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Comparison of Marshall and Superpave Asphalt Design Methods for Sudan Pavement Mixes

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***Abstract*—**The quality of asphalt concrete in flexible pavements plays a major role in the performance and durability of these pavements. The literature review revealed that Superpave mix design provides better performance than Marshall method, especially for roads exposed to heavy traffic loadings and climatic changes. This study aims to compare the design of asphaltic concrete by the traditional Marshall and the Superpave methods of mix design. Intensive laboratory testing program was conducted on samples of both mixes prepared at the design asphalt contents and aggregate gradations. A comparison between the design results obtained by two mix design procedures is presented. The Superpave mix showed better results of the studied properties compared to Marshall mix. This result proved the superiority of Superpave mixes over Marshall mixes. Therefore, adopting the Superpave design procedure in Sudan might help in enhancing the performance of the asphalt surface roads.

***Keywords*—** Asphalt concrete; Marshall method; mix design; performance; Superpave method.

I. INTRODUCTION

The performance of flexible pavements is greatly affected by the quality of the asphalt concrete. The highways in Sudan are typically designed and constructed to last for at least 20 years. They are performing poorly with pavement life much shorter than the expected. However, it is common to see cracking, rutting and potholes in asphalt pavements well before that period. The high traffic intensity in terms of commercial vehicles, the serious overloading of trucks and significant variation in daily and seasonal temperature of the pavement have been responsible for early development of these distresses in asphalt pavements.

A variety of asphalt mix design methods are practiced all over the world such as Asphalt Institute Triaxial, Marshall, Hubbard field, Superpave, and Hveem mix design methods. Out of these three are most widely practiced: Marshall; Superpave; and Hveem mix design methods [1]. The Marshall mix design procedure is currently practiced in Sudan for the design of asphaltic concrete. The use of the Marshall mix design procedure is one of the contributing causes to the early distresses developed in Sudan pavements. The primary problem of the Marshall Design method is that the asphalt mixes are designed based on empirical laboratory procedures, without simulating the actual field conditions. This makes it difficult to accurately predict how a particular mix will perform in the field [2]. The Supepave mix design method was developed to fill this need. To design proper asphalt mix, this method is based on performance-related criteria which allow a direct relationship to be drawn between the lab and field performance of the asphalt mix. This technology has a tremendous potential to be implemented in Sudan, which will pay itself with higher performance and longer lasting roads. Hence, there is great need to have a comprehensive study comparing the design of asphalt mixes using both Superpave and the Marshall method of Mix Design.

II. LITERATURE REVIEW

The purpose of any asphalt mix design method is to determine the optimum proportions of aggregate and asphalt cement to be used in asphalt mixture. The traditional Marshall method of mix design has outlived its usefulness for modern asphalt mix design. This has led the highway engineers to think of a performance based mix design, which can predict the fundamental properties of asphalt mixes such as rutting and fatigue. The primary objective of the performance based mix design method is to establish the appropriate amount of binder content in a mix that simultaneously satisfy the rut resistance and fatigue cracking requirements for given traffic and environmental conditions. This led to develop the Super Performance Pavements (Superpave) mix design by Strategic Highway Research Program (SHRP), USA. Differences between the Superpave and the Marshall mix design methods are mainly in the selection procedure of the materials, the compaction method, specimen dimensions, void analysis approach and specifications. The following sections provide a brief history and description of Marshall and Superpave methods.

A. *Marshall Design Method*

This method was developed by Bruce Marshall for the Mississippi Highway Department in 1939. It is still widely used in many countries because the equipment is relative inexpensive and portable. The Marshall method criteria allows the engineer to choose an optimum asphalt content to be added to specific aggregate blend to a mix where the desired properties of density, stability and flow are met. The Marshall method uses standard hot mix asphalt (HMA) samples that are 102 mm in diameter and 63.5 mm high. The preparation procedure is carefully specified, and involves heating, mixing, and compacting asphalt/aggregate mixtures. Test specimens are compacted by applying 50 or 75 blows per side with the

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Marshall compaction hammer. The number of blows is determined by the expected traffic level of the pavement section, [2]. Once the Marshall samples have been prepared, they are used to determine the average asphalt mix properties for each asphalt cement content. A density-voids analysis is used to determine the unit weight, air voids (AV), voids in mineral aggregate (VMA), and percent voids filled with asphalt (VFA). The Marshal test machine is used to measure stability and flow of the specimens. Stability is a value for the load under which the specimen fails. Flow is the amount of deformation that occurs when the specimen fails. If a sample has a low stability and a high flow value, the mixture will tend to rut and deform under a load. If the sample has a high stability and a low flow value, the mix will tend to be brittle and crack under a load, [3].

