Impact of Aggregate Gradation and Filler Type on Marshall Properties of Asphalt Concrete

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ABSTRACT

As asphalt concrete wearing course (ACWC) is the top layer in the pavement structure, the material should be able to sustain stresses caused by direct traffic loading. The objective of this study is to evaluate the influence of aggregate gradation and mineral filler type on Marshall Properties. A detailed laboratory study is carried out by preparing asphalt mixtures specimens using locally available materials including asphalt binder (40-50) penetration grade, two types of aggregate gradation representing SCRB and ROAD NOTE 31 specifications and two types of mineral filler including limestone dust and coal fly ash. Four types of mixtures were prepared and tested. The first type included SCRB specification and limestone dust, the second type included SCRB specification and coal fly ash, the third types included ROAD NOTE 31 specification and limestone dust and the fourth type included ROAD NOTE 31 specification and coal fly ash. The optimum asphalt content of each type of mixtures was determined using Marshall Method of mix design. 60 specimen were prepared and tested with dimension of 10.16 cm in diameter and 6.35 cm in height. Results of this study indicated that aggregate gradation and filler type have a significant effect on optimum asphalt content and Marshall Properties. From the experimental data, it was observed that the value of Marshall Stability is comparatively higher when using fly ash as filler as compared to limestone dust.

Keywords: asphalt concrete mixture, aggregate gradation, mineral filler, Marshall Properties.

تأثير اختلاف تدرج الركام ونوع المادة المالئة على خصائص مارشال للخرسانة الاسفلتية

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الخلاصة

ان طبقة الخرسانة الاسفلتية هي الطبقة العليا في تشكيل الرصفة وهذا يتطلب ان تكون المواد المستخدمة قادرة على مقاومة الاجهادات الناتجة عن حركة المرور العالية المباشرة. الهدف الرئيسي من البحث هو تحديد تاثير اختلاف التدرج ونوع المادة المالئة على خصائص مارشال للخرسانة الاسفلتية. الدراسة المختبرية المفصلة نفذت بتحضير نماذج من الخرسانة الاسفلتية عن طريق استخدام مواد متوفرة محلياً والتي تتظمن اسفلت سمنت ذو الاختراق (40-50) ونوعين من تدرج الركام الذين يمثلان المواصفة العراقية للطرق والجسور والمواصفة البريطانية وكذلك تم استخدام نوعين من المادة المالئة والذين يمثلان غبار الحجر الجيري ورماد الفحم المتطاير. تم تحضير اربعة انواع من الخلطات, كانت الخلطة الاولى مكونة من تدرج مواصفة الطرق والجسور وغبار الحجر الجيري والثانية مكونة من تدرج مواصفة الطرق والجسور ورماد الفحم المتطاير

والثالثة مكونة من تدرج المواصفة البريطانية وغبار الحجر الجيري والرابعة مكونة من تدرج المواصفة البريطانية ورماد الفحم المتطاير. تم ايجاد نسبة الاسفلت المثلى لكل نوع من الخلطات باستخدام طريقة تصميم مارشال. تم تحضير وفحص 60 نموذج بقطر 10,16 سم وارتفاع 6,35 سم . اظهرت نتائج هذه الدراسة الى ان تدرج الركام ونوع المادة المالئة لهما تاثير كبير على خصائص مارشال ونسبة الاسفلت المثالية. لوحظ ايضاً ان قيمة ثبات مارشال اعلى نسبياً عند استخدام رماد الفحم المتطاير كمادة مالئة بدلاً عن غبار الحجر الجيري.

الكلمات الرئيسيه: خلطة الخرسانة الاسفلتية, تدرج الركام, المادة المعدنية المالئة, خصائص مارشال.

