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A Study of Superpave Design Gyrations for High Traffic Surface Mixtures

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ABSTRACT
The methodology of the research that was used to evaluate the comparative results of surface mixes with a nominal maximum aggregate size of 12.5mm is presented in this paper. Also presented are the recommended Ndes values for C-level and D-level mixes, which are designed to handle traffic levels of 3-30 Million and greater than 30 Million ESALs, respectively. In order to determine the amount of asphalt that was present, asphalt concrete mixes were fabricated utilizing the Superpave design process at Ndes levels of 50, 75, 100, and 125 gyrations. Using the Asphalt Mixture Performance Tester instrument, we were able to determine the dynamic modulus (E*) at the design asphalt content for a number of different gyration levels. The E* data and related binder properties were used as input in the AASHTO Darwin-ME software to anticipate the rutting and fatigue performance of the mixtures. This was accomplished by assuming a model pavement section and appropriate traffic levels. In order to determine which Ndes are most appropriate, relative performance indicators for rutting and fatigue have been developed and plotted against asphalt content. The Ndes value of 85 gyrations was found to be ideal for both surface mixes after extensive research.

Keywords: Relative performance; Asphalt concrete mixtures; Superpave; Design gyrations; Fatigue cracking; Rutting;

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1. Introduction

The number of design gyrations (N_{des}) is a critical element in the Superpave asphalt concrete mix design procedure. The selection of Ndes is based on total traffic, during service life of the pavement, which is indicated in ESALs. Asphalt concrete mixtures for higher traffic volumes are compacted to higher Ndes because a denser mix resists rutting better. However, this results in a reduced design asphalt content, which reduces the mix's fatigue performance. As a result, a performance-oriented strategy to determining N_{des} that maximizes mix performance in terms of both rutting and fatigue cracking was devised [1].

The Superpave mix design approach, created as part of the Strategic Highway Research Program, combines into the design process performance-related design parameters, environmental variables, load factors, and material characterization. The requirements created for the mix design process are intended to improve the performance of asphalt pavement structures by decreasing rutting, thermal cracking, and fatigue cracking [2].

The Superpave method employs a volumetric technique in which the aggregate gradation and optimal asphalt content are determined by examining the mix's air void proportion and other volumetric features. The gyration levels are established by the anticipated total traffic in Equivalent Single-Axle Loads (ESALs) over the pavement's anticipated service life (Prowell & Brown, 2007). According to the current Superpave specifications for characterization of asphalt concrete mix materials, rutting resistance is measured for the asphalt binder using the G*/sinδ parameter and fatigue cracking resistance is measured using the G*sinδ parameter, where G* is the complex shear modulus of the asphalt binder and represents the phase angle δ. In addition to the volumetric requirements, these characteristics can be utilized to develop a mixture that performs well in the field in terms of rutting and fatigue cracking [2].

However, the mix's performance is not expressly considered during the design phase. This is owing to the fact that the design method determines only the aggregate structure and the matching asphalt content required to produce 4% air voids, without any extra mix performance characterization [3]. Consequently, numerous State Highway Agencies have implemented additional specification requirements based on performance tests, such as the Hamburg Wheel Tracking Device (HWTD) and Asphalt Pavement Analyzer (APA), to assess the rutting potential of asphalt concrete mixtures [4].

As a result of their robust aggregate skeletons, superpave mixtures often display adequate rutting resistance. In addition, mixtures that meet the approval criteria of wheel tracking device testing, as stated previously, exhibit enhanced field rutting performance. To ensure a high rutting performance, the asphalt percentage of the mix is decreased, resulting in a comparatively drier mixture with less plastic flow of the asphalt binder. The decreased asphalt percentage, however, causes an increase in fatigue cracking, which is becoming a frequent issue, particularly in relatively young pavements that are 5-7 years old (Maupin, 2003). In order to obtain an acceptable mixture, it is required to enhance the fatigue cracking resistance without compromising the rutting resistance [[3], [4], [5], 6], [7]].

