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Effect of "n" Exponent in Fuller Equation of Gradation on Hot Mix Asphalt Resistance to Permanent Deformation

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Abstract: Mineral aggregates constitute a large proportion of an asphalt mixture. Gradation, on the other hand, is one of the most important properties of an aggregate blend. Hence, the link between aggregate gradation and hot mix asphalt (HMA) performance is a considerable issue and has been recognized since HMA was first used. Fuller Equation of gradation is one of the best known aggregate grading methods, which is developed in the early 20th century. In this paper, resistance to permanent deformation of mixtures made of Iran Highway Asphalt Paving Code (IHAPC) gradations and mixtures made of Fuller Equation gradations with various "n" exponents are compared. Optimum bitumen content for each gradation was determined using Marshall Method (ASTM D1559) and HMA specimens were objected to Dynamic Creep Test. Finally, test results showed that all gradations generated by Fuller Equation result in mixtures with more resistance to permanent deformation compared to mixtures made of IHAPC gradations. Even though, for some of the Fuller gradations, due to low bitumen contents, an evaluation of aging and fatigue is recommended.

***Key words**: Dynamic Creep Test; Fuller equation; Gradation; HMA; Permanent deformation.*

Introduction

Gradation is probably the most important property of an aggregate blend. It affects almost all the important properties of HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage [1].

Traditionally, in Iran and many other countries, gradations for dense-graded HMA are specified using "gradation limits" recommended by asphalt paving codes. Since code recommended gradations are constant for all types of aggregate blends, desirable results are not always expected from them.

Another means for determining a proper aggregate gradation is the Fuller Equation of Aggregate Gradation. Fuller and Thompson (1907) developed one of the best-known grading charts in the early 20th century [2].

The Fuller Equation of gradation is as follows [2]:

$$P = 100 \times \left(\frac{d_i}{D_{\max}} \right)^n \tag{1}$$

where,

d_i = diameter of the sieve in question;
P = total percent passing or finer than the sieve;
$D_{\max}$ = maximum size of the aggregate; and
n = exponent of the Fuller Equation.

For a determined Maximum Aggregate Size (MAS), "n" is the only variable parameter that changes the percent passing a specific sieve, with a diameter of "d." Various values of "n" exponents are discussed Applied Gradations' section.

Permanent deformation refers to the plastic deformation of HMA under repeated loads [2]. Many studies have been intended on the link between aggregate gradation and resistance of HMA to permanent deformation. Results of a research performed by Brown and Basset [3] showed that mixtures with a larger aggregate size and the same air void content (4%) generally show more resistance to permanent deformation than mixtures with smaller aggregates. Also, mixtures with larger aggregates required significantly less binder contents. Shiau et al. [4] implemented a research to evaluate the rutting resistance of different asphalt concrete mixtures, produced by different aggregate gradations including dense gradation, stone mastic asphalt (SMA), and hot rolled asphalt. They concluded that SMA had notable performance on resistance to permanent deformation, even though an additional evaluation of aging, fatigue, and stripping were highly recommended. A research by Kandhal et al. [5] indicates that finer gradations or oversanded mixtures are more susceptible to permanent deformation.

In this study, two gradations from the Iran Highway Asphalt Paving Code (IHAPC) are considered as the control gradations. Other gradations are generated using the Fuller equation of gradation. Finally, resistance to permanent deformation of mixtures made of Fuller gradations and control gradations is compared.

Objective and Scope

The objective of this research is to evaluate the effect of the "n" exponent of the Fuller Equation on resistance to permanent deformation of HMA. In fact, various "n" exponents are selected for the Fuller Equation to generate different gradations, and HMA made of these gradations are compared with each other. Finally, rutting resistance of mixtures that are made of Fuller gradations instead of conventional mixtures (using IHAPC gradations) is evaluated.

The control gradations, which are used in this research, include IHAPC No. 4 and 5 gradations.