1. INTRODUCTION

In order to provide comfortable ride and withstand the effects arising from traffic loading and climate, pavement materials should be designed to achieve a certain level of performance and the performance should be maintained during the service life, **Zhi Suo and Wing, 2008**. Fillers as one of the components in an asphalt mixture, play a major role in determining the properties and the behavior of the mixture, especially the binding and aggregate interlocking effects, **Sarsam, 1984**. Mineral fillers serve a dual purpose when added to asphalt mixes, the portion of the mineral filler that is finer than the thickness of the asphalt film blends with asphalt cement binder to form a mortar or mastic that contributes to improved stiffening of the mix. Particles larger than the thickness of the asphalt film behave as mineral aggregate and hence contribute to the contact points between individual aggregate particles, **Puzinauskas, 1969**. In general, filler have various purposes among which, they fill voids and hence reduce optimum asphalt content and increase stability, meet specifications for aggregate gradation, and improve bond between asphalt cement and aggregate, **Bouchard, 1992**. Gradation is defined as the distribution of particle sizes expressed as a percent of the total weight. If the specific gravities of the aggregates used are similar, the gradation in volume will be similar to the gradation in weight.

2. RESEARCH OBJECTIVE

The objective of this research is to investigating the influence of using two types of aggregate gradation and two types of mineral filler on optimum asphalt content and Marshall Properties.

3. BACKGROND

Ali et al. 1996 investigated the effects of fly ash on the material and mechanical properties of asphalt mixtures; results from this study indicated that fly ash can be used as a mineral filler to improve resilient modulus characteristics and stripping resistance. **Sarsam, 2015**, studied the effect of adding nano material such as fly ash and silica fumes on the properties of asphalt cement, it was concluded that such nano materials have positive effect on asphalt cement rheological properties. **Sarsam, 2013** concluded that nano materials such as coal fly ash and lime have improved the physical properties of asphalt cement. **Kallas and Puzinauskas, 1967** believed that filler performed a dual role in asphalt-aggregate mixtures. A portion of the filler with particles larger than the asphalt film will contribute in producing the contact points between aggregate particles, while the remaining filler is in colloidal suspension in the asphalt binder, resulting in a binder with a stiffer consistency. They also found that the stabilities of asphalt mixtures increased up to a certain filler concentration, then decrease with additional filler. A study was made by **Matthews and Monismith, 1992** on effects of gradation on the asphalt content where both wearing and binder mixes were considered. Further, they have carried out regression analysis on test data to investigate the relationship between asphalt content and gradation. Their study shows that no correlation exists between asphalt content and the percent passing the 4.75mm (No. 4) and 2.36mm (No. 8) sieves for the wearing mix. On the other hand, for binder mixes there exists a relationship between changes in gradation and measured asphalt content that shows as the mix becomes finer for the given sieve size, the asphalt content increases. **Roberts et al., 1996** suggested that gradation is perhaps the most important property which affects almost all the important properties of a bituminous mixture, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. **Sarsam, 1987** studied the effect of various gradations on Marshall properties of asphalt concrete, it was concluded that gap gradation exhibit more stability and low flow values when compared to dense graded mixes.

4. MATERIAL CHARACERISTIC

4.1 Asphalt Cement

Asphalt cement of (40-50) penetration grade from Nasiriya refinery was used in this work. The physical properties of original asphalt cement are presented in **Table 1.**

4.2 Aggregate

Coarse and fine aggregates were obtained from AL-Ukhaydir- Karbala quarry; their physical properties are listed in **Table 2**.

4.3 Mineral Filler

Two types of mineral filler were used in this work; limestone dust produced in the lime factory in Karbala governorate and coal fly ash obtained from local market. **Table 3** shows major physical properties.

4.4 Selection of Design Aggregate Gradation

The selected gradation in this work followed the **SCRB, 2003** specification, with 12.5 (mm) nominal maximum size and **ROAD NOTE 31, 1993** specification with 12.5 (mm) nominal maximum size. **Fig.1, Fig. 2, Table 4** and **Table 5** show selected aggregate gradation. The implementation of both aggregate gradations in this research work could aid in understanding the effect of environmental condition on physical properties of asphalt concrete since the SCRB specification is recommended for hot climate, while ROAD NOTE 31 is recommended for cold climate condition.

