Experimental Investigation of the Coarse Aggregate Angularity Effect on Mechanical Performance of HMA

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Abstract

The variation of the coarse aggregate angularity (CAA) can influence the interlocking of the stone particles and consequently have an important effect on the shear strength, stiffness and asphalt-aggregate interaction.

The present study related the coarse aggregate angularity to the laboratory fatigue and creep performance of asphalt pavements. Asphalt mixtures with different levels of crushed gravel were evaluated through static and dynamic loading tests. Coarse aggregate properties were characterized through fracture surface counts, direct shear and resilient modulus tests.

The results of this research indicated that coarse aggregate properties, mainly CAA have significant effect on mechanical properties of HMA.

Keywords: Asphalt pavements, coarse aggregate angularity, mechanical properties, fatigue life, creep compliance.

Introduction

With the development of the higher tire pressures and larger traffic loads, permanent deformation has become a critical concern during mix design of HMA. Severe rutting will cause safety problems for the traffic and lower the performance of asphalt pavements [1]. Rutting in asphalt mixture is generally caused by the densification and/or the shear flow of materials under repeated traffic loads [2].

Rutting resistance of asphalt concrete under traffic and environmental loads depends on the stability of aggregate structure in the asphalt mix [3]. Previous research studies that realized the important role the coarse aggregate plays in the rutting behavior of HMA related stability of aggregate structure to coarse aggregate morphologies [4,5]. Effects of coarse aggregate morphologies on the rutting resistance of HMA have been highlighted according to different levels of shape irregularities, such as the overall shape, angularity, and texture, by both field observations and laboratory standard tests. In these studies, asphalt mixes that included particles with angular shape and/or rough texture were found to have higher stability of the aggregate structure. The proper selection of materials is one of the most important tasks in developing an asphalt mixture that shows improved resistance to permanent deformation. Results of previous investigations to determine the type of aggregates that provide better resistance to permanent deformation show that angular aggregates play a major role in contributing to greater stability (resistance to deformation and plastic flow) of hot mix asphalt concrete. These studies show that angular aggregates, through interlocking and shear resistance, can improve mixture shear strength that is a measure of load bearing capacity and resistance to rutting and shoving (horizontal displacement of an asphalt mixture) [6,7,8,9].

In studying an asphalt mixture's rutting resistance, three phases of this composite material can be identified as the coarse aggregate particles, fine aggregate particles, and the mastic. The mastic phase consists of the asphalt binder, air voids, and a small amount of solid fines or fillers (passing 0.075 mm or No. 200 sieve in mechanical sieve analysis). Both the coarse aggregate phase and the fine aggregate phase have a comparatively high uniformity in composition and high physical stiffness and resistance to permanent deformation. Having a composite nature and a much lower stiffness, the mastic material has a higher potential to generate permanent deformation under traffic loads and therefore has a minor contribution to the rutting resistance of dense graded

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asphalt mixture compared to that of the two aggregate phases. The coarse aggregate particles in asphalt mixes refer to the portion of aggregate retained above the No. 4 sieve in the mechanical analysis. But according to previous researches, coarse aggregate particles contribute more to the rutting resistance of HMA through particle interlock. However the effect of the fine aggregate phase on the rutting resistance of HMA is also important. Fine aggregate particles refer to the portion between No. 4 sieve and No. 200 sieve in a mechanical sieve analysis, which are usually used as the intermediate sized materials filling the voids between the coarse aggregate particles [3]. Research studies based on conventional laboratory tests have reported contradictory findings about fine aggregate contributions to rutting and permanent deformation performances of asphalt mixes [4,10].

However, many concerns have been raised on the coarse aggregate angularity. For the most part, the requirements for CAA have been too stringent for practical applications. The recently finished National Cooperative Research Program (NCHRP) 9-35 has been focusing on the literature of this topic. According to the NCHRP report (NCHRP 2005), the current findings about the CAA to the rutting performance of HMA can mainly concluded in one sentence that the increased coarse aggregate fractured surfaces provide an increase in rutting resistance [11].

