CHAPTER 5

DESIGN OF BITUMINOUS CONCRETE MIXES

5.1 Preamble

This chapter investigates the influence of different fillers and their quantities on the Marshall stability, flow, and volumetric properties (air voids, voids in mineral aggregates, and voids filled with bitumen) of the bituminous concrete mixes. Bituminous concrete mix primarily consists of three components: mineral aggregates (including filler), bitumen, and air. The primary objective of mix design is to estimate the optimum combination of aforesaid components to ensure the long-lasting performance of mix as part of a pavement structure (Asphalt Institute, 2014). This procedure includes the determination of an optimum blend of aggregates and the bitumen. The Marshall mix design procedure is prescribed in Indian specification for the design of bituminous concrete mixes and the same is used in the study (MoRTH, 2013). The bituminous concrete (grade II) mixes were prepared with stone dust, glass powder, Kota stone and glass – hydrated lime composite fillers at four different proportions (4.0, 5.5, 7.0 and 8.5%). This chapter explains the mix design procedure along with calculation of optimum bitumen content. It also compared the Marshall stability, flow and volumetric properties of different bituminous mixes prepared at OBC and discussed the effect of fillers on them.

5.2 Materials

Various physical and chemical properties of aggregates, bitumen and fillers have been already discussed in Section 4.3 and all materials fulfilled the requirements as per MoRTH (2013) and IS 73 (2013) specifications. In this study, bituminous concrete mixes were prepared with four different filler percentages (4.0, 5.5, 7.0 and 8.5% by weight of total aggregates in the mixes). In case of glass – hydrated lime composite mixes, 2% of glass powder was replaced with the hydrated lime at each filler proportion. The replacement proportion of 2% is fixed as per the guidelines prescribed in MoRTH (2013), which permitted the replacement of 2% hydrated lime with the filler in the dense-graded mixes in case of a possibility of the formation of moisture susceptible mixes. The relative proportion of glass powder and hydrated lime at different filler proportions is reported in Table 5.1.

Table 5.1 Proportion of glass powder & hydrated lime in glass - hydrated lime composite

Proportion of glass – hydrated lime composite filler in mix (%)	Proportion of type of material	
	Glass powder (%)	Hydrated lime (%)
4.0	2.0	2.0
5.5	3.5	2.0
7.0	5.0	2.0
8.5	6.5	2.0

5.3 Aggregate Gradation

Bituminous concrete (Grade II) gradation recommended by MoRTH (2013) specification was adopted in this study. It is amongst the most widely used dense-graded mixes in India which constitute of aggregates of nominal maximum aggregate size of 13.2 mm and used as the surface course on state highways, national highways, and expressways. The details of the specified limits and the chosen gradation are stated in Figure 5.1. This investigation was initially planned to cover the entire permissible range (4-10%) of filler content of bituminous concrete (Grade II) as specified in MoRTH (2013) guidelines. However, during the initial investigations, it was observed that mixes containing 10% of filler failed to fulfill the minimum volumetric requirements (especially optimum bitumen content and voids in mineral aggregates) stated in MoRTH (2013) guidelines. Hence the investigation was conducted for the four filler proportions (4, 5.5, 7, and 8.5%) and was limited up to 8.5%.