The optimum asphalt binder content is determined based on the combined results of Marshall Stability and flow, density-void analysis. Plots of asphalt binder content versus measured values of Marshall stability, unit weight, flow, %AV, %VFA, and %VMA are generated. Optimum asphalt content is selected corresponding to maximum stability, maximum unit weight and at 4 percent air voids. Then check this percentage of asphalt cement to insure that it is within the limiting criteria for flow, stability, AV, VMA, and VFA, [3]. Pandey [4] reported some of the limitations of Marshall method of mix design include:

- It is unconfined test, but actual pavement material is subjected to triaxial stress.
- It is empirical test parameters are not related directly to the pavement performance such as permanent deformation and fatigue cracking behavior.
- It does not identify easily compactable mixes under traffic
- Impact compaction used in this method does not simulate the mixture densification as it occurs in a real pavement.

B. *Superpave Design Method*

Superpave stands for Superior Performing Asphalt Pavements. Superpave was initially developed by the Strategic Highway Research Program (SHRP) (1987-1993) and it continues to improve. This method was mainly developed to improve previous HMA design methods. Some of the primary goals of this method are: (1) better incorporation of traffic and climatic conditions, (2) better asphalt binder and aggregate evaluation and selection and (3) better volumetric approaches to mix design [5]. The unique feature of Super-pave system is that it is a performance-based specification. The tests and analysis have direct relationships to field performance. The Super-pave mix design procedure involves selecting of asphalt and aggregate materials that meet the super-pave specifications and then conducting a volumetric analysis of mix specimen compacted with the Superpave gyratory compactor. The Gyratory Testing Machine (GTM) developed by US Corps of Engineers [6]. This machine has the capability to compact HMA mixtures using a kneading process that simulates the action of rollers during construction. The GTM was operated at vertical pressure of 8.2 kg/cm^2, which was approximately equal to the truck tyre inflation pressures, the gyration angle degree and 300 revolutions. The GTM can be used for achieving the ultimate density is obtained in the actual field.

Superpave Specifications on Aggregates

The Superpave mix design process starts with aggregate evaluation. Aggregate characteristics are identified as consensus properties and source properties. The consensus properties include coarse aggregate angularity, fine aggregate angularity, flat-elongated particles, and clay content [7]. Angularity of the aggregates ensures a high degree of internal friction and shear resistance. Limiting elongated pieces ensures that the mixture will not be susceptible to aggregate breakage during handling and construction and under traffic. Limiting the amount of clay ensures the adhesive bond between asphalt binder and the aggregate. The source properties include toughness, soundness, and deleterious materials. Those properties are source specific and are used to qualify local sources of aggregates.

The aggregate gradation is one of the most important properties in the asphalt mix. To specify aggregate gradation, Superpave uses the 0.45 power gradation chart with control points and a restricted zone to develop a design aggregate structure. Control points function as master ranges between which gradations must pass. They are placed on the nominal maximum sieve, an intermediate sieve (2.36mm), and the smallest sieve (0.075mm). The restricted zone, residing along the maximum density gradation between an intermediate sieve and the 0.3mm sieve, forms a band through the gradation cannot pass. Gradations that pass through the restricted zone have been called “humped gradations” because of their characteristic hump shape in this area. In most cases, a humped gradation indicates a high proportion of fine sand relative to total sand. If the aggregate meets the suggested Superpave criteria, it is suitable for use in asphalt mixes [7].

Asphalt Cement Grading

Asphalt selection for the Superpave mix design is performance-based and dependent on climate and traffic conditions. The high and low temperature requirement of the binder differentiates among the various grades of binders. For example, an asphalt binder grade of PG 58-28 means that the asphalt must meet high temperature requirements of 58°C and low temperature requirements of -28°C. Once a binder grade is selected based on temperature, the grade may be adjusted for different loading conditions [7].