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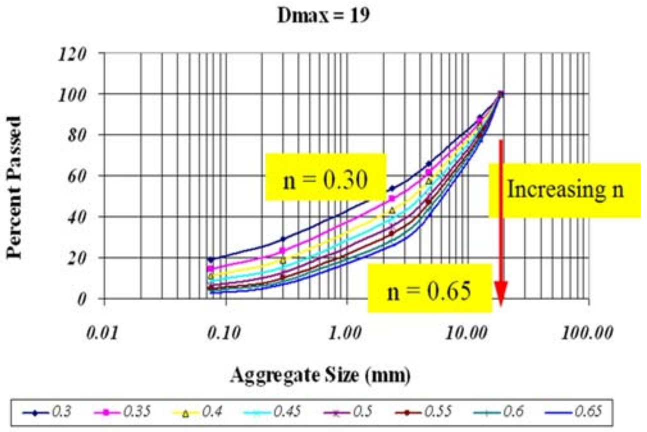

Fig. 1. Fuller Gradation Curves for Different Values of "n" and D_{max} = 19*mm*.

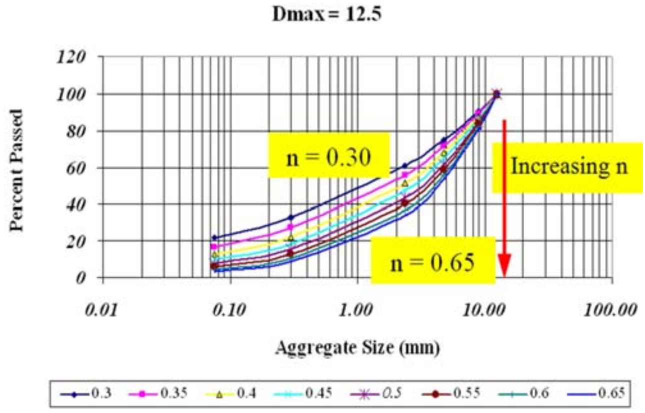

Fig. 2. Fuller Gradation Curves for Different Values of "n" and D_{max} = 12.5*mm*.

Table 1. Values of C_u and C_c for the Selected Fuller Equation Gradations.

D	"n" Exponent					
	NMAS = 12.5			NMAS = 19		
	0.45	0.5	0.55	0.45	0.5	0.55
D10	0.07	0.13	0.19	0.11	0.19	0.29
D30	0.86	1.13	1.4	1.31	1.71	2.13
D60	4.02	4.5	4.94	6.11	6.84	7.51
C_u	54	36	26	54	36	26
C_c	2.5	2.3	2.1	2.5	2.3	2.1

HMA specimens are prepared using the Marshall Method (ASTM D1559), and the optimum bitumen contents are obtained using the National Asphalt Pavement Association (NAPA) method [3].

A Dynamic Creep Test is performed to compare resistance to permanent deformation of different types of HMA.

Applied Gradations

Control Gradations

In this research, the applied gradations are divided into two categories:

The control gradation for the first category is IHAPC No. 4 gradation, which is recommended for binder course. For this gradation, MAS is 19*mm* and the control sieves (according to IHAPC) are 19, 12.5, 4.75, 2.36, 0.3, and 0.075*mm* sieves. To generate Fuller gradations, in Eq. (1), D_{max} is equal to 19*mm* and d_i values conform to the mentioned control sieves.

The control gradation for the second category is IHAPC No. 5 gradation, which is recommended for surface course. For this gradation, MAS is 12.5*mm* and the control sieves (according to IHAPC) are 12.5, 9, 4.75, 2.36, 0.3, and 0.075*mm* sieves. To generate Fuller gradations, in Eq. (1), D_{max} is equal to 12.5 *mm* and d_i values conform to the mentioned control sieves.

Fuller Equation Gradations with Various "n" Exponents

Taking D_{max} and d_i from the control gradations, the "n" exponent remains the only variable in Eq. (1). Fuller gradation curves for different values of "n" and D_{max}= 19 and 12.5*mm* are demonstrated in Figs. 1 and 2, respectively. Gradation curves of Figs. 1 and 2 show that an increase in "n" values results in more percentage retained on 4.75*mm* sieves, i.e., the coarse portion of an aggregate blend.

Studies by Fuller and Thompson showed that in the Fuller Equation, when "n" is equal to 0.5, a gradation with the highest density is achieved. After that, Federal Highway Administration (FHWA) introduced a 0.45 exponent for the highest density [2]. Generally, an aggregate blend with the highest density is not desirable, because it results in insufficient space between aggregates for bitumen to cover them [2]. However, in this study, since there are some gaps between IHAPC recommended control sieves, 0.45 and 0.5 exponents do not necessarily result in insufficient space between aggregates. Proper values of air voids and voids in mineral aggregate (VMA) are investigated for each gradation while determining the optimum bitumen content.

