The Effect of Filler/Asphalt Ratio on Voids in Mineral Aggregate and Asphalt Film Thickness in Hot Mix Asphalt

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Abstract

Asphalt durability is often linked to the thickness of the asphalt coating on the aggregate particles. In order for a pavement to have adequate film thickness, there must be sufficient space between the aggregate particles in the compacted pavement. This void space is referred to as Voids in the Mineral Aggregate (VMA). It must be sufficient to allow adequate effective asphalt (that which is not absorbed into the aggregate particles) and air voids.

Marshall mix design was used, first to determine the optimum bitumen binder content and then further to test the mixtures properties of the various filler / asphalt ratio asphalt mixtures. In total, 75 samples were prepared to investigate the optimum asphalt content of the various mixes and to specify properties of them. Five proportions of asphalt cement binder were used for each mix type and state by weight of the total mix (4, 4.5, 5, 5.5, and 6). The tests include the determination of bulk specific gravity, maximum (theoretical) specific gravity, stability and flow. Marshall mix design requires the determination of the percentages of air voids, voids in mineral aggregate, and voids filled with asphalt.

Due to the results, we found out that when the filler asphalt ratio is in the range between 1.2 and 1.5, the mixture's performance are better in all respects. If some aspects of mixture performance need to be modified, the filler asphalt ratio can adjusted on this basis.

Key words: Hot Mix Asphalt, filler / asphalt ratio, voids in mineral aggregate.

المستخلص:

إن ديمومة الإسفلت تربط في اغلب الاحيان بسمك طبقة القير المحيطة بحبيبات الركام. لكي يتمكن التبليط الاسفلتي من امتلاك السمك الكافي من القير، لا بد ان تكون هناك فراغات كافية بين حبيبات الركام في التبليط المضغوط. هذه الفراغات يشار لها بـ (الفراغات في الركام المعدني) (VMA). وهذه الفراغات يجب ان تكون كافية للسماح بكمية كافية من القير الفعال (الذي لم يمتص من قبل حبيبات الركام) و الفراغات الهوائية.

ان طريقة مارشال لتصميم الخلطة الاسفلتية استعملت اولاً لتحديد المحتوى القيري الامثل ثم بعد ذلك لاختبار خواص الخلطات لنسب مختلفة من المادة المالئة الى القير. كمجموع فانه تم تحضير 75 نموذج لهذا الغرض. خمسة نسب من المادة الرابطة استعملت لكل نوع من الخلطات محسوبة من الوزن الكلي للخلطة (6 ,5.5 ,5 ,4.5 ,4). تتضمن الفحوصات تحديد الوزن النوعي الكلي، الوزن النوعي الاقصى (النظري)، وثبات و زحف مارشال. طريقة مارشال لتصميم الخلطة الاسفلتية تتطلب ايضا تحديد النسب المئوية للفراغات الهوائية (AV%)، الفراغات في الركام المعدني (VMA)، والفراغات المملوئة بالقير(VFA).

وفقا للنتائج، فانه عندما تكون نسبة المادة المالئة الى الاسفلت في المدى بين (1.2 و 1.5), فتصرف الخليط يكون افضل بالكامل. اذا احتاجت بعض مواصفات الخلطة للتحسين، فانه يمكن تعديل نسبة المادة المالئة الى القير على هذا الاساس.

1. Introduction:

It is generally believed that an asphalt paving mixture should have an adequate asphalt film thickness around the aggregate particles to ensure reasonable durability (resistance to aging) of the mixture. The minimum asphalt film thickness generally recommended ranges from six to eight microns. However, no significant background research data is available in the literature to support these recommended minimum asphalt film thicknesses. Some states specific minimum asphalt film thickness for mix designs (Kandhal and Chakraborty (1996)). One of the advantages of the Marshall Mix Design method is that the performance of the mixes can be expected for local materials and environmental impact.

The Marshall design method was used to determine the optimum asphalt content for different filler asphalt ratios of hot mix asphalts. Based on this method, the pavement performance of different filler asphalt ratios is recommended.This parameter is very important in the application of hot mix asphalt.

In this study, Marshall Mixes will be designed for surface course of pavement. The experimental design used in this study provides a comparison among five types of mixtures using different filler/asphalt ratios (0.9, 1.1, 1.3, 1.5, and 1.7). We used Portland cement as filler.

The work was limited to one type of gradation and one source of aggregate (Al Nibaae aggregate), and one type of asphalt cement from Al Dora refinery in Baghdad with 40-50 gradation. One nominal maximum size aggregate (12.5mm) was used in these mixes.

1.1 Objectives:

The main objective of this research was to review several researches implemented to establish a foundation for the filler asphalt ratio, voids in mineral aggregate, and asphalt film thickness to help for further work, and to recommend limits for these parameters. Incorporation of the concept of filler asphalt ratio and its relationship to asphalt film thickness and VMA was also investigated.

Final conclusions and recommendations are based on a summary of the data accumulated during the research.

