Comparison between Marshall and Superpave mix design method for flexible pavements

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Abstract

Asphalt pavement is a mixture of binder and aggregate under specified volume parameter, the quality and mix design of flexible pavements plays a major role in the performance and durability of these pavements. Several methods have been developed for determining the quantities of aggregate and asphalt cement used in the asphalt concrete such as Marshall, Hveem and Superpave system (AI, 2014).The Marshall procedure is empirical and suffers in the accuracy in determining the full effects of variation in environmental and loading conditions, also material properties and types on pavement performance, the empirical nature and the drawbacks of the Marshall mix design procedure the Strategic Highway Research Program (SHRP) has developed a Superior Performance Asphalt Pavements (Superpave) mix design procedure. (SHRP, 1994).

Reviewing pavement mix design for Kurdistan Region-Iraq is important due to Poor performing roads with shorter expected live of pavement, 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 distress like rutting, fatigue and thermal cracking on bituminous surfacing. This review is intended to compare the Superpave asphalt mix design procedures with the Marshall asphalt mix design method. The comparison was based on several issues including evaluation of materials prior to mixture design, the design asphalt content and the relationship between mixture design and pavement performance. The literature review revealed that Superpave mixes prove their superiority over Marshall mixes especially for roads exposed to heavy traffic loadings and climatic changes. Therefore, serious plans should be set up to shift from the presently used Marshall mix design procedure to Superpave mix design, adopting the Superpave design procedure might help in enhancing the performance of the asphalt roads.

Keywords: Marshall, Superpave, mix design, gyratory compaction, optimum asphalt content

1. Introduction

Asphalt pavement is considered as one of essential issues of highway flexible pavement technology. Better performance of roads can be achieved by improving methods of asphalt mixture design and efforts on improving construction practices, technology, and quality. There are many mix design methods used throughout the world such as Marshall mix design method, Hubbard-field mix design method, Hveem mix design method and Asphalt Institute Triaxial method of mix design. Currently, the conventional Marshall method is widely used in some countries to design asphalt layers of flexible pavement (ASTM, 1997).

In Sulaimanya City Marshall mix design procedure is used for designing the asphalt concrete mixes, most of the roads are performing poorly with pavement life much shorter than expected, they are suffering from severe rutting and cracking in asphalt pavements due to increased traffic loads and environmental conditions. Early distresses in pavements due to the continuation of the use of Marshall mix design procedure for asphalt mixtures (Asi, 2007). Therefore, it is strongly recommended that the Superpave methodology be adapted and to be implemented immediately in the construction specifications in Kurdistan.

1.1 Marshall Mix Design Overview

Bruce Marshall, an engineer with the Mississippi Department of Highways, formulated the concept of this method in 1939. In 1943, the U.S Army Corps of Engineers refined and adopted the Marshall method for selecting optimum asphalt content as a function of gradation and traffic conditions. A standard compaction procedure was adopted using a sliding hammer with 98.4 mm diameter head, weighing 5.54 kg to deliver and specific amount of blows per side on samples with 63.5 mm height and 102 mm in diameter. (ASTM, 2000). The Marshall compaction device shown in Figure 1.

In 1954 stability, flow, density, and void criteria were established. Volumetric criteria were added to the method in 1973 by the Asphalt Institute. These studies improved and added new features to Marshall design method, resulting the present form of the mix design method. The dimensions of the standard Marshall sample limited the method to aggregate with a nominal maximum aggregate size of 19 mm or less. A modified procedure was later introduced using 15cm diameter molds to accommodate aggregate up to 37.5 mm NMAS. (AI, 1993). While there are national standards for the Marshall mix design method most state highway agencies have tailored the method to meet local conditions. (Diaz, 2003).

Marshall method primarily addresses the determination of the asphalt binder content. In addition, the equipment required for the Marshall mix design method is relatively inexpensive and portable and thus lends itself to remote quality control operations. Side by side, the disadvantages of this method are that impact compaction used with the Marshall method does not simulate mixture densification as it occurs in the real pavement. (AI, 2014). Marshall stability does not adequately estimate the shear strength of hot mix asphalt (HMA). So there was a growing feeling among the asphalt technologists that Marshall method has outlived its usefulness for modern asphalt mixture design as reported by (White, 1985).