4.5 Preparation of Marshall Specimen

Four groups of Marshall Specimens were prepared and used in this work to obtain optimum asphalt binder content; five percentages of asphalt cement (3.5, 4, 4.5, 5 and 5.5) % and 15 specimen were used for each type of mixture. These four groups of mixture were tested for determination of optimum asphalt requirements as follows:

a.) Determine the optimum asphalt binder content for SCRB grading specification and using limestone dust as a mineral filler, Mixture Type I.
b.) Determine the optimum asphalt binder content for SCRB grading specification and using coal fly ash as a mineral filler, Mixture Type II.

c.) Determine the optimum asphalt binder content for ROAD NOTE 31 grading specification and using limestone dust as a mineral filler, Mixture Type III.

d.) Determine the optimum asphalt binder content for ROAD NOTE 31 grading specification and using coal fly ash as a mineral filler, Mixture Type IV.

60 specimens were used in this work to determine optimum asphalt binder content, The specimens were prepared in accordance with (ASTM D1559), Marshall mold, spatula, and compaction hammer were heated on a hot plate to a temperature between (140-150 ºC). The aggregate was first sieved, washed, and dried to a constant weight at 110 ºC. Coarse and fine aggregates were combined with mineral filler to meet the specified gradation in section (4.4). Aggregates and filler were heated to (160 ºC), asphalt was heated up to (150) ºC prior to mixing, and it was added to the hot aggregate and mixed for two minutes on hot plate until all aggregate particles were coated with asphalt cement. The compaction temperature was (140) ºC, which gives a viscosity (280 $\pm$ 30) cSt. The (75) blows of compaction hammer are applied with a free fall of 4.536 kg (10 lb) sliding weight and a free fall of (457.2) mm. After compaction, the base plate is removed and the same blows are applied to the bottom of the specimen that has been turned around. The specimen in mold was left to cool at room temperature for 24 hours, then it was extracted from the mold using mechanical jack. **Fig. 3** shows preparation of Marshall Specimens.

4.6 Testing of Marshall Specimens

4.6.1 Determination of maximum theoretical specific gravity

The purpose of conducting this test is to determine the maximum theoretical specific gravity of loose HMA specimens. The maximum theoretical specific gravity was determined according to (ASTM D2041-03). 1500 gm was needed in this test for each type of mixture with maximum nominal aggregate size of (12.5 mm). This test was conduct for each percent of asphalt content (3.5, 4, 4.5, 5 and 5.5)%. **Fig. 4** presents the apparatus used to obtain maximum specific gravity.

4.6.2 Determination of flow and stability of specimens

Procedure of preparing and testing specimens was according to (ASTM D1559) .This method covers the measure of the resistance to plastic flow of cylindrical specimens (2.5 in. height × 4.0 in. diameter) of asphalt paving mix after conditioning in water bath at 60 °C for 30 minute. A load was applied with a constant rate of (50.8) mm/min until the maximum load was reached. The maximum load resistance and the corresponding strain values were recorded as Marshall stability and flow respectively. Three specimens for each type of mixture were prepared and tested and average results are reported. **Fig. 5** shows Marshall apparatus of this test.

5. DISCUSSION OF TEST RESULTS

5.1 Optimum Asphalt Content (OAC)

The optimum asphalt content was 4.9 %, 4.7 %, 4.7 % and 4.5 % for mixtures type I, type II, type III and type IV respectively. The Marshall Properties which are considered to select the optimum asphalt content; stability, bulk density, and air voids, while other properties; flow, VMA, and VFA are considered to confirm the required limits by SCRB specification.

5.2 Marshall Stability

Stability is an important property of the asphalt mixture in the wearing course design. Marshall Stability gives the indication about the resistance of asphalt mixture to permanent deformation, a high value of Marshall stability indicates increased Marshall Stiffness. The high stiffness of asphalt mixture means good resistance to traffic loadings but it also indicates lower flexibility which is required for long term performance, high stiffness values are not recommended due to thermal cracking which expected to occur in future. **Fig. 6** shows the effect of aggregate gradation and filler type on Marshall stability. It is noted that the Marshall stability was increased by 13.39% when using fly ash as a mineral filler instead of limestone dust with SCRB gradation and it was increased by 32.63 % when using fly ash as a mineral filler when compared to mix with limestone dust with ROAD NOTE 31 gradation. such results comply with the findings of **Pradan and Roy, 2008**. Also, It is noted that the Marshall stability was decreased by 15.17 % when using ROAD NOTE 31 gradation as compared with SCRB gradation with using limestone dust as a mineral filler, while it was decreased by 0.78 % when using ROAD NOTE 31 gradation instead of SCRB gradation with using coal fly ash as a mineral filler. The data are listed from **Table 6** to **Table 9**.