Both fatigue cracking and rutting are load-related distresses that result from a loss of structural integrity in the asphalt concrete layer. Rutting can also be caused by potholes. Rutting in the asphalt layer is assessed in terms of millimeters (or inches) of deformation, whereas fatigue cracking in a flexible pavement is quantified in terms of the percentage of cracking that has occurred per unit area. During the process of optimization, it is not possible to make a direct comparison against the number of design gyrations because of differences in the methods used to measure the degree of the two types of distress. The mixture provides the maximum performance possible against fatigue cracking at the Ndes level that is lowest, and it provides the maximum performance possible against rutting at the Ndes level that is highest [8].

Locking point (Prowell & Brown, 2007, Hornbeck, 2008) and Ndes level reduction are two common strategies for optimizing mix performance (Hornbeck, 2008, Aschenbrenner & Harmelink, 2002). Locking point correlates laboratory mix density to ultimate field density, but weakly (Prowell & Brown, 2007). The laboratory-field density correlation ignored aggregate type, gradation, and angularity, which affected the locking point. Christensen and Bonaquist (2006) used the Ndes reduction strategy to show that rutting performance rose by 25% with one level of compactive effort (25 gyrations) and fatigue performance decreased by 20% [[1], [2], [8], [9]].

Prowell and Brown (2007), Hornbeck (2008), and Button, Chowdhury and Bhasas (2009) examined how compactive effort affects rutting and fatigue cracking (2006). Superpave mixtures' rutting and fatigue performance was tested at various Ndes levels in the Ndes level reduction approach. Asphalt content was adjusted to match a 4% air void content for four Ndes levels—50, 75, 100, and 125 gyrations—proposed by the NCHRP for different traffic loads (Prowell & Brown, 2007) [[3], [10]].

The aims of the study were to:

1. Evaluate the sensitivity of asphalt volumetric properties to varying levels of design gyrations;
2. Determine the optimal design gyrations for asphalt pavements.
3. Determine the effect of changes in N_{des} on the stiffness and performance characteristics of the mix by comparing the fatigue and rutting performance anticipated by the mechanistic-empirical design approach for a typical pavement segment.
4. Recommend N_{des} values for surface mixes S12.5C and S12.5D.

On the basis of the volumetric design approach, there are two methods for enhancing fatigue cracking resistance:

1. Increasing the relative density objective for a given number of design gyrations by increasing the asphalt composition of the design.
2. Reducing the amount of design gyrations while keeping a 4% air void design content in the mix.

This research utilized the second method to enhance rutting and fatigue performance because increasing the desired relative density has the potential to cause performance issues, particularly with soft binders (Prowell & Brown, 2007) [[1], [3], [11]]. For the design gyration optimal number determination, asphalt concrete mixes were prepared at various Ndes levels, and their performance was characterized. Mix design, performance testing, and evaluation are described in depth in the sections that follow.

2. Experimental technique

2.1 Design Gyrations Optimum Number Determining Method.

For fatigue and rutting, relative performance indicators were constructed using a control or base level that indicates the maximum performance of the mixture. Performance is defined as the number of ESALs required to attain failure for a given distress, where failure limits are specified as 10% cracking of the entire fatigue place and 6.35 mm permanent deformation of AC layer for rutting [[12], [13], [14]]. The control fatigue performance, $P_{Fatigue}$, will be clear at 50 gyartions fatigue life measurement, as the mix design results in a higher asphalt content, which makes the asphalt concrete layer more flexible and therefore more resistant to fatigue cracking. Similarly, the control rutting performance $P_{Rutting}$ will be determined by cycles number to failure for a mixture intended for 125 gyrations, as a higher amount of compaction results in increased rutting resistance [[15], [16]]. Therefore, relative performance is computed using Equation (1) for fatigue cracking and Equation (2) for rutting (Button, Chowdhury, and Bhassa, 2006):