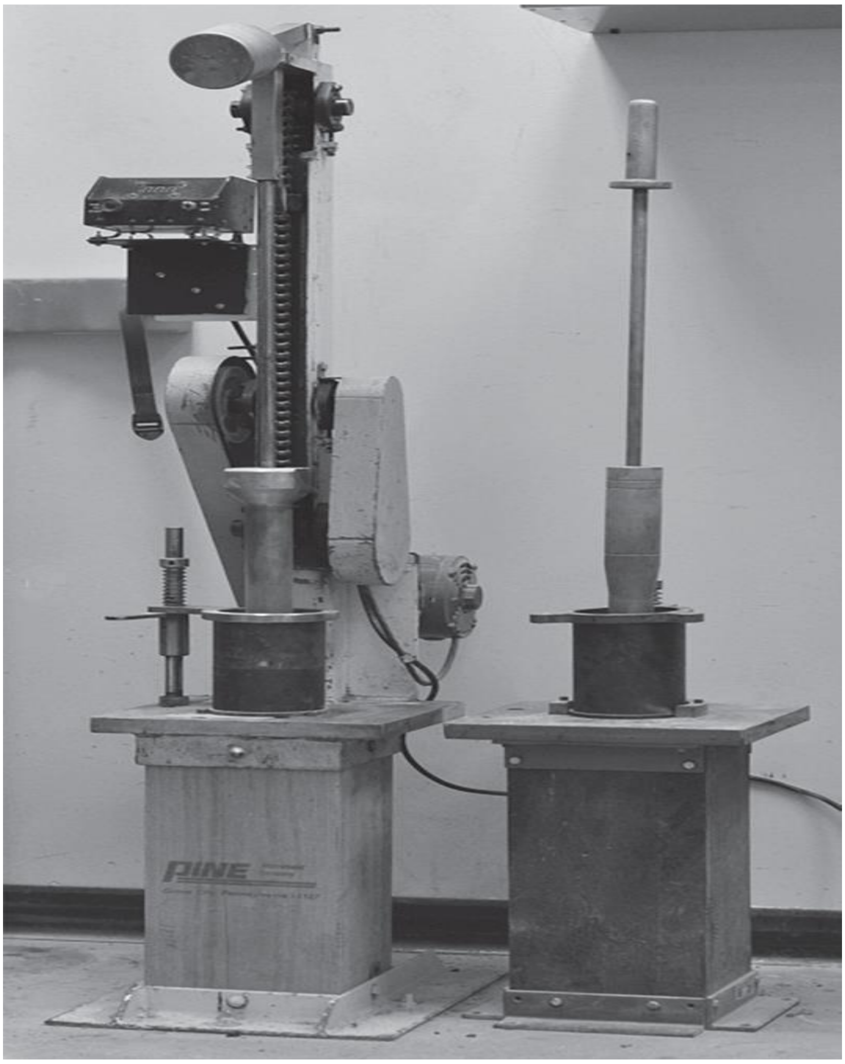

Figure 1: Manual and mechanical hammer configurations (AI, 2014)

The Marshall stability device measures the flow and the stability at the same time, the flow is equal to the vertical deformation of the sample (measured from start of loading to the point at which stability begins to decrease). The maximum load carried by a compacted specimen tested at (60° C) at a loading rate of 5 cm/minute is recorded. The Marshall stability- flow device shown in Figure 2. In this method the stability, flow, unit weight, air voids, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA)are plotted versus the asphalt content (AC). The optimum asphalt content (OAC) of the mix is determined from the data obtained from the plots. The optimum asphalt content should achieve the specification requirement from the volumetric properties of the mix. (ASTM T 245).

