networks for developing generic pavement rutting predictive models. *Int J Pavement Eng*. 2022;23(12):4260–76.
- [127] Button JW, Perdomo D, Lytton RL. Influence of aggregate on rutting in asphalt concrete pavements. *Transp Res Rec*. 1990;1259.
- [128] Albayati AH, Abdulsattar H. Performance evaluation of asphalt concrete mixes under varying replacement percentages of natural sand. *Results Eng*. 2020;7:100131.
- [129] Zhang J, Cao J, Huang W, Shi X, Zhou X. Rutting prediction and analysis of influence factors based on multivariate transfer entropy and graph neural networks. *Neural Netw*. 2023;157:26–38.
- [130] Partl MN, Bahia HU, Canestrari F, De la Roche C, Di Benedetto H, Piber H, et al. Advances in interlaboratory testing and evaluation of bituminous materials: state-of-the-art report of the RILEM technical committee 206-ATB. Springer Science & Business Media; 2012.
- [131] Hamid A, Baaj H, El-Hakim M. Rutting behaviour of geopolymer and styrene butadiene styrene-modified asphalt binder. *Polymers*. 2022;14(14):2780.
- [132] Bulatović VO, Rek V, Marković KJ. Rheological properties and stability of ethylene vinyl acetate polymer-modified bitumen. *Polym Eng Sci*. 2013;53(11):2276–83.
- [133] Yin H, Zhang Y, Sun Y, Xu W, Yu D, Xie H, et al. Performance of hot mix epoxy asphalt binder and its concrete. *Mater Struct*. 2015;48:3825–35.
- [134] Geng H, Clopotel CS, Bahia HU. Effects of high modulus asphalt binders on performance of typical asphalt pavement structures. *Constr Build Mater*. 2013;44:207–13.
- [135] Al-Tameemi AF, Wang Y, Albayati A. Experimental study of the performance related properties of asphalt concrete modified with hydrated lime. *J Mater Civ Eng*. 2016;28(5):04015185.
- [136] Albayati A, Wang Y, Haynes J. Size effect of hydrated lime on the mechanical performance of asphalt concrete. *Materials*. 2022;15(10):3715.
- [137] Aljbouri HJ, Albayati AH. Effect of nanomaterials on the durability of hot mix asphalt. *Transp Eng*. 2023;11:100165.
- [138] Abd Al Kareem HM, Albayati AHK. The Possibility of Minimizing Rutting Distress in Asphalt Concrete Wearing Course. *Engineering. Technol Appl Sci Res*. 2022;12(1):8063–74.
- [139] Guo R. Analysis of influencing factors on rutting resistance of stone matrix asphalt mixtures. *Sci Iran*. 2020;27(3):1039–49.
- [140] Alzaidy F, Albayati AHK. A Comparison between Static and Repeated Load Test to Predict Asphalt Concrete Rut Depth. *Engineering. Technol Appl Sci Res*. 2021;11(4):7363–9.
- [141] Brown E, Mallick RB, Haddock JE, Bukowski J. Performance of stone matrix asphalt (SMA) mixtures in the United States. USA: National Center for Asphalt Technology; 1997.
- [142] Topal A, Oner J, Sengoz B, Dokandari PA, Kaya D. Evaluation of rutting performance of warm mix asphalt. *Int J Civ Eng*. 2017;15:705–14.
- [143] Abass BJ, Albayati AH. Influence of recycled concrete aggregate treatment methods on performance of sustainable warm mix asphalt. *Cogent Eng*. 2020;7(1):1718822.