The objective of the present study was to evaluate the effect of coarse aggregate angularity on the mechanical performance, mainly permanent deformation, creep phenomena and fatigue resistance of HMA mixtures through laboratory testing. The results of this work provide a basis for developing aggregate-related specifications in an attempt to provide the ability (level of stability and shear strength) of asphalt concrete to withstand the stresses in asphalt concrete pavements.

Experimental studies

-Laboratory program

A laboratory experiment was conducted to characterize the shear strength characteristics of coarse aggregate with various CAA levels. The rut-performance of laboratory–made HMA mixtures containing these aggregates was also evaluated in this study. Two types of coarse aggregate (crushed and uncrushed gravel) were used. Direct shear test and resilient modulus tests were performed to evaluate the shear strength and the stiffness under cyclic loading of aggregates. Furthermore resistance against creep and fatigue characteristics of mixture were examined through Nottingham Asphalt Tester device. The tests include indirect tensile fatigue test (ITFT) and dynamic creep test. The laboratory program can be seen in table 1.

Table 1- Laboratory Program

Material		Aggregate Tests		HMA Tests	
Aggregate	CAA	Direct Shear	Resilient Modulus	ITFT	Creep Test
Gravel	30	Yes	Yes	Yes	Yes
	45	Yes	Yes	Yes	Yes
	60	Yes	Yes	Yes	Yes
	70	Yes	Yes	Yes	Yes
	95	Yes	Yes	Yes	Yes

-Materials

The coarse aggregate used in this study were gravel with nominal maximum size of 12.5-mm. The two types of gravel (crushed and uncrushed) used in this study were of the same gradation and have the same bulk specific gravity of 2.54. The crushed (CAA=100%) and uncrushed (CAA=0) gravels were blended in different proportions to obtain the coarse aggregate of different CAA levels.

-HMA mixture design

Standard Marshall Mix design procedure (2×75 blows) (ASTM D1559) was used to design the asphalt mixture [12]. In order to compare the effect of CAA level only, common asphalt content of 6% was used for HMA mixture with different CAA levels. The mixture was designed to satisfy the conditions of Iranian Standards of highway and pavement design (Issue number 101) Topeka mixture. 150-mm diameter cylindrical samples were compacted by the Marshall compactor. Five samples with each CAA level were made and tested.

-Direct shear test

The direct shear test of coarse aggregate is similar to the direct shear test of soil except its difference in shear box size. The size of the square shear box is 2516 cm^2. The aggregate sample was carefully prepared by letting coarse aggregate falling down freely from same height to the shear box. The shear forces and displacements were continuously recorded while the aggregate material is sheared under different normal stresses. The shear rate was adopted at 25.4 mm/min to simulate the vehicles speed. The Mohr-Coulomb shear strength of coarse aggregate can be expressed as:

$$\tau = \sigma_n tan\phi \quad (1)$$

Where τ is the shear stress at failure, while σ_n is the normal stress at which failure take place. The results were used to define the internal friction angle of aggregates for each CAA levels.

-Resilient modulus test

The resilient modulus test of aggregates was conducted in accordance with AASHTO T 307 to obtain the stiffness of coarse aggregates [13]. During the test a cylindrical specimen is subjected to a repeated axial cyclic stress of fixed magnitude, load duration (0.1 s) and a static confining stress. The resilient modulus is defined as the ratio of the amplitude of the repeated axial stress to the amplitude of the resultant recoverable axial stress,

$$M_r = \frac{\sigma_{cyclic}}{\varepsilon_r} \quad (2)$$

Where in the following equation, M_r is the resilient modulus of the aggregates mix, σ_{cyclic}, cyclic axial deviatoric stress, and ε_r is the recovered axial strain.

-The Indirect Tensile fatigue test (ITFT)

The fatigue performance of the asphalt mixture was determined by means of the ITFT. Among the various types of the fatigue tests, ITFT is an effective and also widely used method. The ITFT tests were performed using the following test parameters:

-Specimen's diameter: 100 mm,
-Specimen's height: 40 mm,
-Loading condition: controlled stress,
-Loading rise-time: 124 ms,
-Load pulse rate: 40 pulses/min and
-Failure indication: 9 mm vertical deformation.