Air Void Considerations

The packing characteristics of asphalt-coated aggregate properties in an asphalt mixture are related to both aggregate surface characteristics and gradation. Aggregate surface characteristics include angularity and surface texture. Surface properties contribute to stability and skid resistance. Sufficient voids are needed to develop adequately thick asphalt films for adhesion and durability. Aggregate gradation has a major influence in the formation of intergranular void space between the aggregate particles. The volume of this intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of total volume, is called the Voids in the Mineral Aggregate (VMA).

A gradation with maximum density has no or very little air voids. The addition of asphalt to this maximum density gradation only serves to separate the aggregate particles, which reduces the shear strength of the mix and increases the potential for lateral flow. Too much air voids makes the mixture highly permeable and thereby reduces the resistance to the action of air and water. High permeability to air causes embrittlement of the binder due to oxidation, causing the pavement to crack. High permeability to water encourages stripping of the asphalt from the aggregate particles, and endangering the subgrade layer and base course as well [8]. Thus air voids in the compacted mixture play an important role in the durability of asphalt concrete. Therefore, the voids' content must be carefully chosen so that none of the important characteristics are sacrificed.

Mix Design Procedure

The mix design procedure requires three basic steps. First, select the proper aggregate and asphalt cement. Next, select the design aggregate structure and estimated optimum asphalt cement content by preparing test specimens using trial aggregate gradations and trial asphalt content. A design aggregate structure and estimated optimum asphalt content are selected by estimating a trial mix's VMA, VFA, and percent of maximum density at the initial and maximum compaction levels at 4 percent air voids and determining if they meet limiting criteria. Compaction levels are measured in terms of the gyratory compactor. Finally, the optimum asphalt cement content for the design aggregate structure is determined by compacting two test specimens at four different asphalt cement contents. The asphalt contents are 0.5 percent above and below, 1.0 percent above, and one at the estimated optimum asphalt cement content. The design optimum asphalt cement content then is selected by determining which asphalt cement content satisfactorily conforms with the requirements for air voids, VMA, VFB, and dust proportions at the design compaction level. Percentage of maximum density criteria at the initial and maximum compaction levels is also used. The moisture sensitivity of the design mixture can be evaluated at an air void content of 7 percent [9]. The Superpave criteria for material selection and the compactive effort required for the test samples is determined using the design Equivalent Single Axle Loads (ESALs) for the project.

C. Review of Previous Investigations

Various papers have been published in the literature regarding the comparison between Marshall and Superpave methods for design of asphalt mixtures. Recently, several studies have been conducted to evaluate the feasibility and performance of Superpave-designed mixtures.

Wang et al [10] in his study compared the volumetric and mechanical performance properties of Superpave mixtures and typical Taiwan mixture (TTM) using the Marshall method. His results showed that the asphalt binder contents for the Superpave-designed mixtures are lower than TTM Marshall-designed mix and TTM mixtures exhibited low densification values.

Jasim [11] evaluated the volumetric, mechanical properties and moisture susceptibility for both Marshall and Superpave design methods. She found that the estimated asphalt content for the Superpave mix design is lower than that obtained by Marshall Mix Design. This indicates that the Superpave mix design is more economical.

A study in India by Swami et al. [12] was conducted to ascertain and evaluate how well Superpave designed mixtures performed compared to conventional Marshall mix with respect to permanent deformation (rutting) using local materials in Malaysia. The study results showed that the Superpave gyratory compactor (SGC) is capable of achieving lower air void contents than that could be achieved by the mechanical Marshall hammer compactor. Also they found that Superpave mixes have less asphalt binder contents than the Marshall mixes.

Asi and Khalayleh [13] who study the possibility of adopting the Superpave mix design procedure in Jordan to solve the bleeding problem and some of the distresses common in asphalt roads. They found that using local aggregate gradation for heavy traffic in the Superpave design method gave dust proportion higher than the maximum specified limit by the Superpave procedure. High dust proportion will usually lead to brittleness of the mixes. Therefore, they recommend shifting to the Superpave design procedure.