$$RP_{Fatigue} = \frac{P_{Fatigue,N_{des}=i}}{P_{Fatigue,N_{des}=50}}$$

$$RP_{Rutting} = \frac{P_{Rutting,N_{des}=i}}{P_{Rutting,N_{des}=125}}$$

Where, $P_{FatigueNdes=I}$ is the estimated fatigue life and $P_{FatigueNdes=I}$ is the estimated rutting life for the mix designed using “i” number of design gyrations. $RP_{Fatigue}$ is equal to 1 at 50 gyrations of Ndes and diminishes as Ndes increases. RPRutting is 1 at Ndes of 125 gyrations and decreases as Ndes decreases. The examination of relative performance data involved graphing relative performance values expressed as a percentage versus asphalt content. Instead of design gyrations, the asphalt content was chosen as the independent variable in this study since it is more logical to relate performance to a mix attribute. By graphing the relative performance values against the asphalt content and locating the intersection of the curves, the optimal asphalt content was identified. The best Ndes was found by plotting the number of gyrations versus the asphalt composition [[17], [18]].

State highway agencies' performance test methodologies can be utilized to validate mix performance, thereby enhancing the mix design process. In evaluating mix performance, these test methods are not based on fundamental material properties (measurement of real material reaction to an applied stress or strain) and do not account for variations in mix design factors such as asphalt content variation. Additionally, these experiments are undertaken at temperatures unique to the mix type, and the effect of aggregate gradation is not assessed adequately (Prowell & Brown, 2007, Watson, Moore, Heartsill, Jared & Wu, 2008). As a key material property, the dynamic modulus of the asphalt concrete mix was employed to evaluate mix performance in this study. The AMPT was used to measure the dynamic modulus, and the DARWin-ME program was used to forecast the rutting and fatigue performance of the mixes at different design gyration levels [[19], [20], [21], [22]].

2.2 Superpave Mix Design Criteria for Surface Mixes

The surface mixes are often designed on 9.5mm and 12.5mm NMAS (nominal maximum aggregate size). Based on traffic level (design number of ESALs), surface mixes are further classified as (0.3 Million for A), (0.3 - 3 Million for B), (3 - 30 Million for C), and (>30 Million for D). S12.5C mixes are compacted to 75 gyrations and S12.5D mixes are compacted to 100 gyrations Superpave requirements [[21], [23]]. Notably, the drop in N_{des} levels on NCHRP-recommended C and D mixes, respectively, have gyration values of 100 and 125, is not based on mix performance, which was the objective of this study.

This article recommends a change of Superpave mix design requirements for S12.5C and S12.5D mixes, which are utilized in surface courses intended for traffic intensities in excess of 3 Million ESALs. As recommended, the performance grade of asphalt binder PG 70-22 was used in the S12.5C blend, while PG 76-22 was used in the S12.5D blend.

3. Results and Discussion

3.1 Design and Modification of Superpave Mixes for Different N_{DES} Levels

Through the utilization of the Superpave mix design procedure, the two mixtures S12.5 C and S12.5 D were developed. Calculations were made to determine the asphalt content based on 4% air voids at N_{des} levels of 75 gyrations for S12.5C mix and 100 gyrations for S12.5D mix. By performing volumetric back-calculations of specimen heights at a given asphalt content and making use of the theoretical maximum specific gravity (Gmm) of the mix in conjunction with the asphalt content, we were able to determine the asphalt content that was necessary to generate 4% air voids at N_{des} levels of 50, 75, 100, and 125 gyrations. This was accomplished by using the asphalt content as the input variable (Pb). The mix volumetrics for S12.5C and S12.5D mixes are displayed in Table 1 at a variety of different N_{des} values. The statistics show the average of three different specimens that were compressed to the number of gyrations that was requested for each N_{des}.