It should be noted that for a better comparison, fatigue life tests were carried out at a constant initial strain of 0.001 (mm/mm) at the bottom of the asphalt concrete layer.

-Creep test

The creep compliance is determined by applying a dynamic compressive load of fixed magnitude along the diametral axis of a cylindrical specimen. The vertical deformation was measured by two LVDTs. Load is selected so as to keep the material's response in the linear viscoelastic (LVE) range. This is accomplished by keeping horizontal deformation below 0.089 mm. Vertical deformation is measured in the central region of the specimen, away from the localized stress concentration caused by the loading conditions. The creep compliance test is performed on each specimen at temperature of 25°C. In this experimental work, specimens were tested with diameter of 100 mm and the height of 70 mm for creep test. The specimens that were used in the creep test are kept in an environmentally protected (enclosed area not subjected to the natural elements) storage area at temperature about 24°C.

Results and discussion

-Direct shear test results

The result of direct shear test on aggregate mixtures with determined CAA levels can be seen in Fig. 1. It can be concluded from the results that the shearing angle of coarse aggregates having a CAA level of more than 70 percents are generally higher than those with a CAA level of less than 45 percents.

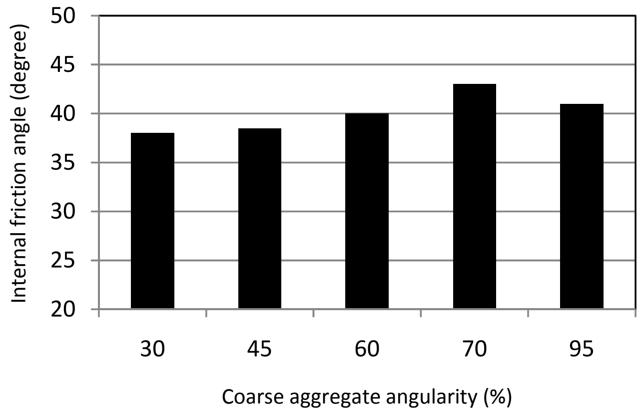

Figure 1- Internal fiction angles of coarse aggregate vs. CAA levels

However at high CAA levels the results did not indicate any significant differences. The results are consistent with the ones obtained by previous researchers [1]. It can be stated that angularity represents the irregularity of particle surfaces. High stress concentrations often exist at sharper corners in the contacting angular aggregates, which make interlock the primary mechanism for stability. Interlock characterizes behavior of a group of physically connected particles, which possess a somewhat stable structure and allows little relative movement between the particles.

-Resilient modulus test results

Resilient modulus tests were conducted on 30,45,60,70 and 95% CAA levels. The resilient modulus M_r was determined from the average of the last five measurements (95th to 100th load cycles) of the resilient strain ε_r and deviator stress σ_d :

$$M_r = \frac{\sigma_{cyclic}}{\varepsilon_r} \qquad \text{(repeated)}$$

Since the void ratio (density) and the overall angularity of the mixture affect the resilient modulus, the results were analyzed at a constant density to determine the influence of the mixture angularity on the resilient modulus.