5.3 Marshall Flow

Generally, high flow values indicate a plastic mix that is more prone to permanent deformation problem due to traffic loads, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability and could result premature cracking due to mixture brittleness during the life of the pavement. **Fig.7** shows the effect of aggregate gradation and filler type on Marshall flow. It can be observed that the Marshall flow was increased by 24.13 % when using fly ash as a mineral filler instead of limestone dust with **SCRB, 2003** gradation. such results comply with the findings of **Rahman and Sobhan, 2013**. and **Kar et al., 2014**. Also it is also noted that the Marshall flow was decreases by 6.06 % when using fly ash as a mineral filler instead of limestone dust with ROAD NOTE 31 gradation. such results comply with the findings of **Pradan and Roy, 2008**. Also, it is noted that the Marshall flow was decreases by 13.79 % when using SCRB gradation Instead of ROAD NOTE 31 gradation with using limestone dust as a mineral filler, while Marshall flow was increases by 13.88 % when using SCRB grading Instead of ROAD NOTE 31 gradation when using fly ash as a mineral filler. The data are listed from **Table 6** to **Table 9**.

5.4 Bulk Density

In the Marshall Mix design procedure, the density varies with asphalt content in such a way that it increases with increasing asphalt content in the mixture. The density reaches a peak and then begins to decrease because additional asphalt cement produces thicker films around the individual aggregates, and tend to push the aggregate particles further apart subsequently resulting lower density. The effect of aggregate gradation and filler type on bulk density is illustrated in **Fig.8**. This figure indicates that the bulk density increases when using fly ash as a mineral filler for both SCRB gradation and ROAD NOTE 31 gradation. It is also found that the bulk density was decreased when using SCRB gradation as compared to ROAD NOTE 31 gradation when using limestone dust as a mineral filler, and it is noted that the bulk density was decreased when using SCRB grading as compared to ROAD NOTE 31 gradation when using fly ash as a mineral filler. The data are listed from **Table 6** to **Table 9**.

5.5 Voids in Total Mixture (VTM %)

Air void in the mixture is an important parameter because it permits the properties and performance of the mixture to be predicted for the service life of the pavement, and percentage of air voids is related to durability of asphalt mixture. Air void proportion around 4% is enough to prevent bleeding or flushing that would reduce the skid resistance of the pavement and increase fatigue resistance susceptibility. **Fig. 9** shows the effect of aggregate gradation and filler type on voids in total mix (VTM) percent’s. It is clear from the figure that the air void was decreased when using fly ash as a mineral filler as compared to limestone dust with SCRB gradation. such results comply with the findings of **Kar et al., 2014**, while when using fly ash as a mineral filler with ROAD NOTE 31 gradation, air void is increases. such results comply with the findings of **Rahman and Sobhan, 2013**. It is also found that the air void is decreases when using ROAD NOTE 31 gradation with using limestone dust as a mineral filler, and it is noted that the air void is increases when using ROAD NOTE 31 gradation with fly ash as a mineral filler. The data are listed from **Table 6** to **Table 9**.

5.6 Voids Filled with Asphalt (VFA%)

Voids filled with asphalt (VFA) are the void spaces that exist between the aggregate particles in the compacted paving asphalt mixture that are filled with binder. The purpose for the VFA is to avoid less durable asphalt mixtures resulting from thin films of binder on the aggregate particles in light traffic situations. **Fig. 10** shows the effect of aggregate gradation and filler type on void filled with asphalt. It indicates that void filled with asphalt was increased when using fly ash as a mineral filler with SCRB gradation. Such results comply with the findings of **Rahman and Sobhan, 2013**, while when using fly ash as a mineral filler with ROAD NOTE 31 gradation, void filled with asphalt was decreased. It is also noted that void filled with asphalt was decreased when using ROAD NOTE 31gradation with using both limestone dust and coal fly ash as a mineral filler. The data are listed from **Table 6** to **Table 9**.