Selecting "n" Exponents for Fuller Equation

For each category, eight different gradations were generated by Eq. (1). However, not all generated gradations are appropriate. Uniformity coefficient (C_u) and coefficient of gradation (C_c) are two criteria that help evaluate the gradation of a blend.

C_u and C_c are calculated, using the following equations [6]:

$$Cu = \frac{D_{60}}{D_{10}} \tag{2}$$

$$Cc = \frac{{D_{30}}^2}{D_{10} \times D_{60}} \tag{3}$$

where,

D_{10}, D_{30}, and D_{60} are the diameters through which 10, 30, and 60% of the total mass is passing.

A large value of C_u defines a well-graded blend. Generally, $C_u >$ 4-6 and $1 < C_c < 3$ define a well graded aggregate blend [6].

Finally, values of 0.45, 0.5, and 0.55 were selected as "n" exponents in Eq. (1). Table 1 presents the values of C_u and C_c for each of the generated gradations. Based on these values, all the selected gradations are well graded.

Table 2. The Applied Gradation Types.

Gradation Type	Description
B-1	IHAPC No. 4 Gradation
B-2	Generated by Fuller eq. — n = 0.45 & D_{max} = 19*mm*
B-3	Generated by Fuller eq. — n = 0.50 & D_{max} = 19*mm*
B-4	Generated by Fuller eq. — n = 0.55 & D_{max} = 19*mm*
S-1	IHAPC No. 5 Gradation
S-2	Generated by Fuller eq. — n = 0.45 & D_{max} = 12.5*mm*
S-3	Generated by Fuller eq. — n = 0.50 & D_{max} = 12.5*mm*
S-4	Generated by Fuller eq. — n = 0.55 & D_{max} = 12.5*mm*

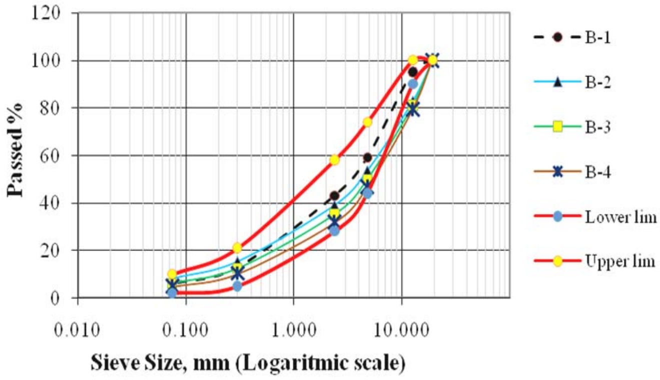

Fig. 3. Applied Gradations with the Lower and Upper Limits of IHAPC No. 4 Gradation (Appropriate for Binder Course).

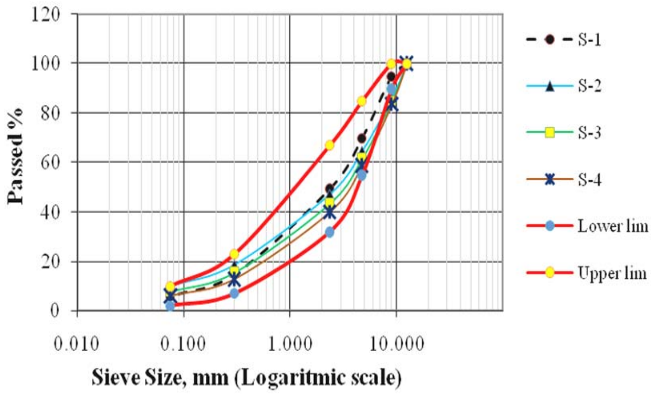

Fig. 4. Applied Gradations with the Lower and Upper Limits of IHAPC No. 5 Gradation (Appropriate for Surface Course).

Final Applied Gradations

The applied gradations are obtained and entitled as presented in Table 2. B-1 to B-4 mixtures belong to the first category, i.e., coarser mixtures, and S-1 to S-4 mixtures belong to the second category, i.e., finer mixtures.