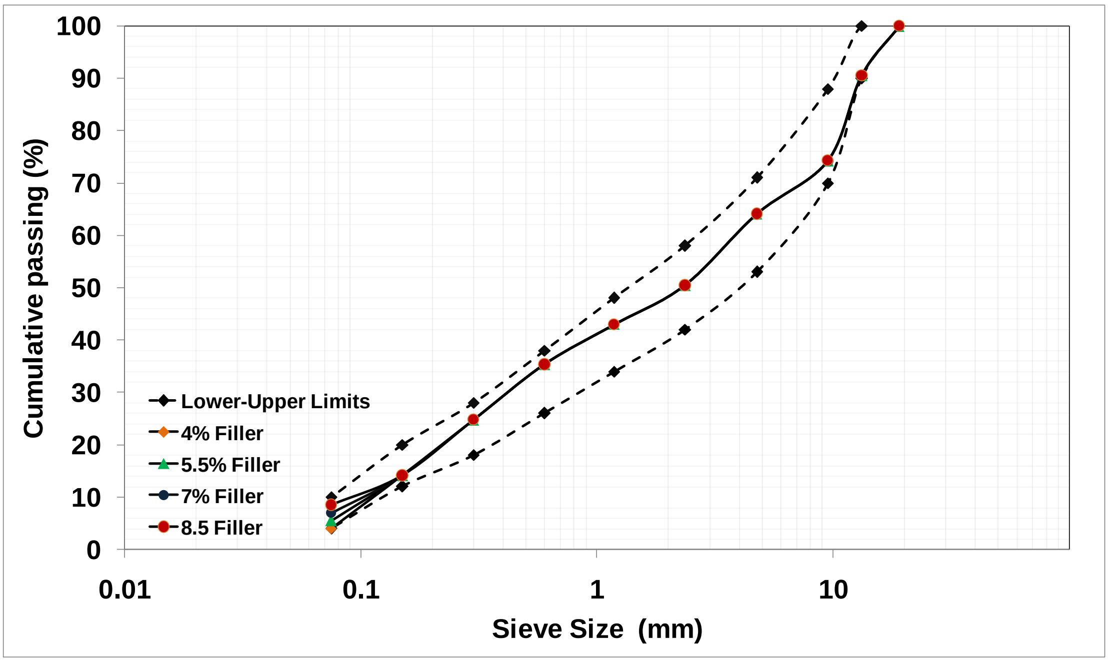
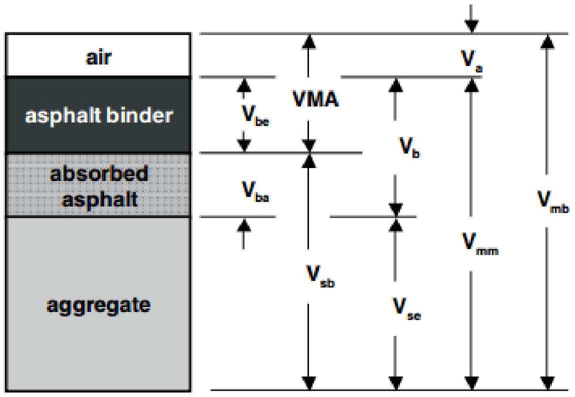


Figure 5.1 Adopted aggregate gradations for bituminous concrete mix

5.4 Volumetric Properties of Bituminous Mixes

The volumetric analysis of bituminous mixes plays a critical role in ensuring its satisfactory strength and durability at the field. It focuses on the accurate calculation of the characteristics including the bulk specific gravity (G_{mb}) of the bituminous mix, its theoretical maximum specific gravity (G_{mm}), percentage air void content in the mix (V_a), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). These components are shown in the phase diagram of the bituminous mix displayed in Figure 5.2 as well as briefly explained in the subsequent section. Any large variation of volumetric properties from its prescribed limit or their inaccurate calculation during the mix design may result in negative performance of mixes.



V_{be} = Volume of effective asphalt binder
VBE = Effective asphalt content, percent by volume
V_{ba} = Volume of absorbed asphalt binder
VBA = Absorbed asphalt binder, percent by total mix volume
V_{ma} = Volume of voids in mineral aggregate
VMA = Voids in mineral aggregate, percent by volume
V_{sb} = Volume of aggregate, bulk (including all permeable surface pores)
V_b = Volume of asphalt binder, total
VB = Total asphalt binder content, percent by volume
V_{se} = Volume of aggregate, effective (excluding surface pores filled with asphalt)
V_a = Volume of air voids
VA = Air void content, volume percent
V_{mm} = Volume of aggregate and asphalt
V_{mb} = Volume of specimen, total

Figure 5.2 Phase diagram displaying volumetric properties of a bituminous mix (NASEM, 2011)