2. Background:

2.1 General Description of Mortar Theory:

Modern mortar theory considers an asphalt mixture as a dispersion system with a multi- dimensional net-like structure. First there is a kind of coarse dispersion system, with the coarse aggregate as the part that disperses in the coarse asphalt mortar. Similarly, the coarse asphalt mortar is a fine dispersion system, with the fine aggregate as the part that dispersed in the asphalt mortar. The mortar itself is a kind of micro-dispersion system, with the filler as the part that disperses in the heavy-consistency asphalt. This theory can be explained by Figure (1). (Cong and Zheng, 2005).

2.2 Durability of Hot Mix Asphalt:

Durability of an asphalt mixture refers to the ability of the mixture to retain the original properties. These include the resistance to load and abrasion. Resistance to load can be impaired when (Bruce and others, 1999):

1. The asphalt becomes hard and brittle and thus cannot withstand strains without fracturing.
2. The asphalt debonds from the aggregate (truly strips) causing the surface to lose strength and subsequently crack and disintegrate.

Durability also refers to the ability of the mixture to resist abrasion of the surface due to the scraping action of tires combined with water. The surface is more susceptible to abrasion if:

1. The void content is high allowing air and water to prematurely harden the asphalt.
2. The asphalt and aggregate are not chemically compatible, making it easier to "strip" the asphalt from the aggregate.
3. The asphalt film thickness is not sufficient to protect the mix from the abrasive action of tires and water.

2.3 Voids in Mineral Aggregate (VMA):

VMA is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of the asphalt not absorbed into the aggregate (Roberts *et al* (1991)). Stated another way, VMA describes the portion of space in a compacted asphalt pavement or specimen which is not occupied by the aggregate. VMA is expressed as a percentage of the total volume of the mix.

Kandhal, Foo, and Mallick, 1998, proposed that rather than specifying a minimum VMA requirement based on minimum asphalt content as recommended by McLeod and adopted by Superpave, a more rational approach is to directly specify a minimum average asphalt film thickness of 8 microns. They pointed out that the term “film thickness” is difficult to define. To calculate an average film thickness, the surface area is determined by multiplying the surface area factors (given in the Asphalt Institute Manual) by the percentage passing the various sieve sizes. However, they could not find the background research data for the surface area factors in the literature. They concluded that further research is needed to verify these surface factors and the concept of film thickness.

When aggregate particles are coated with asphalt binder, a portion of the asphalt binder is absorbed into the aggregate, whereas the remainder of the asphalt binder forms a film on the outside of the individual aggregate particles. Since the aggregate particles do not consolidate to form a solid mass, air pockets also appear within the asphalt-aggregate mixture. Therefore, as Figure (2) illustrates, the four general components of HMA are: aggregate, absorbed asphalt, asphalt not absorbed into the aggregate (effective asphalt), and air. Air and effective asphalt, when combined, are defined as VMA. (Bruce and others, 1999).

Figure (2) illustrates how VMA is derived in terms of volume and mass. VMA is the percentage of the compacted HMA mixture that is made up of asphalt not absorbed into the aggregate and air voids. Asphalt not absorbed into the aggregate is referred to as the effective asphalt binder.

The importance of designing VMA into an HMA mix has been recognized for many years. It was first discussed and used by McLeod in 1956. For many years, the Asphalt Institute mix design procedures have used a minimum VMA criteria that is dependent upon maximum aggregate size. If the VMA is too low, it can be increased by modifying the gradation, asphalt content, or particle angularity. Table (1) shows typical minimum VMA values recommended by the Asphalt Institute, 2001.

2.4 Asphalt Film Thickness:

One of the key elements in the durability and moisture susceptibility of an asphalt mixture is asphalt film thickness. Asphalt film thickness describes the dimension of the asphalt binder coating of the aggregate particles. A thin asphalt coating on aggregate particles is one of the primary causes of premature aging of the asphalt binder, and is one definition of lack of durability.

According to Roberts, et al (16), inadequate film thickness can create a lack of cohesion between aggregate particles and create a "dry" mix. Also, if the asphalt film is too thin, air which enters the compacted HMA can more rapidly oxidize the asphalt, causing the pavement to become brittle. Additionally, if the aggregates are hydrophilic, thin asphalt films are more easily and rapidly penetrated by water than thick ones, causing stripping or debonding of the asphalt binder from the aggregate.

Beyond Heitzman (7), the use of todays’s computing power and mathematical models gives as the opportunity to better understand film thickness as a tool to measure HMA durability. His new model is based on random spatial distribution of particles had applied to the film thickness concept and compared to Iowa DOT HMA mixtures. The results indicate that this new model may better measure mixture durability because it is sensitive to more variables that impact durability.