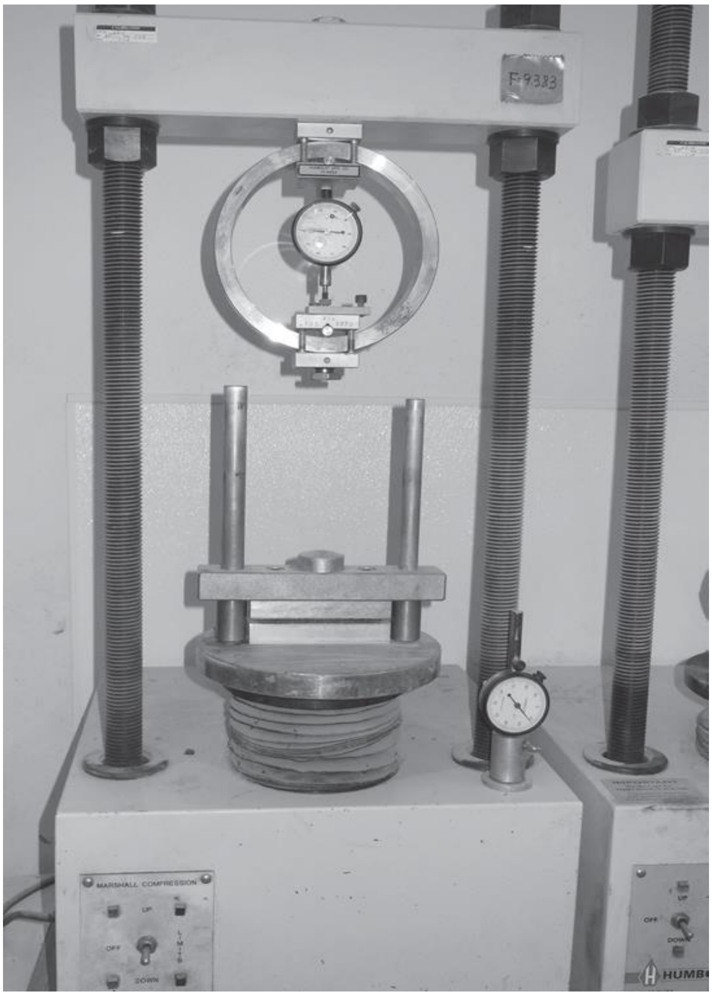

Figure 2: Marshall stability – Flow device (AI, 2014)

Throughout the evolution of asphalt mix design; several different types of laboratory compaction devices have been developed to produce specimens for volumetric and/or physical characterization (Harman et al., 2002).

Although the Marshall Mix design method has used for many years, many engineers believe that the impact compaction used with the Marshall method does not stimulate mixture densification as if occurs in real pavement. (FHWA, 2001).

1.2 Overview of Superpave Mix Design Method

The Superpave (SUperior PERforming Asphalt PAVEments) mix design method was developed to provide highway agencies, engineers and contractors such a system that would perform superior under diverse temperature ranges and traffic loads. Superpave which was developed by the researchers of Strategic Highway Research Program (SHRP).Most of the hot mix asphalt (HMA) produced during the 50 years between the 1940 and mid 1990 were designed using the Marshall methods, and the increase in traffic volumes and heavier loads became initiative for (SHRP) in 1988. After five years of efforts, a new mix design, Superior Performing Asphalt Pavements (Superpave) was developed. Superpave takes into consideration the factors responsible for the typical distress on asphalt pavements, rutting, fatigue, and thermal cracking. With the introduction of Superpave mix design, the Marshall method of mix design has become obsolete in highway pavement. (Vasavi, 2002). SHRP research activities were completed in 1992 and SHRP was closed down in 1993. To date, SHRP has produced more than 100 new devices, tests and specifications and, perhaps more importantly, has spawned a full-scale on-going implementation drive by such organizations as the FHWA, AASHTO and TRB (FHWA, 1994).

The distinctive aspect of the Superpave system is its test procedures which have direct correlations with the field performance. Superpave has advanced system for identifying asphalt binders and mineral aggregates, designing asphalt mix and pavement performance prediction. (Muzaffarkhan, 2008). Superpave is a performance-related asphalt binder and mixture specification, Superpave is not just a computer software package, nor just a binder specification, nor just a mixture design and analysis tool, Superpave is a system which is inclusive of all these parts. The Superpave system is applicable to virgin and recycled, dense-graded, hot mix asphalt (HMA), with or without modification. In addition, the Superpave performance tests are applicable to the characterization of a variety of specialized paving mixes such as stone mastic asphalt (SMA). It can be used when constructing new surface, binder, and base layers, as well as overlays on existing pavements. The Superpave mix design method addresses all the elements of the mix design and was designed to replace the Hveem and Marshall methods. It also explicitly considers the effects of aging and moisture sensitivity in promoting or arresting the development of these three distresses (SHRP, 1994).

The compaction devices used for Hveem and Marshall procedures have been replaced by a gyratory compactor and the compaction effort in mix design is tied to expected traffic. The performance-grading (PG) system used in superpave mix design method is considered better over the viscosity and penetration system as the conditions at which the testing is carried out have close simulation with the actual pavement conditions. According to (Roberts et al., 2002), Superpave predicts much improved reliability as it considers the engineering parameters related to the actual failure mechanism leading to pavement deterioration.

Superpave mix design consists of three levels. These levels relate to expected traffic levels for the design life of the pavement characterized by the equivalent standard axle loads (ESALs) are quantified as low (≤1 million ESALs), medium (1–10 million ESALs), and high (≥10 million ESALs) (Tappeiner, 1996). The three levels are described as follow:

- Level one: mixture design incorporates material selection and volumetric proportioning to produce a mixture that will perform satisfactorily. It is for asphalt pavements exposed to low traffic. The laboratory compacted effort is adjusted to suit the traffic loading expected.
- Level two and three: applies all the level one procedure and at the same time, included two additional pieces of laboratory equipment to test a range of mixture performance tests such as permanent deformation and fatigue cracking to evaluate the asphalt's response to various loading and temperature conditions.

