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Permanent deformation prediction of asphalt concrete mixtures – A synthesis to explore a rational approach

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HIGHLIGHTS

- A parameter of FN Index is explored to predict asphalt concrete rutting.
- Conventional FN parameter is error-prone and yields unreliable estimates of rutting.
- Dynamic modulus should be evaluated at both 38 °C and 54 °C temperatures.
- Rutting as function of dynamic modulus, gradation and volumetric parameters.

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ABSTRACT

Exploring a reliable laboratory test parameter to predict the rutting (permanent deformation) susceptibility of asphalt concrete (AC) mixtures remains a challenge to asphalt industry. Flow Number (FN) test as part of the HMA mix- and structural- design processes is used to characterize the AC mixtures rutting resistance and optimize field performance. Cognizant of the noise-characteristic of FN test data and need to apply post-processing techniques, this study explores a new parameter – FN Index as a ratio of traditional FN (cycles) and corresponding accumulated permanent strains. The FN and dynamic modulus (DM) tests are conducted on the Superpave gyratory compacted specimens. Twelve (six wearing course and six base course) mixtures were selected including Superpave, Asphalt Institute, British Standard dense bituminous macadam, and Pakistan's National Highway Authority gradations. Under the hypothesis of axial compression applied on the cylindrical specimen, first-order multiple linear regression models are developed for FN and FN Index as a function of the binder, volumetric parameters, gradation, and DM to estimate permanent deformation. The results indicate that FN models are strongly correlated with DM values at 38 °C and 54.4 °C temperature, gradation, volumetric, and Superpave rutting parameter. The predictive capability of developed models is validated using data of 16 different AC mixtures acquired from published literature. The findings of this study provide guidance to asphalt mix designers for providing cost-effective designs within specified levels of rutting resistance.

1. Introduction

Permanent deformation (PD) – also known as rutting – is considered as severe distress manifested on the surface of the flexible pavements. The occurrence of rutting can be associated with AC mix, subgrade, or other structural layers, or contribution of all these. However, the surface rutting is largely influenced by the problems in surface AC mix-design rather than PD of the other underlying layers and aforementioned contributing factors [1]. Rutting is a complex problem and requires several factors to be considered. A number of tests have been devised to investigate the PD potential of AC mixtures, for example, Hamburg wheel tracker test, DM, static creep, and repeated load tests. Archilla and Diaz [2] reported that these tests alone may be insufficient to fully characterize the AC mixtures. Therefore, in this study, laboratory tests such as repeated creep and dynamic load test were carried out on AC mixtures in order to determine PD of the mixtures, predominantly allied with mixture selection and effects of

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certain mixtures properties like voids in mineral aggregate (VMA), voids filled with asphalt (VFA), gradation and DM.

The FN test is a standard test procedure in the newly developed AASHTO 2002 Mechanistic-Empirical Pavement Design Guide (M-EPDG), used for assessing the rutting propensity of an AC mix in the laboratory [3]. The FN test applies a vertical loading to the cylindrical specimen to determine the accumulation of PD strains over the passage of time. Researchers claim the FN of a mix as an important parameter that assists in selection, ranking, and characterization of the available materials for producing rut-resistant mixtures [4–6]. Researchers have also reported that the FN test had shown promising correlation results with the field PD of AC mixtures under influence of various traffic loading [4]. FN test is considered as an indicator of ranking of various AC mixtures in the laboratory investigation as well field observation in terms of rutting resistance. However, FN test is characterized by unreliable and inconsistent results in estimating rutting propensity of AC mix which is attributed to the enormous amount of noise present in the data which requires the application of extensive data mining/smoothening techniques. This fact has also been highlighted by numerous researchers around the globe [7–9].

The termination of FN test is subjected to the accumulation of permanent strains of 5% or 10,000 loading cycles, whichever comes first. The accomplishment of any one condition usually takes six to eight hours (1/3rd to 1/4th of a day) for a single specimen. This substantial/excessive testing time may limit or hinder the FN test's utility to ascertain the rutting propensity as a precursor in the routine AC mix design practice. Consequently, the predictive models have been developed and it remained motive of various research studies [5,10–12]. All these aforesaid studies used Superpave mixtures as a subject except that of Gandomi et al., [12], who used Marshall specimens for the development of FN predictive model.