5.7 Voids in Mineral Aggregate (VMA%)

The voids in the mineral aggregate is the total available volume of voids between the aggregate particles in the compacted paving mixture that includes the air voids and the voids filled with effective asphalt content expressed as a percent of the total volume. It is significantly important for the performance characteristics of a mixture for any given mixture, the VMA must be sufficiently high enough to ensure that there is space for the required asphalt cement, for its durability purpose, and air space. If the VMA is too small, there will be no space for the asphalt cement required to coat around the aggregates and this subsequently results in durability problems. On the other hand, if VMA is too large, the mixture may suffer stability problems. **Fig.11** shows the effect of aggregate gradation and filler type on void in mineral aggregate (VMA). It is clear from the figure that voids in mineral aggregate were decreased when using fly ash as mineral filler with both SCRB and ROAD NOTE 31 gradation. It is noted that the void in mineral aggregate was decreased when using ROAD NOTE 31 gradation instead of SCRB gradation when using both limestone dust and coal fly ash as a mineral filler. Such results comply with the findings of Kar **et al., 2014.** The data are listed from **Table 6** to **Table 9.**

6. CONCLUSION

1. Optimum asphalt content requirement was lower when coal fly ash was implemented as a mineral filler at both types of aggregate gradation SCRB and ROAD NOTE 31 specifications.
2. Optimum asphalt content requirement for grading of ROAD NOTE 31 specification was lower than SCRB specification at both types of mineral filler limestone dust and coal fly ash.
3. Marshall stability was increased by 13.39% and 32.63% when using fly ash as a mineral filler instead of limestone dust with both types of aggregate gradation (SCRB and ROAD NOTE 31) gradation. On the other hand, Marshall stability was decreased by 15.17 % and 0.78% when using ROAD NOTE 31 gradation as compared with SCRB gradation for both types of mineral filler limestone dust coal fly ash.
4. Marshall flow was increased by 24.13 % when using fly ash as a mineral filler instead of limestone dust with SCRB gradation, while it was decreased by 6.06 % when using fly ash as a mineral filler instead of limestone dust with ROAD NOTE 31 gradation.
5. Marshall flow was decreased by 13.79 % when using SCRB gradation instead of ROAD NOTE 31 gradation with using limestone dust as a mineral filler, while it was increased by 13.88 % when using SCRB grading instead of ROAD NOTE 31 gradation when using fly ash as a mineral filler.
6. Bulk density increases when using fly ash as a mineral filler for both SCRB gradation and ROAD NOTE 31 gradation.
7. Bulk density was decreased when using SCRB gradation as compared to ROAD NOTE 31 gradation for both limestone dust and coal fly ash.

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Table 1. Physical properties of asphalt cement.

Property	Unit	Test Result	SCRB (2003) Specifications
Penetration, (25˚C, 100 gm, 5 sec) ASTM D 5	0.1 mm	42	40 – 50
Softening point (Ring & Ball) ASTM D 36	℃	49	----
Ductility (25 ˚ C, 5 cm/min) ASTM D 113	cm	140	>100
Specific gravity 25˚C ASTM D70	----	1.04	----
Flash point (cleave land open cup) ASTM D 92	℃	256	>232
After Thin - Film Oven Test ASTM D 1754			
Retained Penetration of Residue (25 ˚C , 100 gm , 5 sec)	%	67	>55%
Ductility (25 ˚ C , 5 cm/min)	cm	83	>25
Loss on Weight % (163 ˚ C , 50 gm , 5 hr)	%	0.35	----

Table 2. Physical properties of aggregate.