1.3 Compaction Method for Superpave Mix Design

The three major components of Superpave are the asphalt binder specification, mixture design and analysis system, and a computer software system. One of the key feature in super pave mix design is the change in laboratory compaction methods. Laboratory compaction is accomplished using a super pave gyratory compactor (SGC) as shown in Figure 3. The SGC is used in Superpave system to produce compacted specimens for volumetric analysis and determination of mechanical properties. The equipment is capable of providing data to indicate the trend of density variation throughout the compaction procedure. (SHRP, 1994). A loading system applies a load to the loading ram, which imparts A 600 kPa compaction pressure to the specimen. A pressure gauge measures the ram loading to maintain constant pressure during compaction. The SGC mold is cylindrical wall (inside diameter of 150 mm) with a base plate at the bottom to provide confinement during compaction. While the mold is positioned at a compaction angle of 1.25°. Figure 4 illustrates the SGC configuration.

Figure 3: Superpave gyratory compactor (FHWA, 2016)

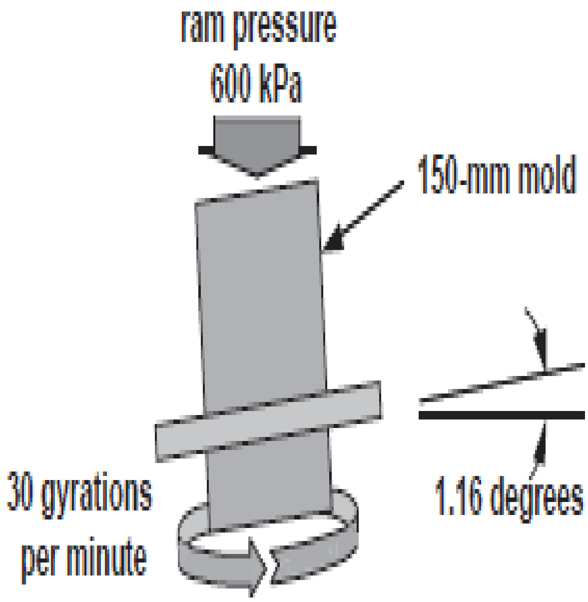

Figure 4: SGC mold configuration (AI, 2014)

The density of specimens made at any time throughout the compaction process. Height is measured by recording the position of the ram throughout the test. Three gyration levels, specified by the Superpave volumetric mixture design procedure are of interest:

- Design number of gyration (N design)
- Initial number of gyration (N initial)
- Maximum number of gyrations (N maximum)

In Superpave, asphalt mixtures are designed at a specified level of compaction effort, identified by N design. As a function of the traffic level, N design is used to vary the compaction effort of the design mixture. Traffic is represented by the design equivalent single axle loads (ESALs). The test specimens are compacted to the maximum level using N maximum gyrations. At N maximum, the density is not allowed to exceed 98% of maximum theoretical specific gravity (Gmm). The compatibility of the mixture is estimated at N initial. (Mansour et al., 1999).

1.4 Concept of Superpave Mix Design

There are four steps immixture design (AI, 2001).

- Selection of materials
- Selection of design aggregate structure
- Selection of design asphalt binder content

- Evaluation of moisture susceptibility.

Selection of the performance grade (PG) of asphalt binder is guided by the high and low pavement design temperatures at the project location. Candidate paving mixes are evaluated for acceptable moisture sensitivity. Asphalt binders and paving mixes are aged in the laboratory to simulate the effects of short and long-term aging on performance (SHRP, 1994).

Trial aggregate blend is selected, initial binder content is calculated, the binder, aggregate and dust mixed with mechanical mixer at mixing temperature then the samples are compacted by SGC to Nd. Volumetric calculations % air voids, VMA, VFA, dust proportion (DP) are made to samples then estimated binder content is calculated based on 4% air voids and required % Gmm at Nd. The design aggregate structure (DAS) is selected corresponding to the estimated binder content.

The estimated binder content must be compared with Superpave mixture criteria; four samples are prepared as follows:
DAS + % estimated binder content ± 0.5%
DAS + % estimated binder content +1%
DAS + % estimated binder content

The samples are compacted to Nd gyration, then % voids, % VMA, %VFA, DP and %Gmm at Nd are calculated and plotted with % asphalt binder content.
The design asphalt content (DAC) found from plotted graphs, the DAC corresponding to 4% air voids is selected then compared with other volumetric criteria, the DAC must be within superpave mix criteria. Final step is N max verification and moisture sensitivity test. The mix must pass all the mentioned criteria. (FHWA, 2016)

2. Objective

The main objective of the review is comparison between traditional Marshall mix design method and the Superpave system design method in the wearing course mixes in flexible pavements, by obtaining the quantitative information on the difference in design asphalt contents determined by Marshall and Superpave mix methods and evaluating the volumetric, mechanical properties for a variety of mixes based on previous studies. The second objective is to evaluate and compare the Marshall and Superpave mix performance.

3. Literature Review

Various papers have been published 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 mixtures.

Wang et al. (2000) compared the volumetric and mechanical performance properties of Superpave mixtures and typical Taiwan mixture (TTM) using the Marshall method. 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.