Figs. 3 and 4 present the four gradation types of each category, accompanied by lower and upper limits of IHAPC No. 4 and 5 gradations (B-1 and S-1).

Experimental Plan

Materials and Related Tests

The applied materials included coarse and fine silicious aggregates, mineral filler, and AC 60-70 bitumen, which are described in the following paragraphs.

Aggregates

Coarse and fine aggregates were provided from Rigzar aggregate source, in Shahriar (a small town near Tehran) and sieved, using the control sieves of IHAPC for No. 4 and 5 gradations. Tests for flakiness and elongation index and percentage crushed in two faces were also implemented to make sure the aggregates are appropriate for HMA. Tables 3 and 4 present test results for aggregates.

Bitumen

AC 60-70 bitumen (the number refers to penetration grade in 0.1*mm*) was used to prepare mixtures. The bitumen was provided from Pasargad Oil Company (Tehran). This type of bitumen is most widely used in Iran. Specific gravity, penetration, ring and ball (for softening point), and ductility tests were implemented on the bitumen. Table 5 presents the bitumen test results.

Mineral Filler

Filler was provided from the Macadam-e-Shargh asphalt plant near Pakdasht (a small town near Tehran). Filler's specific gravity was 2.595gr/cm^3.

Table 3. Test Results for Flakiness and Elongation Index and Percent Crushed in Two Faces.

Type of Test	Test Result (%)	IHAPC Limits		Standard
		Binder Course	Surface Course	
Elongation Index	7	—	—	BS-812
Flakiness Index	16	max 30	max 25	BS-812
Percent Crushed in Two Faces	93	min 80	min 90	ASTM-D5821

Table 4. Test Results for Aggregate Specific Gravity and Absorption.

Mix Type	Aggregate Size	Apparent Specific Gravity (gr/cm^3)	Bulk Specific Gravity (gr/cm^3)	Absorption %	Standard
Surface Course	Retained on Sieve #8	2.644	2.501	2.1	ASTM-C127
	Passed of Sieve #8	2.668	2.487	3.1	ASTM-C128
Binder Course	Retained on Sieve #8	2.621	2.486	2.2	ASTM-C127
	Passed of Sieve #8	2.689	2.485	2.7	ASTM-C128

Table 5. Test Results for the Applied Bitumen.

Type of Test	Test Result	Standard
Specific Gravity @ 25/25ºC	1.03	ASTM-D70
Penetration @ 25ºC	66	ASTM-D5
Softening Point	51	ASTM-D36
Ductility @ 25ºC	101	ASTM-D113

Determining Optimum Bitumen Contents

The mix design method used in this research is Marshall Method (ASTM D 1559) with 75 blows in either side of the mix.

The selected bitumen contents to determine the optimum bitumen content (OBC) were: 4.5, 5, 5.5, 6, and 6.5%and 3 specimens were prepared for each gradation at each asphalt content (i.e., 120 Marshall specimens).

In this study, the NAPA approach was selected to determine the OBC. In the NAPA approach, the proposed OBC is selected at the mid-point of the air void content criterion, which is typically at 4% air voids, and other Marshall parameters at the proposed OBC should be checked against the applicable specifications provided in the codes [2].

Fig. 5 demonstrates the related Marshall Method plots and determined OBC for each gradation.

Dynamic Creep Test and Flow Number

Permanent deformation refers to the plastic deformation of HMA under repeated loads [2]. An approach to determine the permanent deformation characteristics of paving materials is to employ a repeated dynamic load test for several repetitions and record the accumulated permanent deformation as a function of the number of cycles (repetitions) over the testing period [7].

Universal Testing Machine (UTM) is an apparatus that provides repeated dynamic load for a Dynamic Creep Test. In this test, a repeated pulsed uniaxial load is applied to an asphalt specimen and the accumulated deformation of the specimen under the repeated load is measured. Dynamic Creep Test, in this study, is based on Australian standard AS 2891.12.1-1995 [8]. The operator of the UTM can select the loading parameters. Based on AS 2891.12.1-1995, the following loading parameters are used:

Loading wave shape: square pulse; Pulse width: 0.5 sec.; Rest period: 1.5 sec.