Kandhal and Chakraborty (10) noted difficulties in defining the concept of an “average film thickness”. The validity of assigning a film thickness calculated simply by dividing the total surface area of the aggregate, obtained from its gradation, by the volume of effective asphalt binder is questionable. It is unlikely that all the particles in a mix will have the same average asphalt film thickness. Coarser aggregate particles may or may not have the film thickness that fine aggregate particles have, and the extremely fine portions of the aggregate may become embedded in the asphalt binder completely.

The following asphalt mix properties are needed for calculations (standard test procedure manual, 2001):

a) Percent asphalt in mix
b) Theoretical maximum theoretical specific gravity
c) Bulk specific gravity of aggregate
d) Gradation of the designated sieves
e) Asphalt specific gravity

Using the following surface area characteristics for the specified sieve sizes, calculate the total surface area of the aggregate in your mix;

If the gradation analysis is reported in sieve sizes other than those shown, we can interpolate to estimate the percent passing on the above noted sieves.

SST = 0.41 + 0.41a +0.82b +1.64c + 2.87d + 6.14e 12.29f + 32.77g …………(1)

Where: SST = aggregate surface area in m^2/kg of dry aggregate. And **a,b,c,d,e,f** and **g** = the percent of total aggregate passing the #4, #8, #16, #30, #50, #100 and #200 sieves respectively.

Calculate the Absorbed Asphalt using the formula:

$$\text{Absorbed Asphalt } (Pba) = 100 \text{ x } \left(\frac{Gse - Gsb}{Gsb \times Gse}\right) \text{ x } Gb \quad \text{…………..(2)}$$

where:

Gse = effective specific gravity of aggregate
Gsb = bulk specific gravity of aggregate
Gb = specific gravity of binder

$$P_{ba} = \%\text{ Absorbed Asphalt x } \frac{100}{100 + \%\,Asphalt} \quad \text{…………….(3)}$$

Calculate Effective Asphalt (P_{be}) by total mix basis

$$\text{Effective Binder Content (Pbe)} = Pb - \left(\frac{Pba}{100} \times Ps\right) \quad \text{……………(4)}$$

Where:

Pb = binder content, percent by total weight of mixture
Ps = aggregate content, percent by total weight of mixture

Calculate Effective Film Thickness (F_{be}) in ⌠m

$$F_{be} = \frac{981 \times P_{be}}{SST \times (100 - P_b)} \quad \text{……………(5)}$$

The Dust Proportion ratio (DP) is the ratio of the amount passing the75 µm sieve to the effective asphalt content by total mix.

$$DP = \frac{\text{Percent Passing 75 µm sieve}}{\text{Percent Effective Asphalt } (P_{be})} \quad \text{…………...(6)}$$

3. Aggregate Surface Characteristics:

Two primary aggregate surface characteristics are the shape of the aggregate particles and the aggregate surface texture. Aggregate shape is related to angularity (the number of crushed faces on the aggregate particles) and the extent to which the particle is flat or elongated. Aggregate surface texture is a qualitative description of the degree of roughness on the particle surface.

3.1 Aggregate Shape:

Generally, it is desirable to have aggregate particles with a somewhat angular shape in asphalt mixtures. Flat and elongated particle shapes are undesirable. In compacted mixtures, particles that are cubic in shape exhibit greater interlock and internal friction, resulting in greater mechanical stability than flat and elongated particles. According to Roberts, et al (1991), mixtures with flat and elongated particles tend to densify under traffic, ultimately leading to rutting due to low voids and plastic flow. Higher quantities of crushed aggregates and more angular crushed aggregates will generally produce a higher VMA. The increase in VMA results from the angular aggregates creating more void space during compaction due to the increased number of sharp edges and fractured faces. Since VMA includes air voids and the effective asphalt content, increasing the air voids in the compacted mixture will increase the VMA and allow more asphalt into the mix.

3.2 Absorption:

The amount of asphalt binder absorbed by an aggregate is dependent on the porosity, void volume, and pore size of the aggregate, as well as the viscosity of the asphalt binder. Porosity is directly influenced by the void volume and pore size. Aggregates with larger pore sizes allow for increased asphalt binder absorption. However, aggregates with small pores have the potential for selective absorption of the lighter asphalt binder fractions. This accelerates premature aging and can create a lack of durability. (Bruce and others, 1999).

Asphalt binders that are more viscous tend to limit absorption by aggregates due to a lack of fluidity and an inability to fill aggregate pores. Alternatively, asphalt binders that are not as viscous have a greater ability to fill aggregate pores.

3.3 Aggregate Porosity:

All mineral aggregates have some porosity and have the potential to absorb asphalt binder. The absorption may occur continually or at any point during mixing at the HMA plant, storage in a silo, hauling time in trucks, or in service. Kandhal and Maqbool (1991) stated that although some absorption may lead to improved strength in a compacted mixture through particle adhesion, the portion of the asphalt that is absorbed is no longer available as binder. Therefore, aggregates with a large void volume and/or pore size will have reduced effective asphalt content. This will lead to a decrease in VMA provided the air voids remain constant.