Kanneganti (2002) West Virginia Division of Highways in corporation with the US Department of Transportation Federal Highway Administration, conducted a comparison between a 19 mm Superpave and Base II Marshall mixes in West Virginia. The Marshall and Superpave methods were compared by preparing similar mix design with each method. The asphalt contents of Superpave mix designs were higher than Marshall mix design for the same traffic level. The Marshall mix design method provided 4.9% OAC, while the Superpave mix design method provided a 5.1% design asphalt binder content. In addition, the Asphalt Pavement Analyzer (APA) was used to evaluate rutting performance of gyratory compacted samples in the laboratory. The statistical analysis of rut depth results indicated there was not enough evidence to conclude there was a significant difference between the Marshall and Superpave mix design methods.

Zaniewski and Nelson (2003), evaluated the differences between the two design methods for asphalt concrete wearing courses. These are the West Virginia Division of Highways (WVDOH) wearing I mix for the Marshall method and the 9.5 mm design for the Superpave method, mixes were developed for light, medium, and heavy traffic. The differences in asphalt contents between the two-mix design methods range from 0.2 to 0.8%. For the mixes with 13 % natural sand, the Marshall mixes require more asphalt. On the other hand, the Marshall Mix with 13 % sand showed greater rutting potential than the 1% lime stone mix. The Superpave mixes for low traffic roads designed with high sand contents displayed very high rutting potential. The results of this research indicated that the performance of Marshall and Superpave mixes is comparable with respect to rutting performance. This demonstrates that correctly applying the methodology and criteria to a mix design method may be more important than when mix design method is used.

(Diaz,2003) evaluated 4.7mm NMAS of aggregate for low volume roads with less than 0.3 million ESAL, using same aggregate and binder PG 64-22, Nd= 50 for Superpave and 50 blows for Marshall compared the percentage of asphalt binder of Marshall and Superpave, Figure 6 shows that Superpave mixes have a lower optimum asphalt content than the Marshall mixes. The researcher concluded that the Superpave had lower (VMA and VFA) than the equivalent Marshall mixes as shown in Figures 7 and 8.

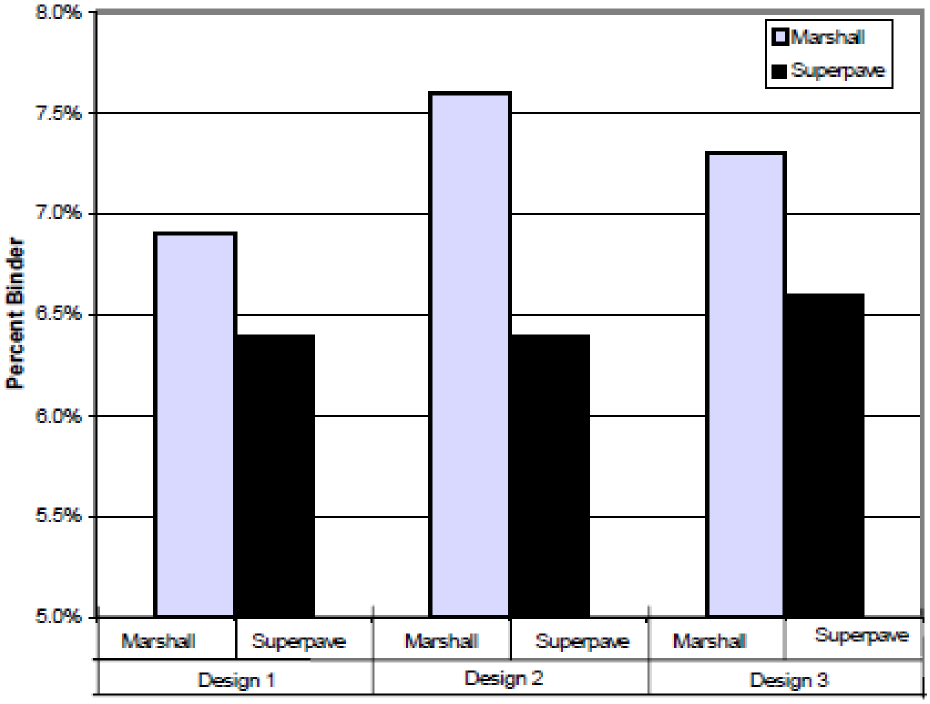

Figure 6: Comparison of Superpave and Marshall optimum asphalt contents (Diaz, 2003)