Contact stress: 2*kPa*; Deviator stress[1]: 300*kPa*.

A temperature of 50°C was utilized for all specimens for three hours (the time required to satisfy the conditions of AS.2891.12.1-note 3) before the test and during the test. Specimens were held in an environmentally controlled chamber throughout the mentioned sequence.

Fig. 6 shows a UTM and a specimen mounted in the machine for Dynamic Creep Test. Implementing the test, UTM software reports the test results in form of an S-shaped curve. This cumulative permanent strain curve is generally defined by three zones: primary, secondary, and tertiary zones (Fig. 7). The starting point, or cycle number, at which tertiary flow occurs is referred to as the flow number [7]. The operator cannot measure the rutting depth using the flow number, but this value is a criterion to compare creep behavior of different HMA specimens or their resistance to permanent deformation. A sample of dynamic creep report provided by UTM software is illustrated in Fig. 7. The report also includes setting parameters.

Using the determined optimum bitumen contents, the main specimens were prepared and exposed to Dynamic Creep Test. For each gradation on each test, three specimens were prepared (AS 2891.12.1).

Results and Discussions

The collected test results are presented and discussed in the following paragraphs.

Determined Optimum Bitumen Contents

Fig. 8 demonstrates the reduction or increment in OBC of Fuller gradations compared to IHAPC gradations.

Compared to IHAPC gradations, gradations that were generated by Eq. (1) with "n" exponents of 0.45 and 0.5 resulted in lower OBC, but the exponent of 0.55 resulted in higher OBC. This happens because compared to IHAPC gradations 0.45 and 0.5 exponents result in denser mixture, but the 0.55 exponent results in a looser mixture. Low bitumen content, however, may result in low durability and low resistance to fatigue cracking. As a result, the mentioned issues are recommended to be evaluated for B-2&3 and S-2&3 mixtures.

Dynamic Creep Test Results

Fig. 9 demonstrates the Dynamic Creep Test results. Flow numbers that are presented in the graph of Fig. 9 are the average flow numbers obtained from three tests for each mixture type. Fig. 9 also presents the values of standard deviation (SD) and coefficient of variation (CV) of the three flow numbers for individual mixture groups.

The results show that all Fuller gradations resulted in mixtures with greater flow numbers, comparing to IHAPC gradations, i.e., more resistance to permanent deformation.

Considering the unit weight versus bitumen content curves (Fig. 5), the 0.45 exponent, resulted in the densest mixtures. Hence, these mixtures have the most aggregate interlock. In addition, OBC of these mixture types is the least, among the four types of each category. These reasons make B-2 and S-2, the most permanent deformation resistant mixtures.

On the other hand, the 0.55 exponent resulted in mixtures that have unit weights close to IHAPC gradations and in contrast with the other two exponents, 0.55 resulted in higher OBC, compared to IHAPC gradations. However, B-4 and S-4 showed more resistance to permanent deformation compared to B-1 and S-1, respectively. This can be justified by the greater particle to particle contact of the first pair compared to the second pair, which is due to their greater portion of coarse aggregates (particles bigger than 4.75*mm*).