Hafez and Witczak [14] have stated that for identical traffic and climatic conditions, the Superpave Level 1 design for polymer modified mixtures, the binder was found to be about 0.5 to 0.8 percent less than the Marshall analysis. For Superpave mixes at traffic level less than 1 x 107 ESALs, simulating 75-blow Marshall Mixes the asphalt design contents were found to be almost equivalent. As the climatic region changes from worm to cool, super-pave required 1 percent higher binder content compared to Marshall procedure.

III. EXPERIMENTAL WORK

In this study, the Marshall and Superpave mix design methods were performed on the same source of aggregate and asphalt. At the time the asphalt cement and aggregate were selected, they also were being used in a construction project in Khartoum. These materials were used so the laboratory and field performance could be compared at a later time.

The performance of asphalt samples based on the Marshall and the Superpave mix design methods were compared through laboratory accelerated performance testing. The results of the tests were analyzed for differences in performance.

A. Materials Characteristics

The properties of the asphalt cement used in this study were determined as shown in table I. The physical and mechanical properties of aggregates used are given in table II.

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The aggregate was crushed and sieved into coarse and fine sizes. The coarse sizes contained materials of three sizes 19, 9.5, 5.0 mm while the fine sizes contained natural sand and mineral filler. The sieve analysis results for aggregate materials are plotted in figure1.

TABLE I. Physical properties of the used asphalt cement.

Property	Test Result	Criteria
Penetration, 0.1mm	62	60 - 70
Ductility at 25 ˚C, cm	112	100 min.
Softening Point, ˚C	52	48 – 56
Rational Viscosity at 135 ˚C, Pa.s	0.488	3 max.
Rational Viscosity at 165 ˚C, Pa.s	0.117	n/a
Flash Point, ˚C	252	230 min.
Fire Point, ˚C	306	230 min.
Specific Gravity at 25 ˚C	1.02	1.01 – 1.06

TABLE II. Characteristics of coarse and fine aggregates and mineral filler.

Property	Coarse Aggregate			Fine aggregate		Com-bined
% used by wt. of agg.	19 mm	9.5 mm	5 mm	Sand	filler	100
Bulk specific gravity of agg.	32	15	23	20	10	2.600
Apparent specific gravity of agg.	2.640	2.460	2.698	2.505	2.675	2.699
Water absorption, %	2.725	2.560	2.839	2.627	2.675	3 max.
Elongation, %	1.23	1.61	1.84	1.85	n/a	
Flakiness, %	15.8	15.3	n/a			
Abrasion loss, %	20.8			n/a		
Sand equivalent, %	n/a			92	n/a	

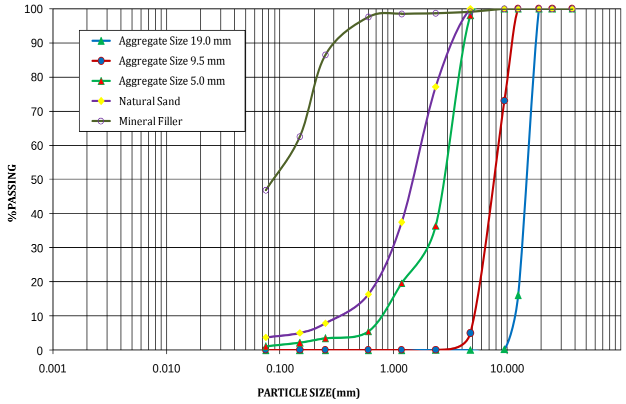

Fig. 1. Sieve analysis of coarse aggregates, natural sand and mineral filler.

B. *Mix Design*

For this study, both the Marshall mix design and the Superpave mix design were performed. Both mix designs used the same aggregates and asphalt cement described in the previous section, but the materials were subjected to different tests and combined differently in each case, as per mix design specifications.

Marshall Mix Design

The aggregate used in the Marshall mix design consisted of 47 percent coarse and 53 percent fine aggregate. The job mix for the combined aggregate is displayed in figure 2. The asphalt cement used to construct the asphalt mix was 60/70. This is the standard asphalt cement grade used in Sudan.