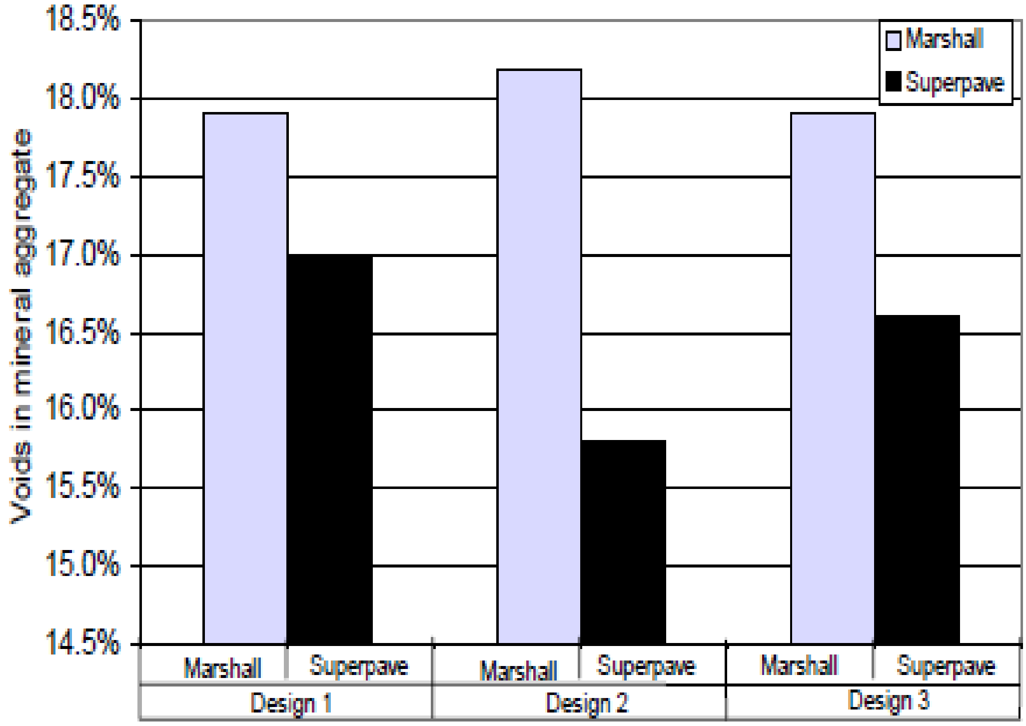

Figure 7: Comparison of VMA for Marshall and Superpave mixes (Diaz,2003)

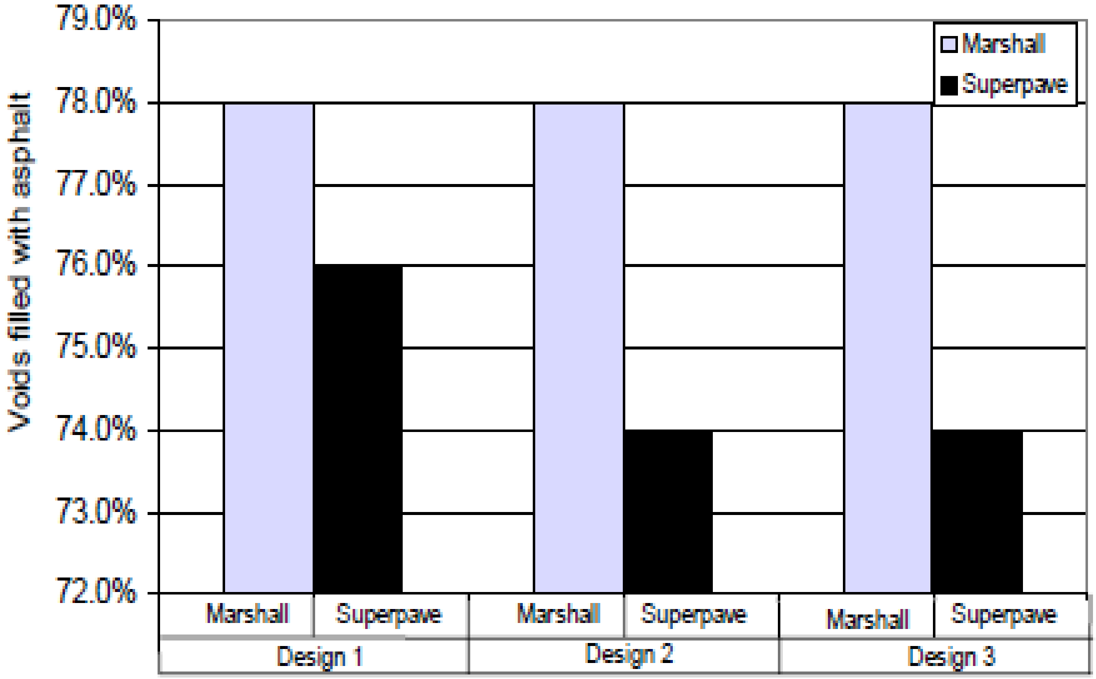

Figure 8: comparison of VFA for Marshall and Superpave mixes (Diaz, 2003)

Xie and Watson (2004) compacted five aggregates in three Nominal Maximum Aggregate Size (NMAS) by Marshall Hammer and Superpave Gyratory Compactor (SGC). The relationship between aggregate breakdown and influencing factors including compaction effort, Los Angeles (LA) abrasion, and flat and elongated (F and E) particles content were investigated. The influence of aggregate breakdown on volumetric properties was also investigated. The aggregate breakdown by the Marshall hammer was found to be significantly higher than the breakdown by the SGC. (LA) abrasion was found to have a strong relationship with aggregate breakdown, and also directly related to the Voids in Mineral Aggregate (VMA) of stone mastic asphalt (SMA) mixtures. F and E content had a moderate relationship with aggregate breakdown, but had relatively little effect on VMA.