5.4.1 Bulk Specific Gravity of Bituminous Mix (G_{mb})

Bulk specific gravity of the compacted bituminous mix corresponds to the mass of specimen (including the mass of aggregates and bitumen) divided by the volume of sample (including effective volumes of aggregates, bitumen, and air voids), multiplied by the unit mass of distilled water (Asphalt Institute, 2014). Since bituminous concrete specimen has water absorption value less than or equal to 2% of its volume, its G_{mb} can be calculated as per the saturated surface dry method specified in ASTM D2726. The formula for the calculation of G_{mb} is:

$$G_{mb} = \frac{W_{ma}}{W_{ms} - W_w} \qquad [5.1]$$

Where,

W_{ma} = dry mass of specimen in air

W_{ms} = saturated surface dry mass of specimen in air

W_w = mass of specimen in water at 25°C

5.4.2 Theoretical Maximum Specific Gravity of Bituminous Mix (G_{mm})

The theoretical maximum specific gravity of the loose bituminous mix corresponds to the mass of loose mix (including the mass of aggregates and bitumen) divided by the volume of mix (including sum of the effective volumes of aggregates and bitumen), multiplied by unit mass of distilled water. The G_{mm} of bituminous mix is determined according to the procedure specified in ASTM D2041 (2019) specification which involves following steps (Asphalt Institute, 2014). The warm loose bituminous mix is prepared and separated into individually coated aggregates. The loose mix is prepared by gently heating the sample in an oven, until it can be easily broken apart. After determining the weight in air of sample, it is placed in a calibrated vacuum container and immersed with water. The container is then connected to a vacuum pump, and vacuum pressure of about 27.5 mm Hg should be applied. The gentle agitation is given to the container at regular intervals to remove the air from sample. The vacuum is then carefully released, the container is filled with water to the calibration mark, and weight of the container, specimen, and water determined. The theoretical maximum specific gravity of the specimen is calculated using following formula:

$$G_{mm} = \frac{W_d}{W_d + W_{ww} + W_{dw}} \qquad [5.2]$$

Where,

W_d = mass of oven-dry specimen in air

W_{ww} = mass of container filled with water up to the calibration mark

W_{dw}= mass of container with specimen filled with water up to the calibration mark

5.4.3 Air Voids (VA)

The air voids in compacted bituminous mix specimen can be defined as the volume of air pockets within the coated aggregate particles in compacted mix specimen. Air voids are also expressed using the term void in total mix as the volume of VA is represented as percentage of the total volume of mix. Mathematically, VA can be calculated using the equation below:

$$VA = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \qquad [5.3]$$

Where,

G_{mm} = Theoretical maximum specific gravity of the bituminous mix

G_{mb} = Bulk specific gravity of the compacted bituminous mix

VA = Percentage air voids in the compacted mix

It is mandatory to ensure that air voids in the compacted bituminous mix fall within a recommended range. This check is applied due to the following reasons. At the field, apart from compaction given to the bituminous mixes during the time of their laying, they also undergo secondary compaction due to traffic load imposed during their service life. Due to this secondary compaction, the mixes having lower air voids may be susceptible to bleeding or flushing at their surface or rutting along their wheel paths. Hence an adequate volume of air voids is intentionally provided to accommodate the effects of secondary compaction as well as bitumen expansion in hotter regions. However, it is also necessary to ensure a surface which is impermeable to air and water to minimize the aging and moisture-related failures. Due to these aforesaid reasons, various agencies have prescribed the range of air void content in the dense-graded compacted bituminous mixes to be 3-5% (Asphalt Institute 2014; MoRTH, 2013). To ensure the air void content to fall within the prescribed range, optimum bitumen content of the bituminous mixes are determined to correspond to the targeted air voids content of 4% (mean value of 3-5% air void range) in the laboratory.

5.4.4 Bitumen Content in the Bituminous Mix

Bitumen content simply represents the amount of bitumen present in the compacted bituminous mix specimen. It can be divided into two parts, effective bitumen content and absorbed bitumen content. Effective bitumen content is the functional portion of bitumen that doesn’t get absorbed in the aggregates and effectively coats them. Absorbed bitumen content is the portion of bitumen that gets absorbed in the aggregates. Both effective and absorbed bitumen content can be expressed in terms of volume and weight. Hence bitumen content in bituminous mix can be calculated in four different ways: total bitumen content in the mix by weight (P_b), total bitumen content in the mix by volume (V_b), effective bitumen content in the mix by weight (P_{be}), and effective bitumen content in the mix by volume (V_{be}).