4. Experimental Design:

Asphalt mortar is composed mainly of asphalt and filler, which usually passes the 0.075mm sieve. The aggregate retained on the 0.300 mm, 0.075 mm sieve can also form a fine dispersion system. The properties of such aggregates are similar to those of the asphalt mortar. In the experimental design, the percentage of aggregate passing 12.5mm and that retained on the 0.300mm sieve were kept invariable. Only the percentage passing 0.3mm, and 0.075mm were changed, to study the pavement performance of the asphalt mixture with different filler asphalt ratios. We used the Marshall test to determine the mixture’s optimum asphalt content. The test design is shown in Table (3).

5. Analysis of Results from Marshall Test:

The acceptance tests on the aggregates and asphalt cement of HMA should pass the procedure included in the ASTM D1559. resistance to plastic flow of bituminous mixtures using the Marshall apparatus. The Marshall criteria includes minimum amount of voids in mineral aggregates (VMA), a range of acceptable air void contents, a maximum stability and a range of flow values, and in sometimes the percent of voids filled with asphalt (VFA) should be within a specified range.

The first step in the analysis of the results is the determination of the average bulk specific gravity for all test specimens having the same asphalt content, the same filler type, and the same mixing method. The average unit weight of each mixture is then obtained by multiplying its average specific gravity by the density of water (γ_w). A smooth curve that represents the best fit of plots of unit weight versus percentage of asphalt is determined, as shown in figure (7). This curve is used to obtain the bulk specific gravity values that are used in further computations.

Five additional separate smooth curves are drawn: Marshall Stability versus percent of asphalt, Flow versus percent of asphalt, percent voids in total mix versus percent of asphalt, percent voids in mineral aggregate versus percent asphalt, and percent voids filled with asphalt percent asphalt. These graphs are used to select the asphalt contents for maximum stability, maximum unit weight, and percent voids in total mix within the limits specified (usually the median of the limits). The average of the asphalt contents is the optimum asphalt content. The stability and flow for the optimum content can then be obtained from the appropriate graphs to determine whether the required criteria are met. Suggested criteria for these test limits are given in Table (4).

5.1 Determination of the optimum asphalt content:

The design method of the Marshall test was adopted to determine the optimum asphalt content of the mixture. The test results are shown in Table (5) and Figure (4).

5.2 Aggregate Surface Area Calculation (SA):

The surface area for the aggregate is determined by multiplying the percent passing a given sieve by the surface area factor. These factors are from the Asphalt Institutes MS-2 Manual (14) and are listed below. The surface area is determined for each sieve size and then summed to calculate a total surface area.

1) The aggregate surface area is calculated by the following formula:

$$\mathbf{SA = 0.41 + 0.41a + 0.82b + 6.14c + 32.77d}$$

Where: SA = aggregate surface area in m^2/kg of dry aggregate. And **a,b,c** and **d**= the percent of total aggregate passing the #4, #8, #50and #200 sieves respectively.

Note: The SA is calculated to the nearest 0.1 m^2/kg .

As the ratio of the filler asphalt increases, the optimum asphalt content of the mixture gradually decreases. The optimum asphalt content do, however, differ from one another, which has a great effect on the pavement performance of the mixture.

Decreasing filler asphalt ratio will increase thickness of binder coating aggregate particles by linear rate, due to the increasing in asphalt content and decreasing of the filler, which mean in turn, more spaces between aggregate particles (VMA), Figures (5) and (6).

5.3 The Optimum Filler Asphalt Ratio:

The maximum bulk density (2.353 gm/cm^3) was reported for asphalt mixture with filler / asphalt ratio (1.5) at proportion of asphalt content (4.95%) by total mix, Figure (7). In general, F/A ratios in the range (1.2-1.55) have the highest bulk densities.

As the filler asphalt ratio increases, the mixture's stability changes to a convex curve. When the filler asphalt ratio is in the range between 1.24 and 1.45, the mixture's stability is above 12.6 kN. When the filler asphalt ratio is at 1.3, the stability reaches the maximum. As the filler asphalt ratio increases, so does the filler content, and the asphalt content decreases. The structural asphalt content is then higher and the free asphalt content is relatively lower, so the asphalt mix is quite loose. See Figure(8).

As the filler asphalt ratio decreases, the filler content becomes lower and the asphalt content becomes higher. The structural asphalt content is then lower and the free asphalt content is relatively higher, so the mixture looks oily. Under loading, the asphalt and mortar will flow at first. Then the coarse aggregates will start to move along the interface of the aggregates under loading, which also results in large deformation. See Figure (9).

As the ratio of filler asphalt increase, the mixture's Marshall flow changes to a concave curve. When the filler asphalt ratio is in the range between 1.3 and 1.6, the mixture's flow is less than 4 mm.

Figure (10) shows that AV % values at OAC for mixtures with F/A ratios range (0.9-1.7) have significant air void content.