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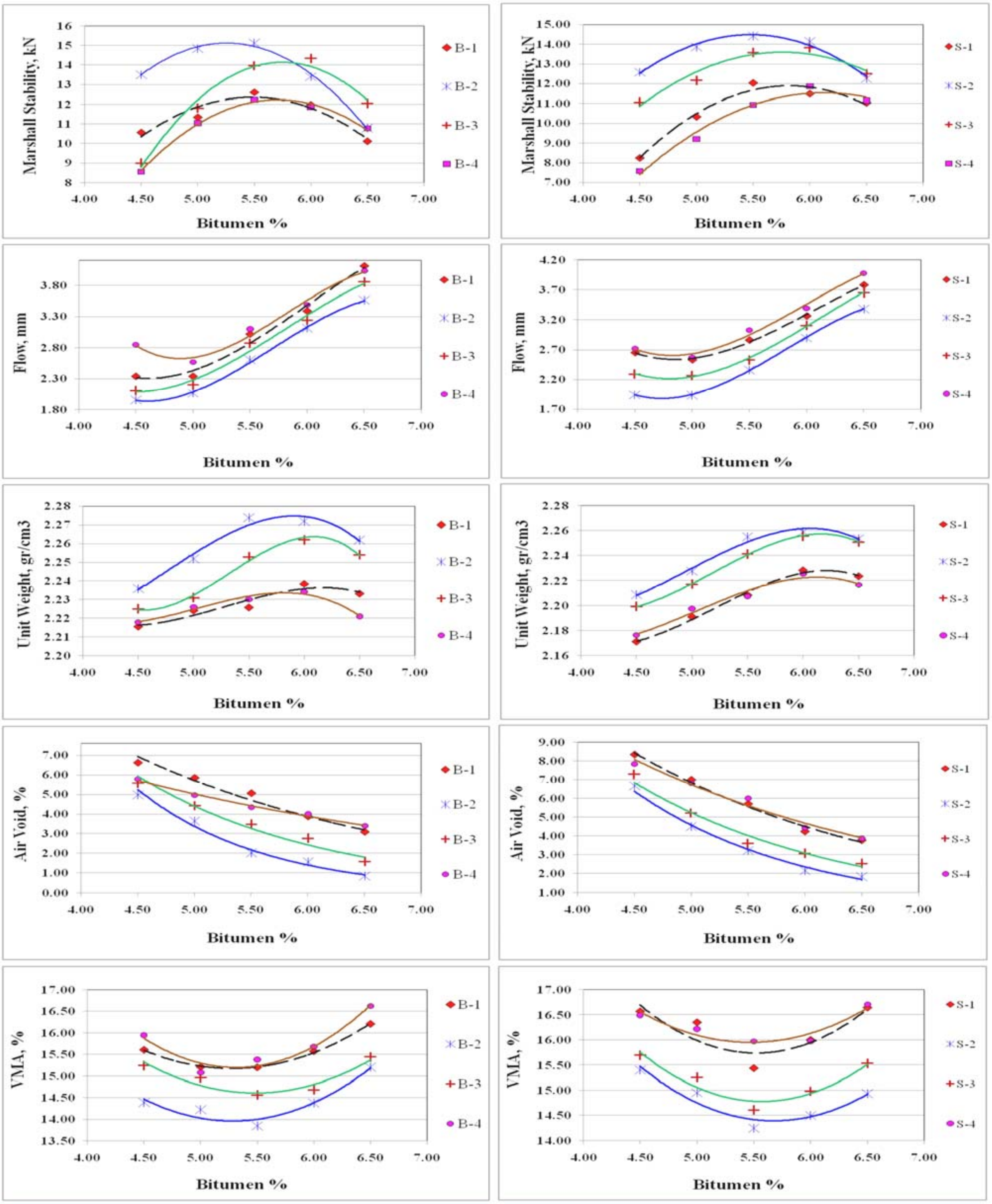
[1] According to AS 2891.12.1, "a range of temperatures and compressive stresses, to match field design conditions may be permitted in other circumstances."



Optimum Bitumen Content			
B-1	**B-2**	**B-3**	**B-4**
5.9	**4.7**	**5.2**	**6.0**

Optimum Bitumen Content			
S-1	**S-2**	**S-3**	**S-4**
6.1	**5.1**	**5.4**	**6.3**

Fig. 5. Marshall Method Plots and Determined Optimum Bitumen Contents.