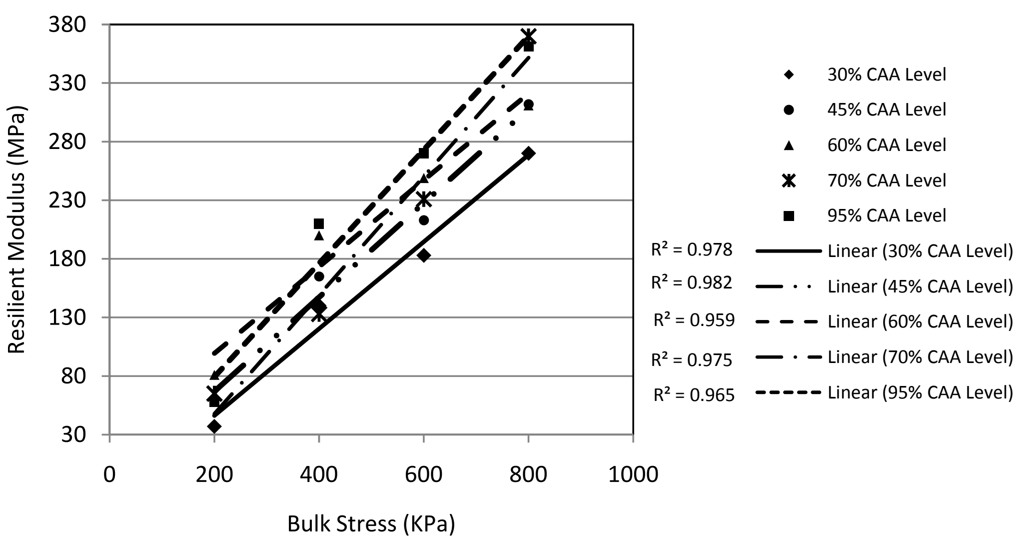

Figure 2- Resilient Modulus vs. bulk stress variation of aggregates with different CAA levels

Results of resilient modulus of aggregates mixture with the variation of bulk stress can be seen in figure 2. From the figure, it can be seen that there is a significant increase in the values of resilient modulus by increasing the CAA level to any levels higher than 45%. However the effect of aggregate angularity on the resilient modulus values will decrease in mixtures of high CAA levels, i.e. CAA levels more than 60%. The other note which can be concluded from figure 2 is that the rate of increase in resilient modulus of aggregates mixtures with increase in bulk stress would rise significantly in mixtures with higher CAA levels. This phenomenon could be the result of the interlocking of the particles. In the aggregates mixtures with higher CAA levels, the interlocking of the particles will increase, therefore their sensitivity to bulk stress rises consequently, which result in higher values of resilient modulus.

-Creep test results of HMA mixtures

Figure 3. shows the results of dynamic creep tests carried out on HMA samples with aggregates of different CAA levels. Dynamic creep tests consisted of 10,000 s of cycles of loading and 1,000 s with no load. Deformation as a function of time was recorded throughout each portion of the test.