The maximum percentage VMA of asphalt mixture 15.3 % was reported for asphalt mixture with F/A ratio 0.9 at 5.3% OAC, while the minimum value was (13.5%) for asphalt mix of F/A ratio (1.5) (below the specification). The other mixture types are within or above 14% the minimum limit. See Figure (11).

An increase in the dust proportion will generally decrease the VMA. Due to the relationship between particle diameter and surface area, increasing the amount of material passing the 75-µm sieve will result in a greater total surface area of the aggregate blend. This results in a thinner average film thickness, lower effective asphalt content, and could lower the VMA.

The satisfactory voids filled with asphalt VFA% over (70%) was reported for asphalt mixture with F/A ratio ranges from (1 to 1.5). See Figure (12).

6. Conclusions:

* From the results, we conclude that the optimum filler asphalt ratio is in the range (1.2 -1.5). In this range there is adequate asphalt film thickness and voids in mineral aggregate.
* The calculated film thickness should be considered an estimate, but it does give a measure of how film thickness will vary with gradation, absorption, and other parameters.
* As the filler asphalt ratio increases, the optimum asphalt content gradually decreases.
* Mixture and aggregate specific gravity has significant influence on VMA calculations while, aggregate surface area has significant influence on optimum asphalt content.
* Generally, it has been found that adequate film thickness can only be made without a tendency to bleeding by providing adequate volume between the aggregate particles. This can be accomplished by selecting an aggregate gradation and mix design with appropriate VMA.
* In order to ensure durable flexible pavements, it is necessary to design mixes with adequate film thickness. The mixes must be able to maintain the design asphalt film thickness in the produced pavement following construction.

7. Recommendations:

Based on the conclusions above, the following recommendations have been determined:

1. The properties and proportions of the materials in hot-mix asphalt need to be measured carefully and consistently using standard ASTM or AASHTO procedures so that their effect on performance can be evaluated.

2. The absorption capacity of the aggregates must also be accurately measured in the design phase. Absorptive aggregates must be acknowledged and designed for appropriately by accounting for the additional asphalt binder that will be absorbed and no longer available to coat the aggregate particles.
3. The bulk specific gravity of the aggregate must be accurately determined in the design phase. It is apparent that the lack of precision in determining aggregate bulk specific gravity and absorption will directly cause poor precision in determining VMA. Standard ASTM and/or AASHTO procedures must be followed carefully and consistently.
4. While asphalt film thickness is a very important parameter with regard to pavement durability, it has to be understood that because of variations in aggregate shape and surface characteristics, it is only an estimate and should be viewed with a level of caution.

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Table (1) Minimum VMA (after Asphalt Institute, 2001).

Nominal Maximum Particle Size[1, 2]		Minimum VMA, percent		
		Design Air Voids, percent[3]		
mm	in.	3.0	4.0	5.0
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	1/2	13.0	14.0	15.0
19.0	3/4	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

1 - Standard Specification for Wire Cloth Sieves for Testing Purposes, ASTM E11 (AASHTO M92)
2 - The nominal maximum particle size is one size larger than the firs sieve to retain more than 10 percent.
3 - Interpolate minimum voids in the mineral aggregate (VMA) for design air void values between those listed.

Table (2) Surface area factors for each sieve size (Bruce and others, 1999).

Sieve Size (mm)	Area Factor (m^2/kg)
+4.75 mm	(0.41x1.00)
4.75mm	0.41
2.36 mm	0.82
1.18 mm	1.64
600 μm	2.87
300 μm	6.14
150 μm	12.29
75 μm	32.77

Table (3). Grading of different filler asphalt ratio mixtures.

	Filler asphalt ratio				
	0.9	1.1	1.3	1.5	1.7
Sieve size (mm)	Percentage passing (%)				
19	100	100	100	100	100
12.5	95	95	95	95	95
9.5	83	83	83	83	83
4.75	59	59	59	59	59
2.36	43	43	43	43	43
0.30	11.01	12	13	14.2	14.82
0.075	5.3	6.2	7	8.11	8.59

Table (4) Suggested Criteria for Test Limits.

Marshall Method Mix Criteria	Heavy Traffic Surface & Base	
	Min.	Max.
Compaction, number of blows each face of specimen	75	
Stability, kN	7	
Flow, mm	2	4
Percent Air Voids	3	5
Percent Voids in Mineral Aggregates	14	
Percent Voids Filled with Asphalt	70	85

Table (5) Optimum asphalt content (OAC) and filler asphalt ratio of the mixture.