5.4.4.1 Total bitumen content in the bituminous mixes by volume (V_b)

The total volume of bitumen in bituminous mix represents the volume of bitumen in the compacted bituminous specimen. The V_b can be expressed as the percentage of total volume of the compacted mix and determined using equation below mentioned.

$$V_b = \frac{\frac{W_b}{G_b}}{\frac{W_{CA}+W_{FA}+W_F+W_b}{G_{mb}}} \quad [5.4]$$

Where,

W_b= Weight of bitumen in the mix

W_{CA}= Weight of coarse aggregates in the mix

W_{FA}= Weight of fine aggregates in the mix

W_F = Weight of filler in the mix

G_b = Bulk specific gravity of the bitumen

G_{mb} = Bulk specific gravity of the compacted bituminous mix

It can also be calculated using the equation below:

$$V_b = \frac{P_b G_{mb}}{G_b} \qquad [5.5]$$

5.4.4.2 Total bitumen content in the bituminous mixes by weight (P_b)

Total bitumen content by weight of the bituminous mix can be calculated as percentage of bitumen by total weight of mix as shown in the equation below:

$$P_b = \frac{W_b}{W_1+W_2+W_3+W_b}\times 100 \qquad [5.6]$$

Where,

W_b = Weight of bitumen in the mix

W_1 = Weight of coarse aggregates in the mix

W_2 = Weight of fine aggregates in the mix

W_3 = Weight of filler in the mix

W_b = Weight of the bitumen in the mix

5.4.4.3 Effective bitumen content in the bituminous mixes by volume (V_{be})

It is the functional portion of bitumen that doesn't get absorbed in the aggregates and effectively coats them. The V_{be} can be determined by subtracting absorbed bitumen from the total bitumen in the mix. This could be expressed as:

$$V_{be} = V_b - V_{ba} \qquad [5.7]$$

Where,

V_b = Volume of total bitumen in the mix

V_{ba}= Volume of bitumen absorbed by aggregates in the mix

V_{be} = Volume of effective bitumen in the mix

The volume of absorbed bitumen (V_{ba}) can be calculated using the expression given below:

$$V_{ba} = G_{mb} \times \left[\left(\frac{P_b}{G_b}\right) + \left(\frac{P_s}{G_{sb}}\right) - \left(\frac{100}{G_{mm}}\right)\right] \qquad [5.8]$$

Where,

P_b = Total bitumen content (% by weight of mix)

P_s = Total aggregate content (% by weight of mix) = 100- P_b

G_{mb} = Bulk specific gravity of the mix

G_{mm} = Theoretical maximum specific gravity of the mix

G_{sb} = Average bulk specific gravity of aggregate blend

G_b = Specific gravity of the bitumen

5.4.4.4 Effective bitumen content in the bituminous mixes by weight (P_{be})

Effective bitumen content by weight of bituminous mix can be calculated as the percentage of the bitumen by total weight of the mix as shown in equation below:

$$P_{be} = P_b\left(\frac{V_{be}}{V_b}\right) \qquad [5.9]$$

Where,

V_b= Volume of total bitumen in the mix

V_{be} = Volume of effective bitumen in the mix

P_b = Total bitumen content (% by weight of mix)

5.4.5 Voids in Mineral Aggregates (VMA)

Voids in mineral aggregates (VMA) can be defined as the inter-granular voids created within the aggregates of a compacted bituminous mixture. It includes the volume of air voids and the volume of effective bitumen. Mathematically it can be expressed as

$$VMA = VA + V_{be} \quad [5.10]$$

Since VMA accommodates the volume of effective bitumen in the mix, it significantly influences the performance of the mixes. The mixes having VMA values lower and higher than optimum values may suffer problems related to durability and low stability respectively. VMA of bituminous mixes is influenced by several parameters. VMA usually increases with decrease in the nominal maximum size of aggregates in the mix. The reason behind this might be the higher total void space between small particles than that of larger particles (Roberts et al., 1996). The VMA also gets significantly affected by type and amount of compacted effort provided in the laboratory. The gyratory compactors used in the Superpave method impart a higher amount of compaction energy than the impact hammer used in the Marshall method, which resulted in formation of mixes with lower VMA. Apart from these two parameters, VMA of the mix also gets influenced by the factors such as type and quantity of bitumen, temperature of the sample, shape, strength, and texture of the aggregates (Asphalt Institute, 2014). To ensure the durability of the mixes, their VMA should be high enough to accommodate sufficient bitumen that can form a protective layer around the aggregates of optimum thickness. Relatively higher VMA is also necessary to ensure the adequate volume of voids after compaction to facilitate the thermal expansion of bitumen during hot climates.