Table 1. Design of Superpave Mix Volumetric Properties

N_{des} Mix Properties	**S12.5C**				**S12.5D**			
Design Gyrations Number (N_{des})	50	75	100	125	50	75	100	125
Total Mix Asphalt Content %	5.71	5.41	5..20	5.03	5.47	5.18	4.97	4.81
Bulk Specific Gravity, Gmb	2.358	2.463	2.458	2.451	2.432	2.442	2.449	2.455
Max.Specific Gravity, Gmm	2.451	2.458	2.463	2.469	2.438	2.452	2.457	2.465
Total Mix Air Voids, %	3.8	4.3	3.7	4.3	4.3	4.1	4.2	4.1
Voids in Mineral Agg.(VMA), %	16.4	16.3	15.5	15.6	17.2	16.5	16.2	15.7
Voids Filled w/binder (VFA), %	76.9	73.8	75.8	72.4	75.2	75.2	73.9	74.1

3.2. Testing and Development of E* Mastercurves for Dynamic Modulus

The Asphalt Mixture Performance Tester (AMPT) was used to conduct the dynamic modulus was determined using the Asphalt Mixture Performance Tester and the AASHTO TP79-09 Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) (AMPT). 150 mm in diameter Superpave gyratory specimens compressed with a height of 178 mm. A test specimen with a 100 mm diameter and a 150 + 2.5 mm height was made by coring and sawing the compacted samples; the desired air void content for the cored test specimen was 4 + 0.5%. Three temperatures and three frequencies were used in the experiment: 4, 20, and 40 degrees Celsius. Table 2 displays the E* (Pa) values for the two mixtures. Using the dynamic modulus values acquired at the three test temperatures and three test frequencies, a non-linear optimization approach given in AASHTO PP61-09 was utilized to produce an E* master curve.

Standard Method for the Development of Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester [Standard Method for the Development of Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA)] (AMPT) [24].

Since the stiffness of an asphalt concrete mix is measured by its dynamic modulus, it stands to reason that a mix compacted at a higher Ndes level, with its lower asphalt content and greater stiffness, should have a larger dynamic modulus. Figure 1 shows that this shape may be detected in the E* master curves of both mixtures.

Table 2. Test Results of Dynamic Modulus (Pa)

Temp. (^{0}C)	Freq. (Hz)	S12.5C Mix, N_{des}				S12.5D Mix, N_{des}			
		50	75	100	125	50	75	100	125
4	10	1.83E10	1.97E10	2.07E10	2.19E10	1.85E10	1.91E10	1.97E10	2.06E10
	1	1.42E10	1.62E10	1.71E10	1.79E10	1.46E10	1.54E10	1.58E10	1.65E10
	0.1	1.02E10	1.24E10	1.34E10	1.38E10	1.08E10	1.18E10	1.19E10	1.25E10
20	10	8.47E09	1.01E10	1.12E10	1.16E10	8.78E09	9.63E09	9.66E09	1.01E10
	1	5.11E09	6.51E09	7.39E09	7.39E09	5.41E09	6.19E09	6.23E09	6.49E09
	0.1	2.69E09	3.78E09	4.45E09	4.42E09	3.05E09	3.57E09	3.69E09	3.85E09
40	10	2.27E09	3.01E09	3.46E09	3.52E09	2.34E09	2.81E09	2.95E09	3.02E09
	1	9.87E08	1.39E09	1.63E09	1.66E09	1.07E09	1.31E09	1.39E09	1.49E09
	0.1	4.76E08	6.69E08	7.68E08	8.08E08	5.54E08	6.97E08	6.71E08	8.16E08