	1	2	3	4	5
OAC (%)	5.33	5.18	5	4.7	4.6
Filler asphalt ratio	0.9	1.1	1.3	1.5	1.7

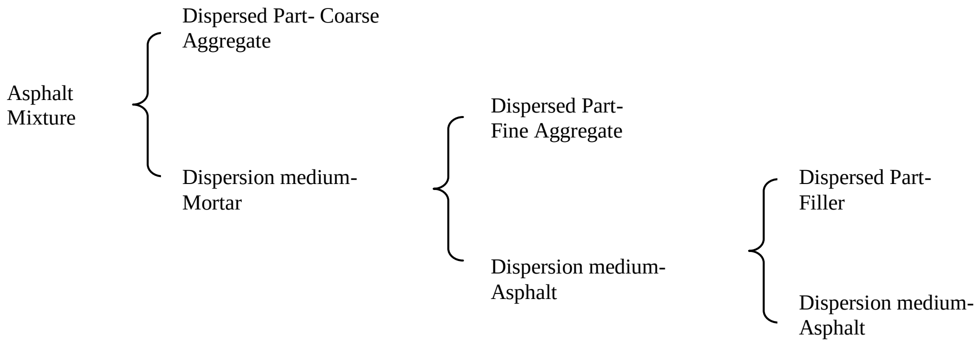

Figure (1) Three graded dispersion system of asphalt mixture. (Cong and Zheng, 2005).

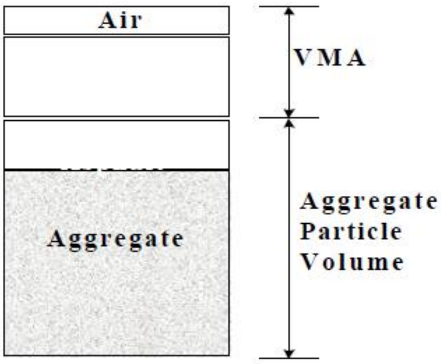

Figure (2). Illustration of VMA (Bruce and others, 1999).

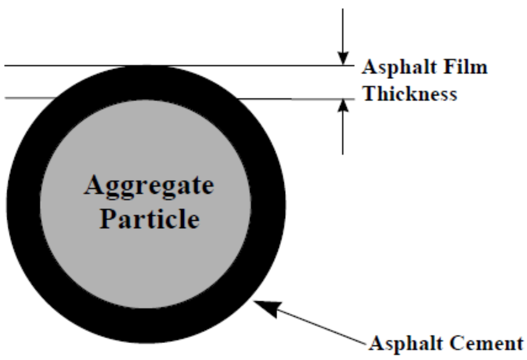

Figure (3) Illustration of Asphalt Film Thickness (Bruce and others, 1999).

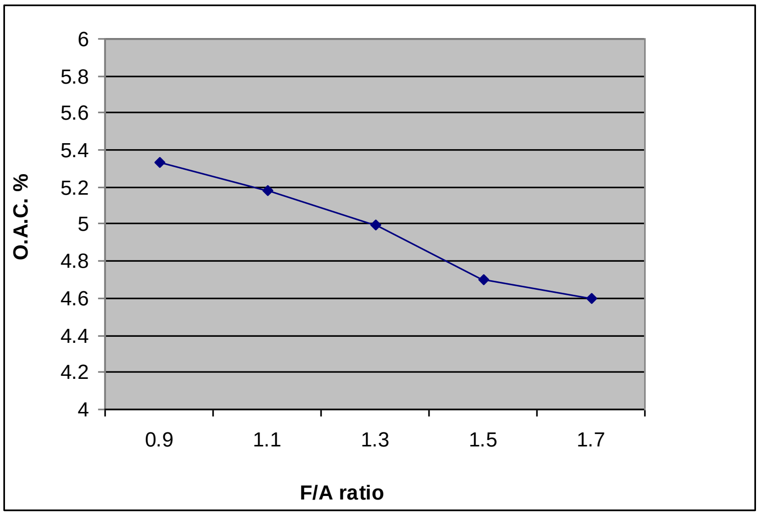

Figure (4) Optimum Asphalt Content of The Mixtures.

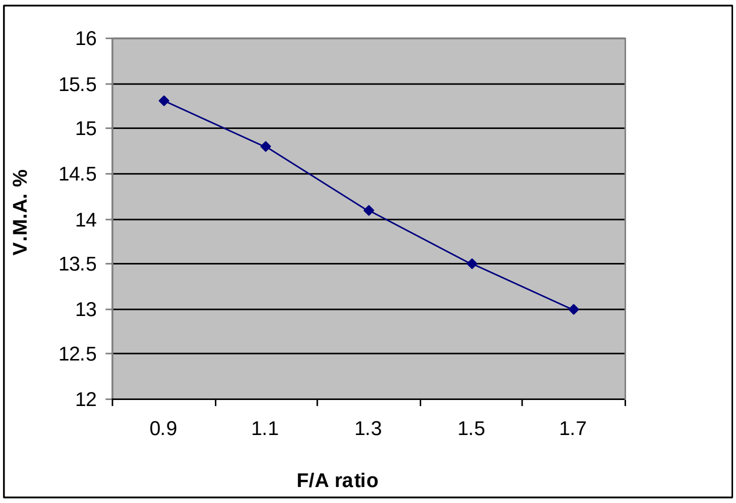

Figure (5) Voids in Mineral Aggregate of The Mixtures.