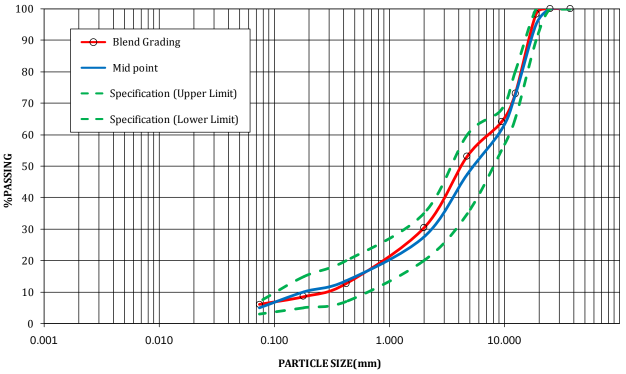

Fig. 2. Job mix for combined aggregate.

The samples were prepared with a compaction effort of 75 blows per side from the Marshall Compaction hammer. The stability, unit weight, flow, air voids, VFB, and VMA relationships with asphalt cement content are used to determine the optimum asphalt content (OAC). The OAC was determined to be 5.5 percent. The properties of the asphalt mix at 5.5 percent asphalt cement content pass the criteria shown in table III.

TABLE III. The properties of asphalt mix and Marshall Criteria

Property	Result	Marshall Criteria
Design Asphalt Content, %	5.5	4.5-6.5
Stability, Kg	1652	1000 min.
Unit Weight, KN/m3	22.6	--
Flow, mm	3.7	2 - 4
Air Void, %	3.8	3 - 5
Voids in Mineral Aggregate, %	15.8	12 min.
Voids Filled with Asphalt, %	75	70 - 80

Superpave Mix Design

The aggregate and asphalt cement used for the Superpave mix design were the same materials used in the Marshall mix design, the Superpave mix design used three different trial blends of the coarse and fine aggregates. The trial blends were chosen to cover a wide range of aggregate gradations as shown in table IV. A gradation chart containing the three trial blends is displayed in figure 3, which includes the Superpave mix design criteria. The criteria were determined based on a 12.5 mm nominal aggregate size.

TABLE IV. Aggregate blending for trial blends of superpave

Trial Blend No.	Coarse Aggregate			Fine aggregate	
	19 mm	9.5 mm	5 mm	Sand	filler
1	8	36	23	25	8
2	11	33	20	30	6
3	5	40	18	27	10

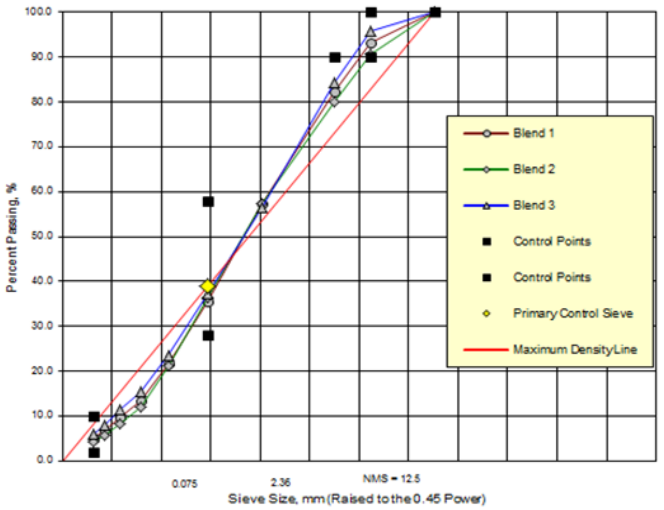

Fig. 3. Gradation chart for Superpave trial aggregate blends

According to the Superpave mix design method, several tests may be performed on the aggregate to determine its consensus and source properties, which help determine if the aggregate is suitable for use in an asphalt pavement. Table V shows the Superpave criteria and consensus and source properties for the three trial blends.

TABLE V. Properties of the used aggregate in Superpave mixes.