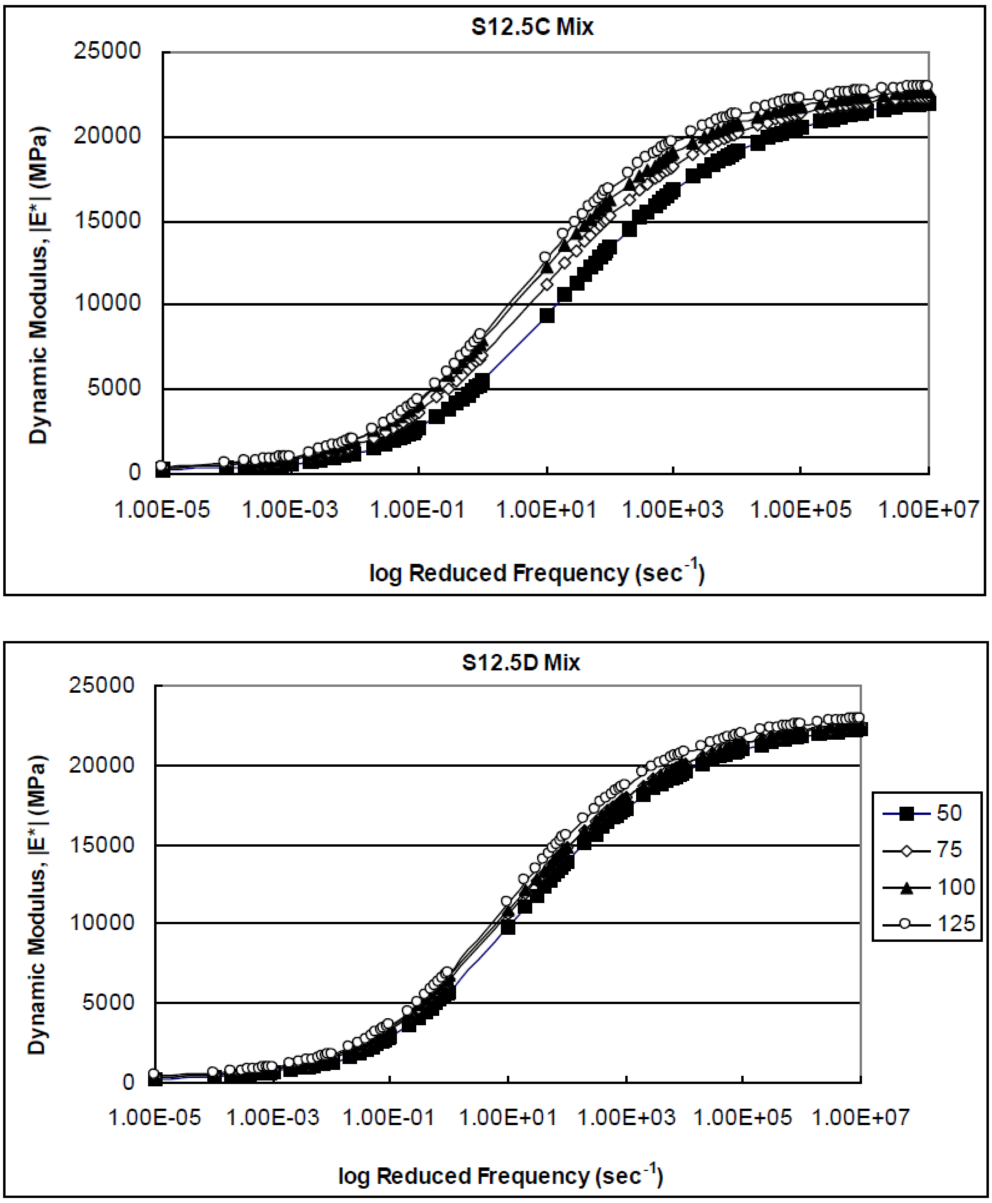


Figure 1. E* Mastercurves for Various N_{des} Levels, Reference Temperature 20°C

3.3 Prediction of Pavement Performance Using DARWin-ME Design Guide Software

The dynamic modulus (E*) is a crucial parameter that correlates material attributes to fatigue cracking and rutting performance and is used in the mechanical-empirical pavement design technique to define asphalt concrete mixes. The fatigue and rutting performances of the mixtures were investigated using the DARWin-ME design guide, the most recent edition of NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide, which has recently been selected as the industry's key instrument for pavement design and performance prediction. The analysis made use of model pavement sections, which are routinely used by some specifications for planning asphalt concrete pavements where C and D mixes are required. There were three distinct parts to the pavement's structure:

Part1: Asphalt concrete surface course, thickness: 7.5 centimeters, air void content: 8%