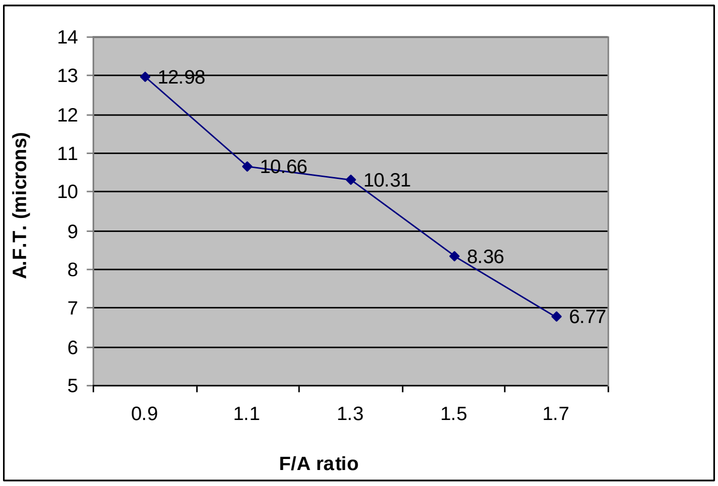

Figure (6) Asphalt Film Thickness of The Mixtures.

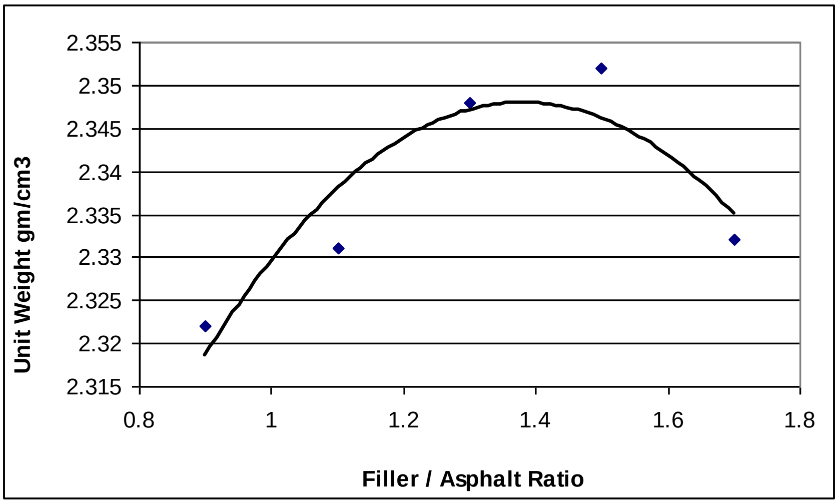

Figure (7) Maximum Unit Weight versus F/A ratio.

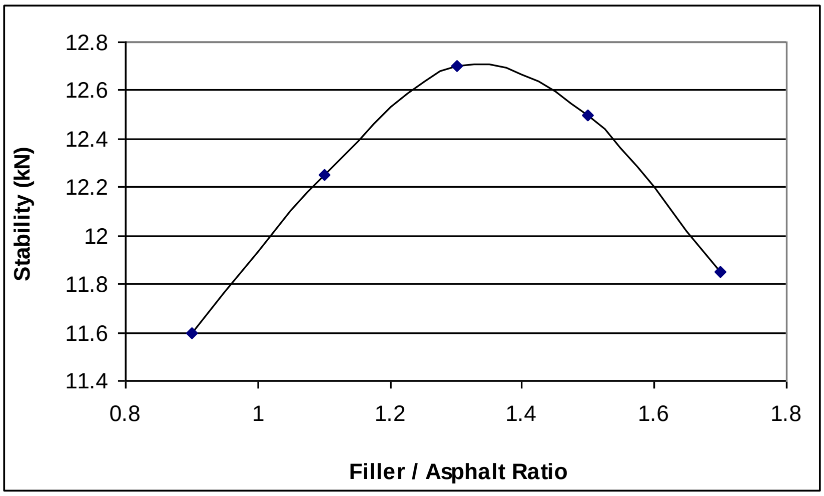

Figure (8) Maximum Stability Versus F / A ratio.

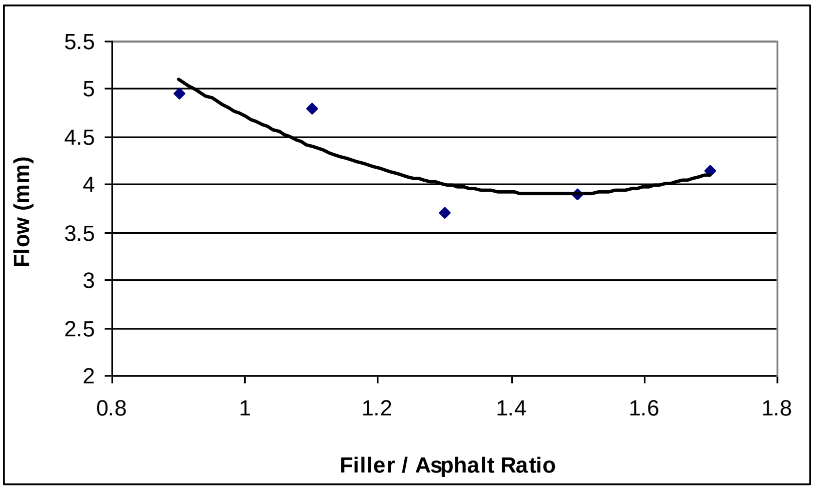

Figure (9) Median Flow versus F / A ratio.