Property	Coarse aggregate		Fine aggregate	
	Test Result	ASTM Designation No.	Test Result	ASTM Designation No.
Bulk Specific Gravity	2. 542	ASTM C 127	2.558	ASTM C 128
Apparent Specific Gravity	2.554		2.563	
Water Absorption %	1.076 %		1.83 %	
Wear % (Los Angeles Abrasion)	17.92 %	ASTM C 131	----	----

Table 3. Physical properties of limestone dust and coal fly ash.

Property	Physical Properties	
	Limestone Dust	Coal Fly Ash
% Passing Sieve No. 200	98%	94%
Specific Gravity	2.617	2.6455
Specific surface area m 2/kg	389	338

Table 4. Specification limits and selected gradation of HMA mixtures for wearing course according to SCRB (2003).

Sieve Opening (mm)	Sieve Size	% passing by weight of total aggregate	
		Selected gradation	SCRB (2003) specifications Limits (Type IIIA)
19	3/4"	100	100
12.5	1/2"	95	90 – 100
9.5	3/8"	83	76 – 90
4.75	No.4	59	44 – 74
2.36	No.8	43	28 – 58
0.3	No.50	13	5 – 21
0.075	No.200	7	4 – 10

Table 5. Specification limits and selected gradation of HMA mixtures for wearing course according to ROAD NOTE 31 (1993).

Sieve Opening (mm)	Sieve Size	% passing by weight of total aggregate	
		Selected gradation	Road Note 31 (1993) specifications Limits
19	3/4"	100	100
12.5	1/2"	90	80 – 100
4.75	No.4	63	54 – 72
2.36	No.8	50	42 – 58
1.18	No.16	41	34 – 48
0.6	No.30	32	26 – 38
0.3	No.50	23	18 – 28
0.15	No.100	16	12 – 20
0.075	No.200	9	6 – 12

Table 6. Effect of asphalt content on marshall and density- air voids properties for mixture Type I.

Asphalt Content %	Bulk density (gm/cm3)	Marshall Stability (KN)	Marshall Flow (mm)	VTM (%)	VFA (%)	VMA (%)
3.5	2.2074	9.48	2.400	9.2165	44.6185	16.6448
4	2.2367	10.50	2.580	7.3753	53.8309	15.9760
4.5	2.2698	11.43	2.700	5.3579	64.6941	15.1767
5	2.2834	11.20	2.980	4.1393	72.6122	15.1152
5.5	2.2759	9.96	3.600	3.8040	75.9795	15.8393

Table 7. Effect of asphalt content on Marshall and density- air voids properties for mixture Type II.

Asphalt Content %	Bulk density (gm/cm3)	Marshall Stability (KN)	Marshall Flow (mm)	VTM (%)	VFA (%)	VMA (%)
3.5	2.2228	9.0580	2.6300	8.6432	46.3833	16.1223
4	2.2589	9.9670	2.9600	6.5141	57.1404	15.2018
4.5	2.3010	10.4730	3.5300	4.1170	70.7385	14.0712
5	2.2953	11.8380	3.7300	3.7004	74.8818	14.7329
5.5	2.2899	8.1130	3.8400	3.2736	78.7153	15.3812

Table 8. Effect of asphalt content on Marshall and density- air voids properties for mixture Type III.

Asphalt Content %	Bulk density (gm/cm3)	Marshall Stability (KN)	Marshall Flow (mm)	VTM (%)	VFA (%)	VMA (%)
3.5	2.1788	12.232	2.460	10.4627	41.1723	17.7827
4	2.2083	12.977	2.720	8.6271	49.5521	17.1013
4.5	2.3002	13.605	3.100	4.1543	70.5442	14.1011
5	2.2882	9.295	3.590	4.0023	73.3116	14.9966
5.5	2.2845	8.573	3.800	3.5017	77.5239	15.5807

Table 9. Effect of asphalt content on Marshall and density- air voids properties for mixture Type IV.