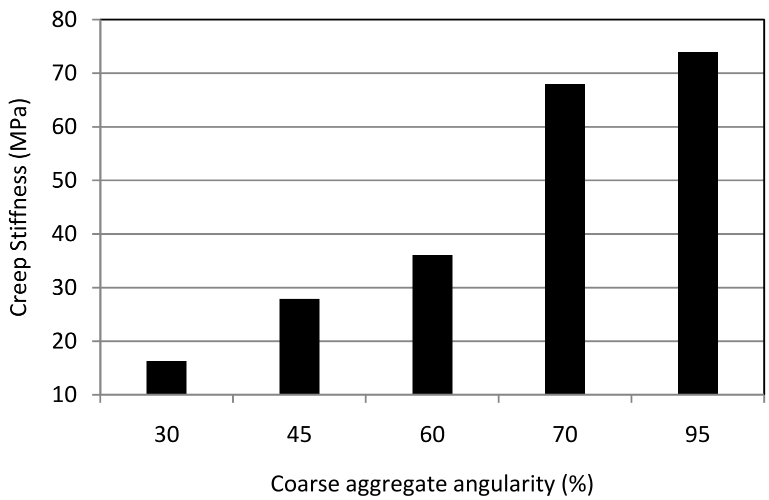

Figure 3- Creep stiffness of HMA mixtures with variation of CAA levels

As can be seen in the results of experiments, the creep stiffness increases with the increase in percentage of crushed coarse aggregates (i.e. increasing the CAA level) since the permanent deformation decreased with the increase in the amount of crushed coarse aggregates. Decreased permanent deformation in this test is indicative of decreased rutting in a corresponding asphalt pavement. From the previous researches carried out on the mechanism of rutting and permanent deformation of HMA mixtures, it is observed that AC surface course rut depths tend to increase as the percentage of flat and elongated particles in the asphalt mixture increases. Therefore, using more of the angular or better-crushed coarse aggregate particles in asphalt mixes, can improve the stability of the HMA and its aggregate structure. The findings, in general, indicate that the asphalt mixes containing more angular coarse aggregate particles possessed stronger aggregate structures and higher stability. The coarse aggregate particles in asphalt mixes refer to the portion of aggregate retained above the No. 4 sieve in the mechanical analysis. However, due to the dominant usage and big particle sizes, coarse aggregate particles contribute more to the rutting resistance of HMA through particle interlock. However the effect of the fine aggregate phase on the rutting resistance of HMA is also important. Fine aggregate particles refer to the portion between No. 4 sieve and No. 200 sieve in a mechanical sieve analysis, which are usually used as the intermediate sized materials filling the voids between the coarse aggregate particles. Research studies based on conventional laboratory tests have reported contradictory findings about fine aggregate contributions to rutting performances of asphalt mixes [4,10]. Therefore, the results of this part of the study about the effect of CAA level on creep resistance of HMA are relevant with the previous researches on the rutting behavior of HMA.

-Indirect tensile fatigue test results of HMA mixtures

The results of indirect tensile fatigue test on HMA specimens are presented in figure 4. The fatigue resistance

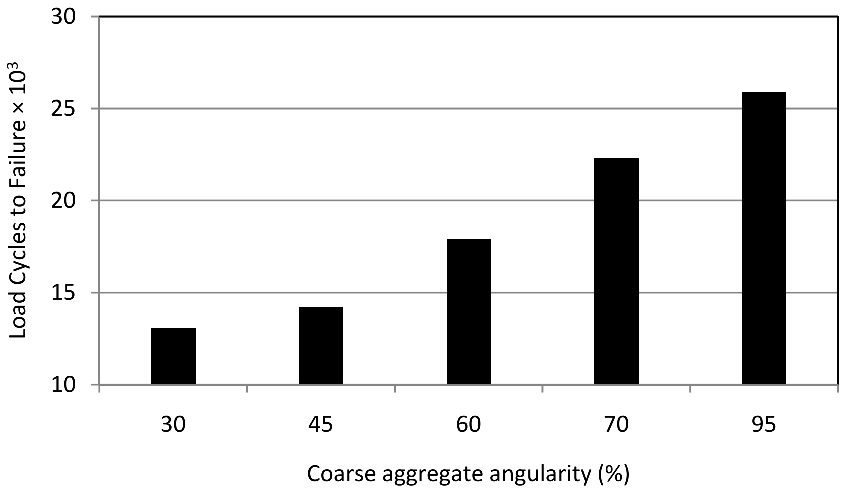

Figure 4- Fatigue life values of HMA mixtures with variation of CAA levels

of HMA mixture was characterized by the load cycles to failure (N). The results indicate a significant increase in the fatigue resistance of HMA with the increase of CAA levels to the values higher than 30%. This phenomenon would be the result of the increase in the resilient modulus of the mixture. However, the mixtures with a higher CAA level would have a greater value of friction angle, which consequently increase the fatigue resistance of the materials and the mixture.

Conclusions

Based on the experimental studies carried out in this research, the following conclusions can be drawn:

- Except of relatively low CAA levels, (<30%) resilient modulus test was not able to characterize the angularity of coarse aggregates. However the relationship between the resilient modulus and bulk stress (confining pressure) indicated that less angular coarse aggregate could be used in the base and subbase layers rather than surface layers.
- There is a thorough consistency between the results presented herein for the creep behavior of HMA vs. CAA levels with the ones obtained by previous researchers for permanent deformation of asphalt pavement structures.
- The increase in the CAA levels of aggregates mixture would lead to an increase in the fatigue resistance of the HMA mixture. However, at CAA levels lower than 45% this increase would be more considerable.
- Considering the effect of CAA level on the mechanical performance of HMA mixtures, either on the materials part (aggregates), or on the behavior and strength of the mixture (including strength against creep and fatigue resistance), this parameter could be characterized as an important one which needs a careful attention in design of asphalt pavement structures.

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