5.4.6 Voids Filled with Bitumen (VFB)

Voids filled with bitumen (VFB) can be expressed as the percentage volume of VMA that is occupied by the effective bitumen. Similar to VMA, VFB also increases with a decrease in the finer nature of the mix. Mathematically it can be expressed as:

$$VFB = \frac{V_{be}}{VMA} \times 100 \qquad [5.11]$$

Where,

V_{be}= Volume of effective bitumen

VMA = Voids in mineral aggregates

VFB = Voids filled with bitumen

5.5 Design of Bituminous Concrete Mixes

5.5.1 Marshall Mix Design

All bituminous mixes in the study were prepared using Marshall mix design procedure. The procedure as recommended by Asphalt Institute MS-2 was adopted for the evaluation of optimum bitumen content (OBC) (Asphalt Institute 2014). According to the method, bitumen content corresponding to 4% air void (by weight of the mix) is determined and Marshall stability, flow, voids in mineral aggregates (VMA), voids filled with bitumen (VFB), and percent voids filled with bitumen (VFB) are calculated. The values so obtained are compared with the specified value corresponding to that property.

For each filler type, samples of conventional bituminous concrete (1200 g) were prepared at specified gradation (Figure 5.1) and at 5 different variable bitumen contents (5.0%, 5.5%, 6%, 6.5%, and 7%). The aggregate and fillers were heated overnight at 105-110°C to remove any pre-existing moisture in them. The aggregate and bitumen are heated to the required temperature in such a manner that at no time the difference between their temperatures exceeds 14˚C. Mixing and compaction temperature of asphalt mixes were determined as per the guidelines specified in MS-2 (Asphalt Institute, 2014). As per the procedure, bitumen should be heated to produce kinematic viscosities of 170±20 and 280±30 centistokes to determine mixing and compaction temperature respectively. According to this mixing and compaction temperatures for VG 30 bitumen came out to be 159ºC and 150ºC respectively. Then, aggregates, fillers, and bitumen were thoroughly mixed at mixing temperature, and subsequently, transferred to a pre-heated cylindrical Marshall mould having a diameter 102 mm and height 64 mm. The compaction was carried with automatic compactor (75 blows on each side) at compaction temperature to produce Marshall specimen with a 101±0.6 mm diameter and 63.5 mm height. Three samples were prepared at each bitumen level, and a total of 240 specimens (5 bitumen contents × 4 types of fillers × 4 filler contents × 3 replicates) were prepared. The compacted samples were allowed to cool at room temperature overnight. The extracted samples were used for the determination of G_{mb}. The samples were then transferred to a pre-heated water bath having a temperature of 60°C for 30 to 40 minutes. Marshall stability is the value of maximum load at failure while flow value is the amount of deformation undergone by the sample as given by the reading of flow meter. Marshall stability and flow of prepared samples were determined as per ASTM D6927 specification. According to the test procedure, the Marshall sample is placed below the Marshall testing head. Compressive load is applied at a constant rate of 51 mm/minutes until the failure of specimen. It may also be noted that during lab compaction the height of compacted specimen might deviate from the standard height (63.5 mm). To take this variation in determination of the stability values, correction factors need to be multiplied with the obtain stabilities to determine corrected stabilities. These factors are stated in Table 5.2.

Table 5.2 Correction factors for the Marshall stability values

Volume of specimen (cm^3)	The thickness of the specimen (mm)	Correction factor
457-470	57.1	1.19
471-482	68.7	1.14
483-495	60.3	1.09
496-508	61.9	1.04
509-522	63.5	1.00
523-535	65.1	0.96
536-546	66.7	0.93
547-559	68.3	0.89
560-573	69.9	0.86

The tested specimen is then loosened by application of heat and is used for the determination of theoretical maximum specific gravity (G_{mm}) as per ASTM D2041. Volumetric properties namely percentage air voids (VA), voids in mineral aggregates (VMA) and voids filled with bitumen (VFB) were measured as per MS-2 specifications. Similarly, whole procedure is repeated at other bitumen contents and a series of Marshall and volumetric properties are determined. Separate graphical plots of each parameter were made against different bitumen contents (Figures 5.3-5.7). The major steps of the procedure are stated in Plates 5.1- 5.4.