Property	Blend 1	Blend 2	Blend 3	Criteria
Coarse agg. angularity, %	97.7	97.7	97.7	90 min.
Fine agg. angularity, %	45	45	45	45 min.
Flat / Elongated, %	7.6	7.6	7.6	10 max
Sand equivalent, %	90	90	90	45 min
Coarse agg. specific gravity	2.550	2.550	2.550	n/a
Coarse agg. water absorption, %	1.4	1.4	1.4	n/a
Fine agg. specific gravity	2.505	2.505	2.505	n/a
Fine agg. water absorption, %	1.8	1.8	1.8	n/a
Combined agg. Specific gravity	2.554	2.550	2.542	n/a
Combined agg. apparent specific gravity	2.659	2.657	2.644	n/a
Combined agg. water absorption, %	1.7	1.7	1.7	n/a
Abrasion loss (500 Rev), %	20.8	20.8	20.8	35 max
Soundness , %	6.1	6.1	6.1	10 max
Deleterious Materials	0.0	0.0	0.0	10 max

The three trial blends were evaluated by compacting two asphalt samples and using volumetric properties to analyze them. The initial trial asphalt content was determined to be 4.8 percent for each of the three blends. The gyratory compaction effort was $N_{initial} = 8$, $N_{design} = 100$, $N_{maximum} = 160$ gyrations, based on the design specification of 10 million ESALs. The maximum specific gravity of the asphalt mixes (G_{mm}), determined using AASHTO T 209, with the average percent of G_{mm} of each trial blend at N_{ini}, N_{des}, and N_{max}, are shown in table VI. The volumetric properties of the asphalt mix and the Superpave criteria are listed in table VII. These criteria also were determined based on the 10 million design ESALs.

TABLE VI. G_{mm} and percent G_{mm} for compacted trial blends at N_{ini}, N_{des}, N_{max}.

Blend No.	Max. Specific Gravity (G_{mm})	% of Maximum Specific Gravity		
		N_{ini}, 8 Gyrations	N_{ini}, 8 Gyrations	N_{ini}, 8 Gyrations
1	2.442	85.3	85.3	85.3
2	2.419	86.3	86.3	86.3
3	2.415	87.0	87.0	87.0

TABLE VII. The properties of asphalt mix and Superpave Criteria.

Property	Result	Superpave Criteria
Design Asphalt Content (DAC), %	5.3	n/a
Bulk Specific Gravity (G_{sb})	2.55	n/a
Effective Specific Gravity (G_{se})	2.609	n/a
Maximum Specific Gravity (G_{mm}) @ N_{ini}	88.2	89
% G_{mm} @ N_{des}	96	96
% Air Voids	4.0	4
% VMA	14.3	14-16
% VFA	72.3	65-75
Asphalt Absorption (P_{ba})	0.78	n/a
% Passing 0.075 mm Sieve	3.8	3 - 5
Effective Asphalt Binder Content (P_{be}), %	4.5	n/a
Dust Proportion (DP ratio)	0.941	0.8-1.6

IV. ANALYSIS AND DISCUSSION

The optimum asphalt binder content obtained were 5.3 percent and 5.5 percent by weight of mix for Superpave and Marshall mixes respectively. From the result it was observed that, the Superpave mix design resulted in lower binder content compared to Marshall mix design. The lower binder content obtained in Superpave mix design may be a cause of concern for durability of mixes.

The air voids relationship with asphalt content for Superpave and Marshall specimens are shown in figure 4. As shown in figure, at 4% air voids the asphalt binder content required for both Superpave and Marshall specimens were found to be 5.3% and 5.4% respectively. From figure it was also observed that, for Marshall specimens at 5.5 % binder, the air voids reduced to 3.7%. This was due to the fact that, in Marshall mix design, air voids is one of the three criteria in selection of optimum asphalt content, whereas in Superpave, air voids is the main criterion for selection of optimum binder content.

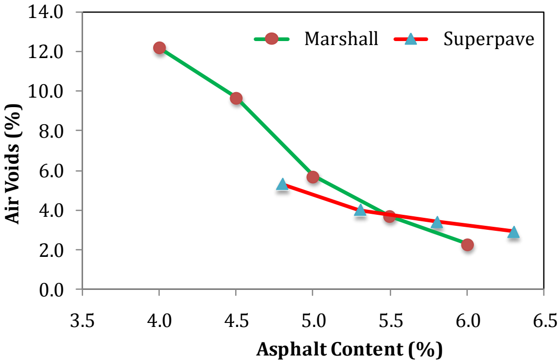

Fig. 4. Relationship of density and air voids with asphalt content.