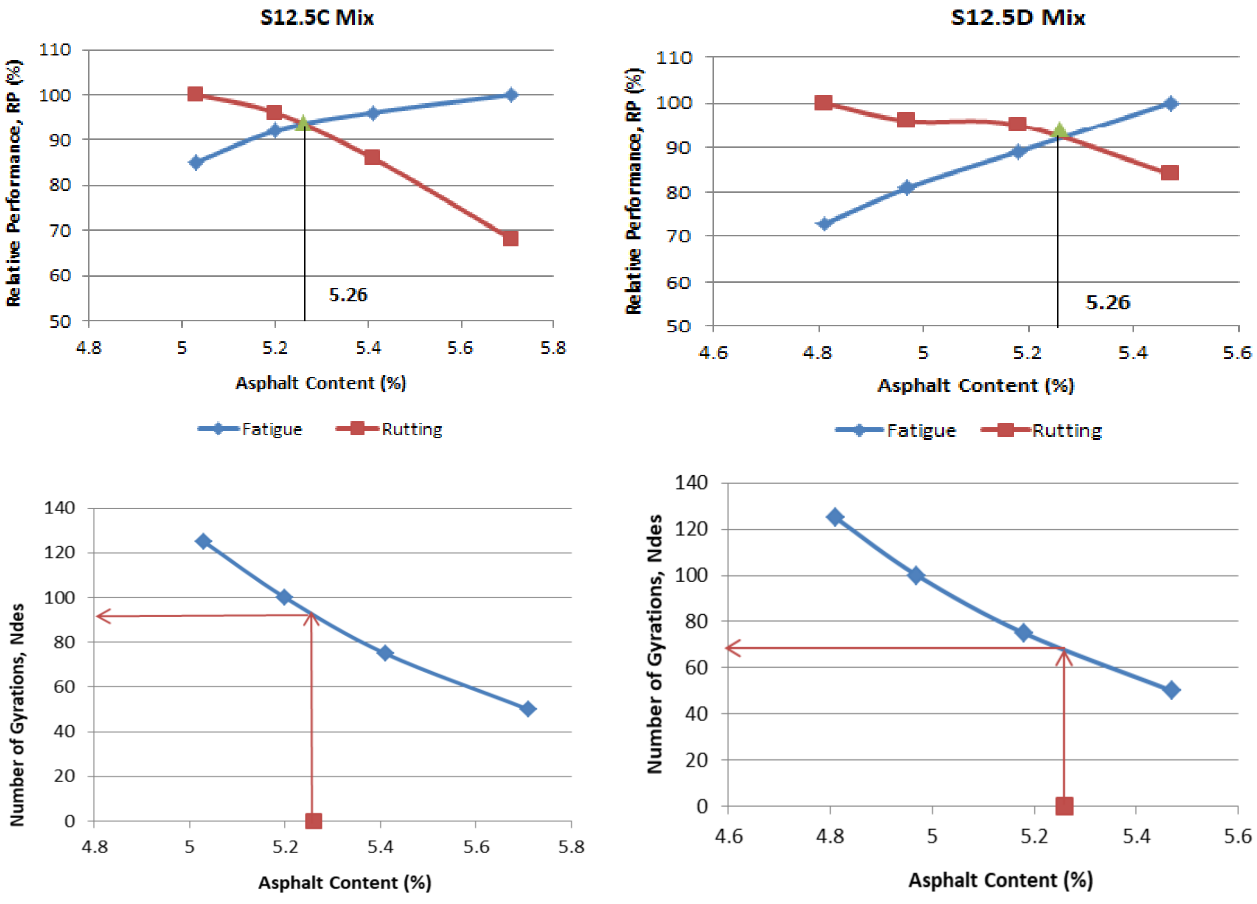
Part2: Crushed stone base course, 25 cm (S12.5C) and 38 cm (S12.5D) thick, 163 MPa modulus.

Part3: Subgrade AASHTO classification A-7-5 (clay), modulus - 46 MPa

Table 3 presents the predicted fatigue and rutting performance, together with the relative performance values at different gyration levels.