Swami et al. (2004) compared the design of asphalt concrete by Superpave and Marshall method of mix design for Indian conditions and studied the properties of Superpave mixes at different angles and different numbers of gyrations. They found that Superpave mixes fulfilled all the criteria for easy and good construction at lesser binder content than the Marshall mixes (4.4 % versus 5.3 %). It was also found that Superpave mixes are least affected by water. Study recommended that Marshall mix design should be replaced by Superpave mix design for Indian national highways.

Asi (2007) conducted a study to find the adoptability of Superpave mixtures specifications to the Hashemite Kingdom of Jordan specific materials, traffic, and environmental conditions. A comparison study was carried out to use local materials to design the asphalt mixtures using both Marshall and Superpave mixtures. For wearing coarse with same gradation of NMAS of 19 mm, heavy traffic condition. Design procedures in addition to performance of both mixtures were evaluated. Conclusions of the study showed that the Superpave design procedure provided lower asphalt content than that predicted by Marshall design procedure. Dynamic creep, static creep, fatigue, resilient modulus and moisture sensitivity testing was selected as performance based testing. Superpave mix showed overall better performance as compared to the Marshall mix.

Khan and kamal (2008) investigated Superpave technology adoption for the design of flexible pavements in Pakistan. The study was done by comparing Superpave and Marshall methods of design using local materials. In order to evaluate mixes, they were subjected to indirect tensile strength, creep performance, and moisture sensitivity. The Superpave mix showed better results compared to the studied properties of asphalt. Guidelines for implementing the Superpave mix design procedure in Pakistan have been proposed.

Al-Khateeb et al. (2010) compared the Superpave asphalt mixture design procedures with the Marshall asphalt mixture design method. The comparison was based on several issues including evaluation of materials prior to mixture design, the design asphalt content, and the relationship between mixture design and pavement performance.

Comparison made for 19mm NMAS same gradation for both mixes and 75 blows for Marshall method, using asphalt binder penetration grade 60/70 for Superpave mixes, the design mix made for 10-30 million ESAL, Nd=109. Results of the study showed that the design asphalt content (DAC) obtained using the Superpave mixture design procedure was 5.4 % and the optimum asphalt content (OAC) obtained using the Marshall mix design method was 5.6 % when taking the optimum at 4.0% air voids; however, when taking the OAC as the average of: the asphalt content at the maximum stability, the asphalt content at the maximum unit weight, and the asphalt content at 4.0% air voids, the OAC was determined as 5.4 %, which was similar to the DAC obtained using the Superpave mixture design procedure. The researcher concluded that the difference between this research and other researches in DAC is aggregate gradation, the researcher concluded that by using same aggregate gradation the DAC in both methods would be similar or very close.

Jasim (2012) performed the comparison between traditional Marshall design method and the Superpave system design method in the wearing course mixes, the researcher evaluated the volumetric, mechanical properties and moisture susceptibility for Marshall and Superpave design methods for level 1 mix design in Iraq/ Baghdad city. The study conducted by using binder of penetration grade (40-50) from Daurah refinery, with two sources of local aggregate (12.5mm) NMAS from Baghdad (AL- Tagi) for Marshall and Superpave mix. Marshall mixes compacted to 75 blows. For Superpave mix the samples are compacted according to Baghdad climate condition with air temperature > 44 ºC and traffic level of 10-30 million ESAL, the Nini=9, Nd=135, Nmax= 220. The OAC for Marshall mix was 4.7% and for Superpave mix was 4.6%. The researcher found that the estimated and optimum 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.

Jitsangiam et al. (2012) they conducted samples for comparison of Marshall and Superpave mix for Thailand climate condition, for Marshall mix using AC 60-70 and polymer modified asphalt, crushed limestone aggregates. For Superpave: binder PG 76-10 for medium traffic 10-30 million ESAL for air temperature = 53-44 C, Nd=135. The OAC for Marshall = 5.2% and 5.0% for Superpave. The researchers concluded that the AC for Superpave is lower than Marshall mix, and the Superpave mix samples showed superior performance to Marshall mixes based on (stability, indirect tensile strength, resilient modulus and dynamic creep test).