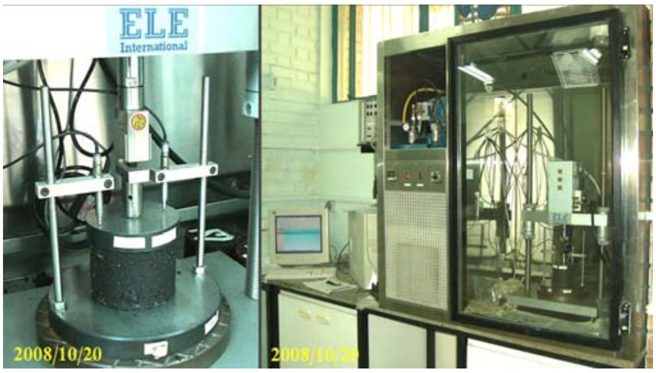
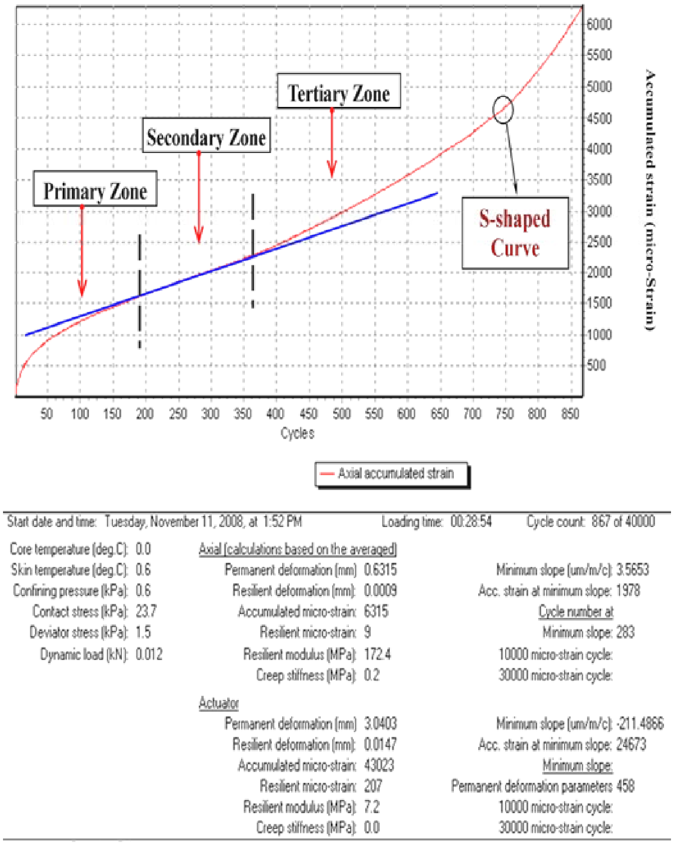


Fig. 6. UTM (Right) and Specimen Mounted in the Machine for Dynamic Creep Test (Left).



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Start date and time:  Tuesday, November 11, 2008, at 1:52 PM        Loading time:  00:28:54      Cycle count:  867 of 40000

Core temperature (deg.C):  0.0     Axial (calculations based on the averaged)
Skin temperature (deg.C):  0.6           Permanent deformation (mm)  0.6315         Minimum slope (um/m/c):  3.5653
Confining pressure (kPa):  0.6           Resilient deformation (mm):  0.0009    Acc. strain at minimum slope:  1978
    Contact stress (kPa):  23.7           Accumulated micro-strain:  6315                  Cycle number at
   Deviator stress (kPa):  1.5               Resilient micro-strain:  9                    Minimum slope:  283
       Dynamic load (kN):  0.012          Resilient modulus (MPa):  172.4        10000 micro-strain cycle:
                                            Creep stiffness (MPa):  0.2          30000 micro-strain cycle:

                                   Actuator
                                         Permanent deformation (mm)  3.0403         Minimum slope (um/m/c):  -211.4866
                                         Resilient deformation (mm):  0.0147    Acc. strain at minimum slope:  24673
                                          Accumulated micro-strain:  43023                 Minimum slope:
                                             Resilient micro-strain:  207   Permanent deformation parameters  458
                                          Resilient modulus (MPa):  7.2          10000 micro-strain cycle:
                                            Creep stiffness (MPa):  0.0          30000 micro-strain cycle:
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Fig. 7. Primary, Secondary and Tertiary Zones on a Printable Dynamic Creep report Provide by UTM Software.