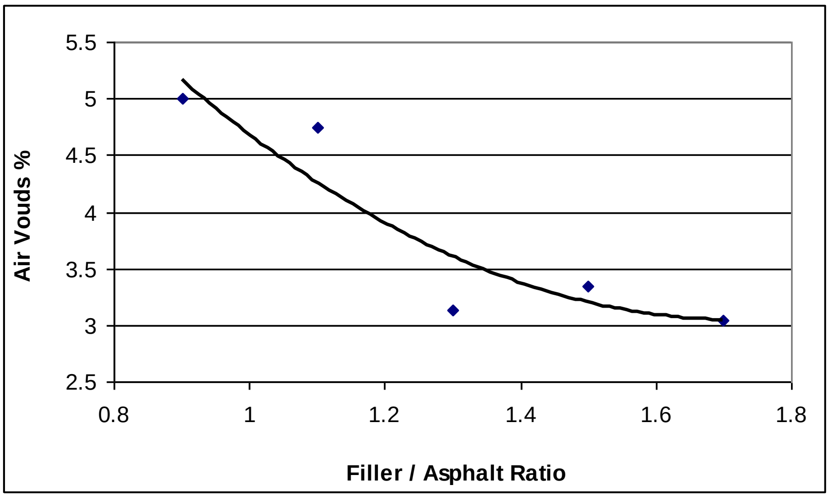

Figure (10) Median voids in total mix versus F / A ratio.

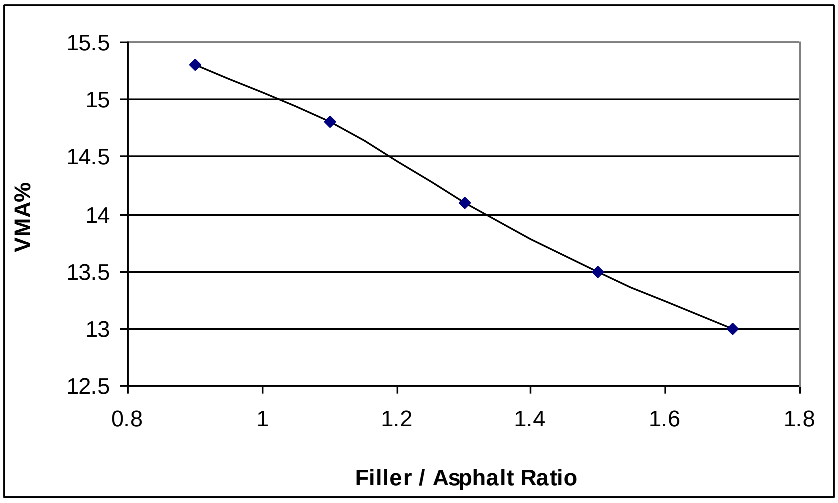

Figure (11) VMA versus F / A ratio.

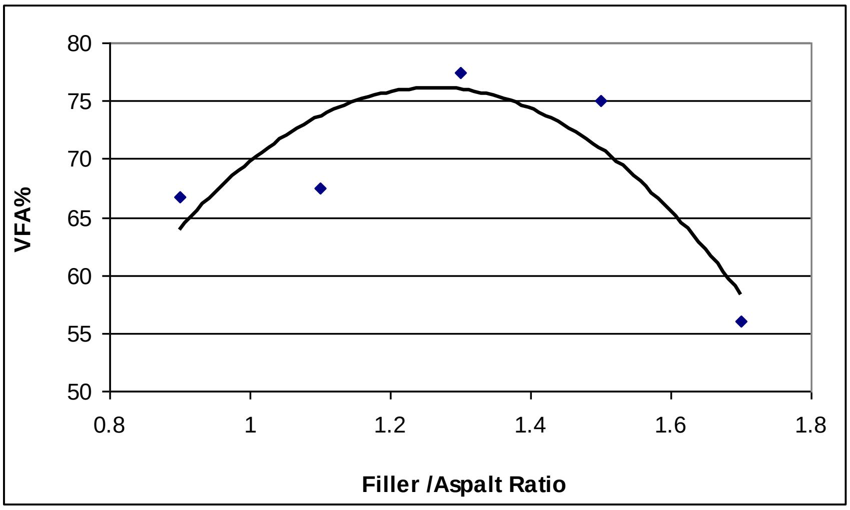

Figure (12) VFA versus F/A ratio.