Zumrawi and Edrees (2016) performed Marshall and Superpave mix samples for Khartoum city in Sudan, for same aggregate and asphalt binder of p 60-70 samples prepared for both mix methods, the compaction made with 75 blows for Marshall and Nd=100 for Superpave, the AC for Marshall mix was 5.5% and 5.3% for Superpave samples, the VMA and VFA for superpave mix was lower than Marshall mix samples , at OAC superpave density was higher than Marshall mix due to the superpave gyratory compactor compaction effort ,they suggest. They conclude shifting to superpave design procedure in Sudan.

Atrash (2020) studied the traditional Marshall and Superpave mix design method in hot climate conditions, binder selection, compaction method and performance mix evaluated, the study was for Libya climate condition, the researcher concluded that the modified mixture or new generation methods for asphalt mix design have a significant impact on performance of pavements of hot climate condition .The study conducted by a proper aggregate gradation and using asphalt binder p 60/70 containing of crumb rubber (CR) the mix performed better than traditional Marshall mix.

The summery of the comparison between Marshall and Superpave mix design for flexible pavements shown in Table 2.

Table 2: Summary of Comparison of Marshall and Superpave Mix Design

Parameter	Superpave mix design	Marshall mix design
Selection of binder	Performance graded (PG) system specifies the binder under weather conditions.	PG is not exist.
Initial binder content	initial binder content is done	initial binder content is not exist
Aggregate gradation	Control point / Restricted zone (FHWA 0.45 power chart) used to determine DAS, determine if the aggregate is Finer or Coarse with respect to Max density line and evaluate (NMS).	Control point / Restricted zone (FHWA 0.45 power chart) which are not exist in the Marshall test.
Aggregate tests	Tests in Mineral Aggregate like coarse aggregate angularity (CAA), fine aggregate angularity (FAA), sand equivalency (SE), and F&E particles) are considered.	Tests in Mineral Aggregate like (CAA, FAA, SE, and F&E particles) are not considered.
Compaction method	Superpave Gyratory compactor(SGC)	Marshall compactor (SGC) is not exist.
Dimension of samples	Dimensions of Gyratory are (150)mm diameter specimen & number of Gyration per min in Super pave= (30)	The diameter of specimen is (102mm) which is less than the diameter of Gyratory in Superpave test.
Level of compaction	Levels of compaction in Superpave System with respect to (N design) which depends on: - 1-Average Design high air Temperature 2- Design ESALs	Levels of compaction depends on type of traffic: 1-Light (ESALs<10000) Level of compaction= 35. 2-Medium (10000<ESALs<1000000) Level of compaction=50 3- Heavy (ESALs>1000000) Level of compaction= 75

N max and Nini	The concept of Nmax and Nini done for the mix.	The concept of Nmax and Nini are not exist.
Mix design method	As per SP-2	As per MS-2
Dust ratio	the dust ratio is calculated for mix and must be within criteria	The concept of dust ratio is not exist
Specific gravity	%G mm @Nmax & % Gmm @ Nini exist.	%G mm @Nmax & % Gmm @ Nini not exist
Moisture susceptibility	Evaluation of moisture Sensitivity of design mixture and determine tensile strength ratio which should not less than (80%).	Evaluation of moisture Sensitivity of design mixture and determine tensile strength ratio are not exist in Marshall test.
Rutting	Less rutting effect	More rutting tendency
Water penetration	Resistant to effects of water penetration	Less resistance of effects of water penetration
Noise pollution	During laboratory compaction no any noise	During laboratory compaction noise pollution due to blows of Marshall hammer

4. Conclusions

The conclusions of the literature review is as follows:

- According to reviews that studied before, Superpave has lower asphalt content than that predicted by Marshall mix design procedure. This might explain the causes behind the bleeding asphalt concrete surfaces and some of the distresses common in the local asphalt structures.
- The percent air void for Superpave achieves lower than Marshall mixes; this prevents additional compaction under traffic, which could result in better performance for pavement distresses (rutting).
- Superpave mixes yield lower asphalt content than Marshall Mixes. As a result, Superpave mixes are better from the economical point of views than Marshall Mixes.
- The mixes prepared under the Superpave method passed the Marshall criteria.

5. Recommendations

1. It is strongly recommended that the Superpave methodologies be adopted and implemented immediately in the construction specifications in Kurdistan. The adoption and implementation of the recommendation would assist the highway agencies in Kurdistan to achieve significant life extension for both newly constructed and rehabilitated road infrastructure.
2. Since aggregate properties vary from source to source, the effect of aggregate properties and sources on the performance of Superpave mixes is recommended to be studied.
3. Similar studies should be conducted on a larger variety of aggregate gradation and binder types to establish more robust confidence in Superpave mix design criteria.

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