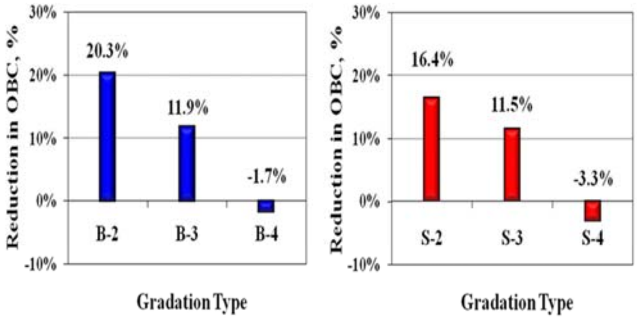
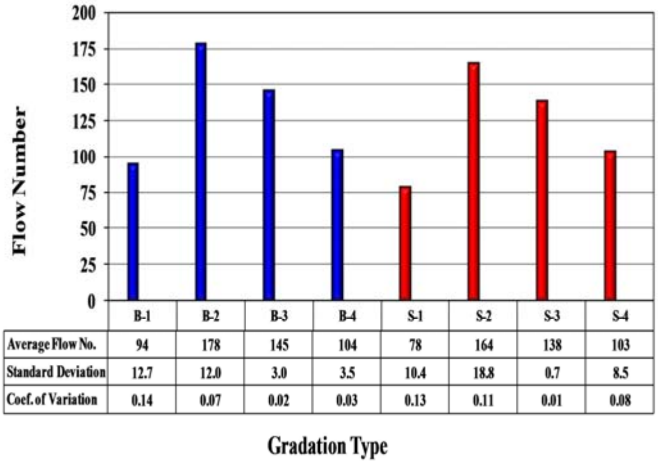


Fig. 8. Reduction or Increment in OBC of Fuller Gradations Compared to IHAPC Gradations.



	B-1	B-2	B-3	B-4	S-1	S-2	S-3	S-4
Average Flow No.	94	178	145	104	78	164	138	103
Standard Deviation	12.7	12.0	3.0	3.5	10.4	18.8	0.7	8.5
Coef. of Variation	0.14	0.07	0.02	0.03	0.13	0.11	0.01	0.08

Fig. 9. Dynamic Creep Test Results for Mixtures with Optimum Bitumen Content and Values of SD and CV for Individual Mixture Groups**.**

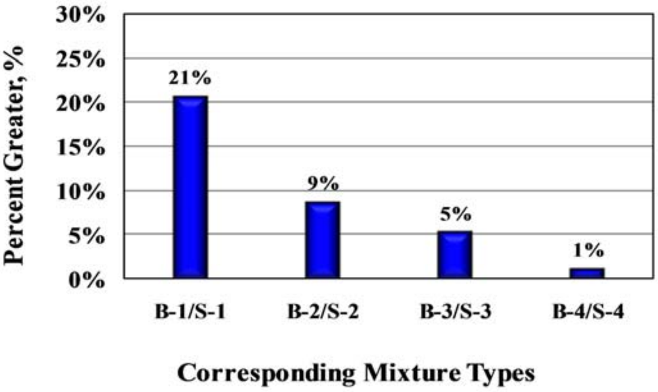


Fig. 10. The Percentage by which the Flow Number of Each Coarser Mixture is Greater than its Corresponding Finer Mixture.

By comparing the Dynamic Creep Test results of the two categories, it is revealed that mixtures of the first category that contain coarser aggregates show more resistance to permanent deformation than their corresponding gradations in the second category. In other words, coarser mixtures are more resistant to permanent deformation than finer mixtures. Fig. 10 shows the percentage by which the flow number of each coarser mixture is greater than its corresponding finer mixture.

Conclusion

Effect of the "n" exponent of fuller equation on resistance of HMA to permanent deformation was evaluated in this research. The conclusions are as the following:

Compared to IHAPC gradations, all applied Fuller gradations resulted in mixtures with greater flow numbers, i.e., more resistance to permanent deformation. However, the low bitumen content of B-2&3 and S-2&3 may result in low durability and low resistance to fatigue cracking. Hence, proper considerations are recommended for these mixtures.

B-2 and S-2 have the greatest aggregate interlock and the least OBC due to their densest gradations. Hence, they show the greatest resistance to permanent deformation. After these types, B-3 and S-3 have the most resistance to permanent deformation for the same reasons. B-4 and S-4 are the loosest mixtures and have the highest OBC, and among the Fuller gradations, they show the least resistance to permanent deformation. However, due to their greater amount of coarse aggregates, which results in more stone on stone contact, they show more resistance to permanent deformation than B-1 and S-1 do.

Generally, mixtures of first category, which contain coarser aggregates, show more resistance to permanent deformation than their corresponding mixtures in the second category. However, the difference between B-4 and S-4 seems negligible.

After all, in case durability and fatigue resistance of these mixtures are proven to be sufficient, respectively, mixtures made of the Fuller Equation with “n” exponents equal to 0.45, 0.50, and 0.55 are suggested to be used instead of conventional mixtures.

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