Table 3. Estimated Levels of Rutting and Fatigue Performance in Comparison to Their Relative Values

Mix Type	Number of Gyrations, N_{des}	Asphalt Content, %	$P_{Fatigue}$ (ESALs)	$P_{Rutting}$ (ESALs)	$RP_{Fatigue}$,%	$RP_{Rutting}$,%
S12.5C	50	5.61	2.25E06	1.78E06	100	68
	75	5.31	2.17E06	2.27E06	96	86
	100	5.10	2.08E06	2.54E06	92	96
	125	5.01	1.94E06	2.65E06	85	100
S12.5D	50	5.17	3.98E06	3.50E06	100	84
	75	5.08	3.54E06	3.94E06	89	95
	100	4.87	3.23E06	3.98E06	81	96
	125	4.71	2.85E04	4.20E06	73	100



a) b)

Figure 2 - Optimal N_{des} estimation from Relative Performance and Asphalt Content Graphs

3.4 An Analysis of the Relative Performance Data and a Suggested Change to the N_{des}

Figures 2(a) and 2(b) show relative fatigue and rutting performance versus asphalt content for S12.5C and S12.5D mixtures, respectively, using the approach stated in Section 1.2. Figures 2(a) and 2(b) show the relationship between the asphalt content and the total number of design gyrations for each of the two mixtures, respectively. A total of 95 gyrations was determined to be the optimum N_{des} value for S12.5C mix based on the relative performance curves, which is higher than the current some specification of 75 gyrations. This improves durability against rutting but lowers its resilience against fatigue cracking. Compared to the current some specification of 100 gyrations, the determined optimal N_{des} value for S12.5D mix was 72 gyrations, which results in increased fatigue cracking resistance. But since the mixture is used in surface courses made to support traffic loads greater than 30 Million ESALs, optimizing its rutting performance is crucial.

Thus, in order to find practically usable values that optimize both distresses, a more in-depth investigation of the relative performance at values other than the anticipated optimums was conducted. It's worth noting that in an attempt to increase the longevity of Superpave mixes, the N_{des} values currently used by various specifications were arbitrarily reduced from the original Superpave N_{des} table.

It was determined that 95 rotations were necessary to achieve optimum performance from the S12.5C blend. It can be seen from the difference in the slopes of the rutting and fatigue relative performance curves in Figure 2(a) that the variation in rutting performance with gyration number is larger than the variation in fatigue cracking performance. Accordingly, raising N_{des} has a bigger impact on enhancing rutting than lowering fatigue resistance. For example, if you set N_{des} to 85 gyrations, you'll see a loss of 2% in fatigue performance and an increase of 5% in rutting. The overall binder weight drops by 2% as a result of the drop in asphalt composition from 5.45% to 5.36%. This results in a N_{des} value of 85 gyrations for the 12.5C mixture. The suggested value of 85 gyrations has real-world implications for rutting resistance and cost savings via reduced asphalt binder usage.

Based on the relative performance research, 72 gyrations was shown to be the optimal N_{des} for the S12.5D mix. The current NCDOT N_{des} value for this mix is 100, although increasing the design asphalt content will increase the pavement's flexibility.

However, the rutting must also be optimized for design traffic reasons. Accordingly, it is suggested that the N_{des} level for this mixture be lowered to 85 gyrations. As the N_{des} climbs to 85 gyrations, fatigue performance improves by 6%, while rutting resistance drops by 2%. Asphalt with 85 gyrations has a higher total binder weight of 5.13%, up from 4.87%.

4. Conclusions

The optimal asphalt concentration decreased as the Ndes level to which specimens were compacted grew, as shown by the mix design results for several countries' surface mixes S12.5C and S12.5D. The modulus of the mixture at different temperatures and frequencies increases with an increase in Ndes, as evidenced by the trend in E* master curves from AMPT testing. These results corroborate the theory behind this work, which suggests that increasing the Ndes during the mix design phase will require less binder, leading to a more rigid final product.

For the S12.5C mix, the optimum Ndes was calculated to be 95 gyrations, while the optimum Ndes for the S12.5D mix was calculated to be 72 gyrations. We used the rutting and fatigue performance data to calculate relative values for the optimal Ndes values that resulted and for the values recommended by the National Cooperative Highway Research Program. Two primary criteria were used to provide guidelines for ideal Ndes:

– Using a lower Ndes has a negative impact on rutting performance, but has a positive impact on pavement life compared to fatigue life.