The insight of literature revealed that DM is also an important parameter affecting PD of AC mixtures. Many researchers have reported the significance of DM on the rutting susceptibility of mixtures [1,13–17]. On the other hand, disagreements were also found in the literature asserting that there is no/little effect of DM on the PD [13,14,18,19]. The potential reason associated with such disagreements could be the variation in testing conditions reported by various researchers for the estimation of the rutting response of AC mixtures. Ekingen [20] reported that loading frequencies ranging from 0.02 to 20 Hz in DM test could be used to evaluate rutting resistance. Shenoy and Romero [21] evaluated PD susceptibility of specimens in the laboratory by developing an approach for selecting normalized frequency coefficient consistent with a DM value of 4 MPa. Conversely, Zhang et al. [1] and Apeagyei [15] showed that DM could be used as an additional parameter to describe the rutting behavior of mixtures at 38 °C.

The synthesis of previously available literature and an insight of aforementioned studies resulted in various factors/parameters affecting rutting response of an AC mix. These parameters can be categorized into two groups. The first group deals with bitumen properties which govern the visco-elastic and visco-plastic behavior of an AC mix, while the second group entails aggregate properties like gradation which takes into account the visco-elastic behavior of mix at higher temperatures. The developed models either used volumetric parameters or gradation exclusively. Also, very few studies used Superpave rutting parameter ($G^*/\mathrm{Sin}\delta$) in addition to volumetric parameters. Therefore, the discrepancies observed in past studies could be solved by explaining the relationship of FN with DM, gradation, Superpave rutting parameter and volumetric parameters which are not explicitly evaluated in previous studies. Different researchers have determined various factors/parameters affecting PD of a mix and the summary of pertinent literature is presented in Table 1.

Hence, additional studies are required to describe the relationship of various factors affecting rutting and results could be used as a basis for optimization of laboratory mix-design and evaluation of rutting by more efficient and rational means.

1.1. The research gap

The previous FN models are developed solely either by using mix volumetric parameters or stiffness parameter. The FN model developed by Apeagyei [15] used DM value of 38 °C, however past studies have reported that rutting is more prominent at higher temperature i.e. 54 °C [1,4,13]. Albeit, these studies have attempted to link DM with FN, the literature is elusive and devoid of characterizing the temperature correspondence of DM with FN. Therefore additional studies are required to explain the

Table 1
Explored PD Explanatory Variables in Past Literature.

Explanatory variables of PD	Reference study
Mix volumetrics	Brown et al. [33]
Volumetric composition, particularly binder content and void content, and loading conditions	Garba [34]
DM	Witczak et al. [13]; Pellinen and Witczak [14]; Ekingen [20]; Zhang et al. [1]
Normalized frequency parameter at 4 MPa	Shenoy and Romero [21]
Temperature, bitumen content, viscosity, and AV (air voids).	Kaloush et al. [35]
High air voids and insufficient compaction	Kandhal and Cooley [36]
Volumetric properties like VMA, VFA, and number of load repetition	Zhou et al. [37]
Frequency sweep and DM	Mohammad et al. [7]
Reclaimed asphalt pavement (RAP) content and nominal maximum aggregate size (NMAS)	Mohammad et al. [38]
Shear and Normal stress (maximum), Viscosity, temperature, AV, gradation (in terms of percent retained on sieves 2.36 mm, 1.18 mm and 4.75 mm), bitumen content, VMA, and VFA.	Rodezno et al. [11]
AV, VMA, Marshall stability, and flow	Gandomi et al. [12]
Number of load cycles	Archilla and Diaz [2]
DM and gradation	Apeagyei [15]
Filler quantity, binder, VMA, Marshall stability, and flow	Alavi et al. [39]
Shear stress and time	Delgadillo et al. [40]
Mix volumetrics	Apeagyei [32]
Superpave's rutting criteria ($G^*/\sin\delta$), zero shear viscosity, non-recoverable compliance (J_{nr}) and recovery parameter (R)	Nejad et al. [41]
Temperature, deviator stress, and load time	Kim [42]
Surface layer type, base layer thickness, and base layer material type	Norouzi et al. [43]
Lateral stress, pressure, and pulse time	Cao and Kim [44]
Visco-elastic strains	Zhang et al. [45]