Asphalt Content %	Bulk density (gm/cm3)	Marshall Stability (KN)	Marshall Flow (mm)	VTM (%)	VFA (%)	VMA (%)
3.5	2.2254	8.004	2.430	8.6115	46.5038	16.0997
4	2.2891	8.148	2.980	5.3425	62.2256	14.1453
4.5	2.3012	9.617	3.180	4.1845	70.4026	14.1410
5	2.2955	8.399	3.410	3.7687	74.5379	14.8021
5.5	2.2886	8.105	3.810	3.4019	78.0547	15.5052

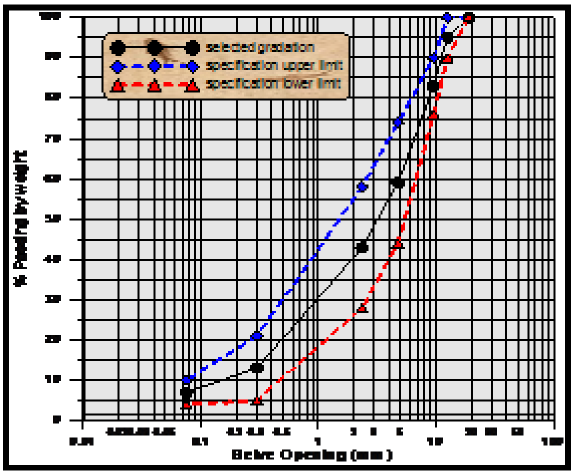

Figure 1. Specification limits and selected gradation according to SCRB (2003).

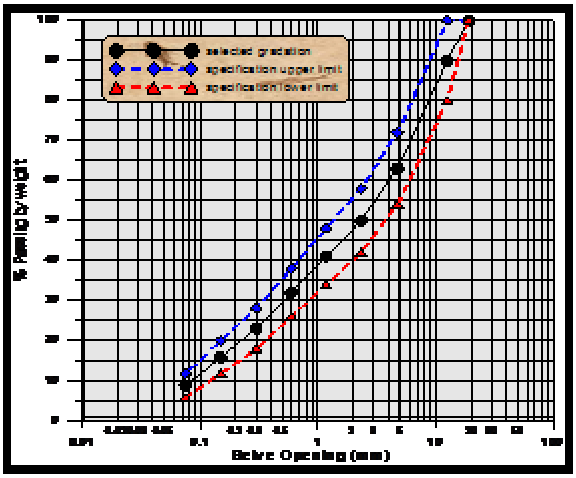

Figure 2. Specification limits and selected gradation according to ROAD NOTE 31 (1993).

Figure 3. Part of prepared of marshall specimens.

Figure 4. Maximum theoretical specific gravity apparatus.

Figure 5. Marshall test device.

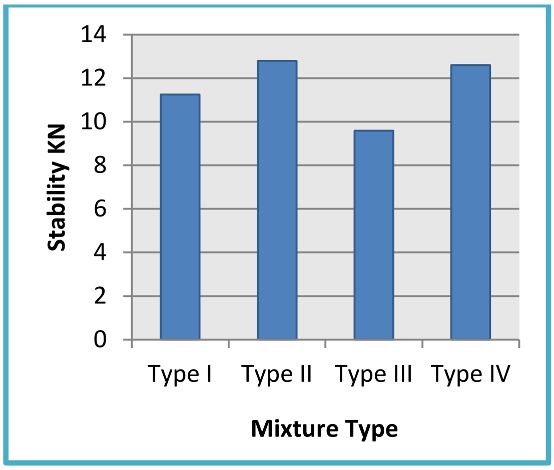

Figure 6. Effect of aggregate gradation and filler type on Marshall stability.

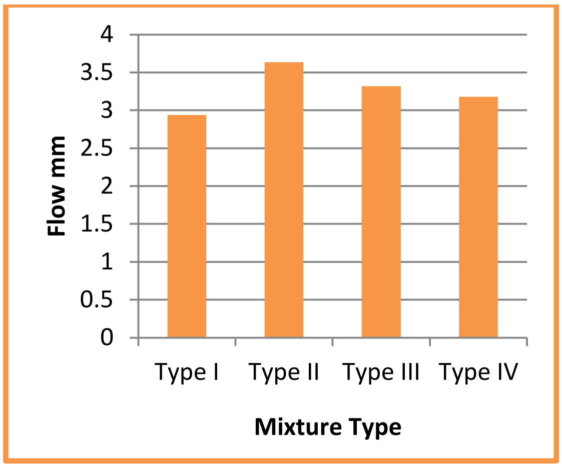

Figure 7. Effect of aggregate gradation and filler type on Marshall flow.