– The economic benefits of utilizing less asphalt binder in the mix and the decrease in fatigue life that results from adopting a higher Ndes are considered and balanced. As a proportion of the asphalt binder required for mix design, the asphalt content decrease is calculated.

For both S12.5C and S12.5D mixes, the optimal Ndes value is 85 gyrations.

Conflict of interest. On behalf of all the authors, the correspondent author states that there is no conflict of interest.

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Қарқынды қозғалыс беттерінің Superpave қоспаларына арналған жобалық гиратор тербелісін зерттеу

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ТҮЙІНДЕМЕ

Бұл жұмыста номиналды максималды толтырғыш мөлшері 12,5 мм болатын беттік қоспалардың салыстырмалы нәтижелерін бағалау үшін пайдаланылған зерттеу әдістемесі берілген. Сондай-ақ, сәйкесінше 3-30 миллион және 30 миллионнан астам ESAL трафик деңгейлерін өңдеуге арналған C-деңгейі және D-деңгейлі қоспалар үшін ұсынылған Ndes мәндері көлтірілген. Асфальттың бар мөлшерін анықтау үшін 50, 75, 100 және 125 айналу Ndes деңгейлерінде Superpave жобалау процесін қолдана отырып, асфальтбетон қоспалары дайындалды. Asphalt Mixture Performance Tester құралын пайдалана отырып, біз әртүрлі айналу деңгейлері үшін асфальттың жобалық құрамындағы динамикалық модульді (E*) анықтай алдық. E* деректері мен байланыстырғыштың сәйкес қасиеттері AASHTO Darwin-ME бағдарламалық жасақтамасында қоспалардың екіге бөлінуі мен тозу өнімділігін болжау үшін кіріс ретінде пайдаланылды. Бұл үлгі тротуар учаскесін және тиісті қозғалыс деңгейлерін болжау арқылы орындалды. Қай Ndes ең қолайлы екенін анықтау үшін асфальттың құрамына қатысты ойықтар мен тозуының салыстырмалы өнімділік көрсеткіштері әзірленді және графигі жасалды. 85 айналымдық Ndes мәні ауқымды зерттеулерден кейін екі беттік қоспалар үшін де өте қолайлы болатыны анықталды.

Түйін сөздер: Салыстырмалы сипаттамалары; асфальтбетон қоспалары; Superpave; гиратор мөлшері; жабынның сынуы; дөңгелек ізінің пайда болуы.

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Исследование проектных колебаний гиратора для смесей Superpave с интенсивным движением поверхностей

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АННОТАЦИЯ

В статье представлена методика исследования, которая использовалась для оценки сравнительных результатов поверхностных смесей с номинальным максимальным размером заполнителя 12,5 мм. Также представлены рекомендуемые значения Ndes для смесей уровней C и D, которые предназначены для обработки уровней трафика 3-30 миллионов и более 30 миллионов ESAL соответственно. Чтобы определить количество присутствующего асфальта, были изготовлены асфальтобетонные смеси с использованием процесса проектирования Superpave на уровнях Ndes 50, 75, 100 и 125 оборотов. Используя прибор для определения характеристик асфальтобетонной смеси, мы смогли определить динамический модуль (E*) при расчетном содержании асфальта для ряда различных уровней гирации. Данные E* и соответствующие свойства вяжущего были использованы в качестве входных данных в программном обеспечении AASHTO Darwin-ME для прогнозирования колейности и усталостных характеристик смесей. Это было достигнуто за счет модели участка дорожного покрытия и соответствующих уровней трафика. Для того, чтобы определить, какие Ndes являются наиболее подходящими, были разработаны и нанесены на график относительные показатели колейности и усталости в зависимости от содержания асфальта. После обширных исследований было установлено, что значение Ndes, равное 85 оборотам, идеально подходит для обеих поверхностных смесей.

Ключевые слова: Относительные характеристики; асфальтобетонные смеси; Superpave; количество гиратора; усталостное растрескивание; колееобразование.

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