The Chart was plotted between asphalt content, bulk density (at 4% air voids) and Ndes gyration for Superpave mixes as shown in figure 5. From this figure, it was observed that, in Superpave specimens to achieve 4% air voids, the required number of gyrations decreased with increase in asphalt content and at the same time, the density decreased with increase in asphalt content. It was also observed that at Ndes gyrations on increasing the asphalt content; the density values followed Marshall trend.

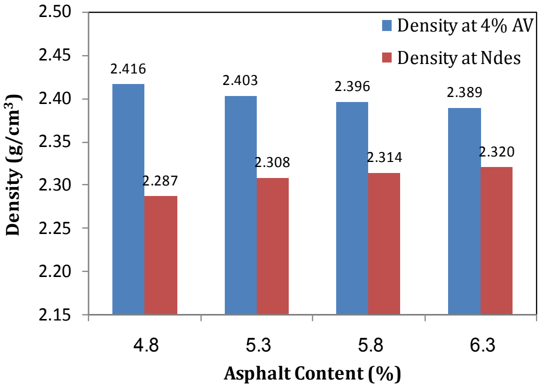

Fig. 5. Densities at N_{des} and 4% Air Voids at varying asphalt content.

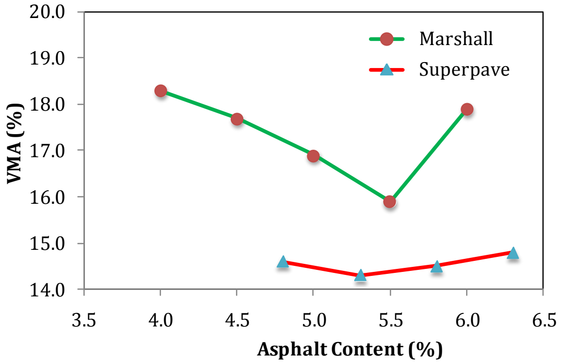

Fig. 6. Relationship of VMA with varying asphalt content.

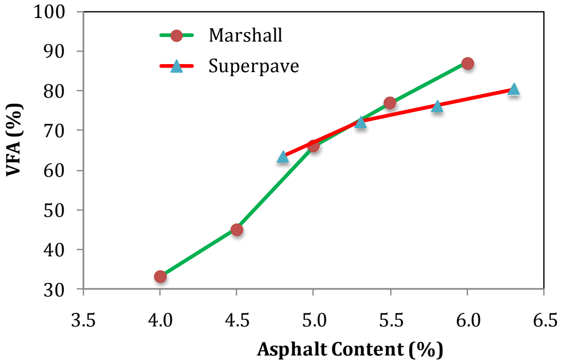

Fig. 7. Relationship of VFB with varying asphalt content.

Relationship between asphalt content, VMA and VFB were plotted for both Superpave and Marshall mixes, as shown in figure 6 and 7. From these figures it was observed that, VMA was 14.3% and 15.8% for Superpave and Marshall mixes respectively. It was also observed that, VFB was 72.3% and 75% for Super-pave and Marshall mixes respectively. From results it was concluded that the VMA and VFA values of Superpave are higher than Marshall values.

V. CONCLUSION

The aim this research was to check whether the Superpave mix design method using local materials, under heavy traffic loading conditions and prevailing temperature regime, has superiority over the conventional Marshall mix design method or not. The following conclusions were drawn:

- From the results, it was observed that the design asphalt content for Superpave and Marshall mixes were found to be 5.3 and 5.5 percent (by weight of mix) respectively. Hence it can be concluded that Superpave mix design results in lesser binder compared to Marshall mix for hot climate and heavy traffic conditions.
- At optimum asphalt content, Superpave and Marshall specimen densities were 2.403 and 2.304 g/cm^3 respectively. It was concluded that, higher density in Superpave is due to Superpave Gyration Compactor compactive effort.
- From the study it was concluded that, performance-based Superpave mixes performed better than Marshall mixes. Therefore in Sudan, shifting to the Superpave design procedure might help solve some of the distresses common in recently constructed roads.

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