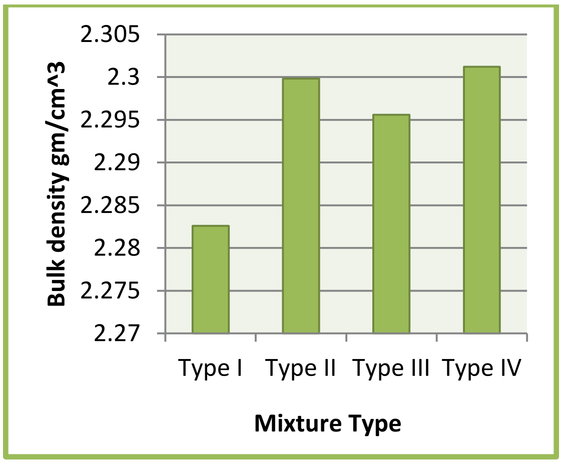

Figure 8. Effect of aggregate gradation and filler type on bulk density.

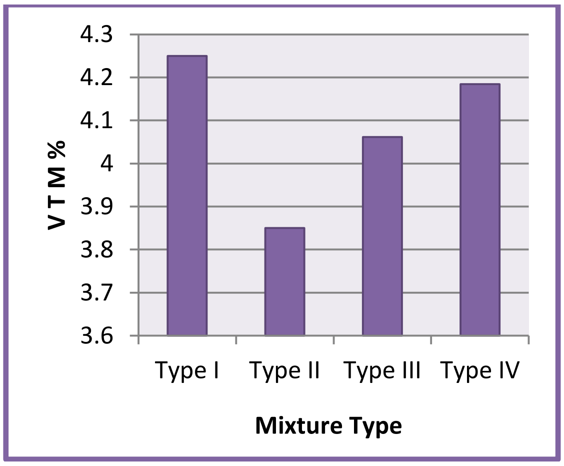

Figure 9. Effect of aggregate gradation and filler type on VTM.

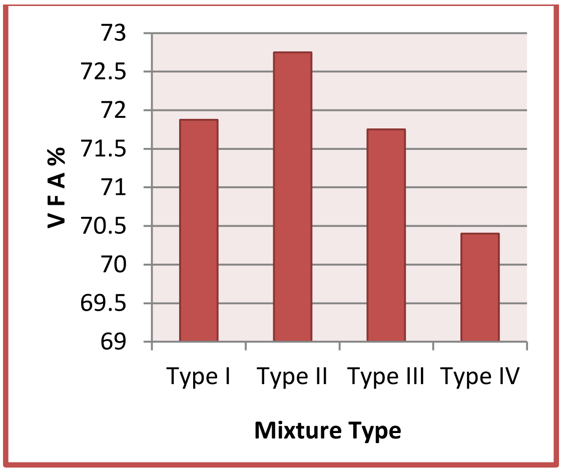

Figure 10. Effect of aggregate gradation and filler type on VFA.

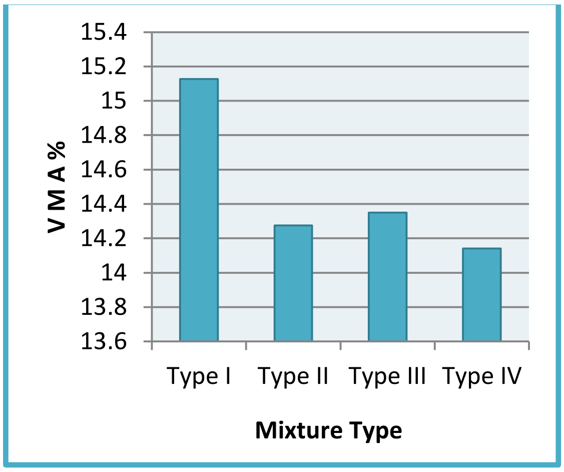

Figure 11. Effect of aggregate gradation and filler type on VMA.