The increment in filler proportion in the designed mix was adjusted by lowering the proportion of fine aggregates accordingly to satisfy the combined grading requirements. OBC is considered as the bitumen content corresponds to 4% VA of the compacted specimen (Asphalt Institute, 2014, MoRTH, 2013). After determination of OBC, 48 samples (4 types of fillers × 4 optimum bitumen contents × 3 replicates) were prepared at it, and average values of Marshall stability, flow, VA, VMA, and VFB were compared with their prescribed limits specified in Indian specification

(MoRTH, 2013). In this study, the bitumen content concerning 4% air void was considered as the optimum and other obtained parameters like stability, flow, VMA, and VFB values were checked to be under the specified limits as per MoRTH. The MoRTH requirements are stated in Table 5.3. The requirements of minimum bitumen content mentioned in MoRTH (2013) are specifically for aggregates having a specific gravity of 2.7. The lower bitumen contents are also permitted for the aggregates having a specific gravity greater than 2.7. Other than these requirements, MoRTH (2013) specification also prescribed additional checks for reliable mix design which include the parameters like Marshall quotient and tensile strength ratio. These parameters will be discussed in subsequent chapters.

Table 5.3 Requirements of Bituminous Concrete Mix (MoRTH, 2013)

Properties	Prescribed limits as per MoRTH (2013) specification
Minimum stability at 60ºC (kN)	9.0
Marshall flow at 60ºC (mm)	2-4
Percentage air voids (%)	3-5
Voids filled with bitumen (%)	65-75
Voids in mineral aggregates (%)	14 (minimum)
Percentage bitumen content	5.4

Plate 5.1 Conditioning of specimens in a water bath maintained at 60°C

Plate 5.2 Testing of Marshall stability and flow

Plate 5.3 Marshall specimens after testing

Plate 5.4 Determination of G_{mm} of mixes as per ASTM D2041 guidelines

5.5.2 Apparent Film Thickness (AFT)

Bitumen film thickness or film thickness is the average thickness of bitumen coating on aggregate particles in the bituminous mix. It is responsible for several performance characteristics such as durability, rutting, and shoving of the bituminous mixes. "Film thickness" is considered as a controversial concept amongst several engineers, since, bitumen in the bituminous mixes exist as a single homogenous phase binding different particles together, rather than in form of real film (NASEM, 2011). Hence, it has been prescribed to use the term “apparent film thickness (AFT)” in place of “film thickness”. Studies have observed an indirect relationship between AFT and rutting resistance of bituminous mixes. It was observed that the mixes having higher AFT may be susceptible to excessive rutting (Christensen and Bonaquist, 2006; NASEM, 2011). However, bitumen films also lubricate the aggregate particles and facilitate their placement and compaction. Hence adequate AFT is also necessary to avoid issues concerning the workability which might cause further negative issues like segregation, surface cracking, increased permeability, and ravelling. Studies have also suggested that bituminous mixes might undergo adhesive failure in case of low film thickness or cohesive failure in case of very thick film (Lytton 2008). A small number of studies on asphalt mixes have observed the average film thickness ranging from 6-8 µm to be most desirable (Campen et al., 1959; Kandhal and Chakraborty, 1996). However, it should also be known that there is no significant research behind it. Another study has found the film thickness of 9-10 µm to be appropriate to avoid excessive aging of bituminous mixes compacted at 8% air voids (Kandhal and Chakraborty, 1996). While another study suggested that aggregates in the bituminous mixes are covered with bituminous mastic film which is highly irregular in shape and has thickness vary in the range of 2-100 µm (Elseifi et al., 2008). Hence it can be said that although AFT is a potentially useful concept, the relationships between AFT and performance are not directly correlated (NASEM, 2011). Many agencies that specify AFT for bituminous concrete mixes ensure to avoid any unintended conflicts simultaneous requirements of primary properties such as aggregate gradation, VMA, VFB, and air void contents. AFT can be calculated using the formula:

$$AFT = \frac{1000V_{be}}{S_s P_s G_{mb}} \quad [5.12]$$

Where,

V_{be} = Volume of effective bitumen

P_s = Total aggregate content (% by weight of mix) = 100 - P_b

G_{mb} = Bulk specific gravity of the mix

S_s = Aggregate specific surface (m^2/kg)

5.5.2.1 Aggregate Specific Surface (S_s)

Aggregate specific surface is the surface area of total aggregates of the bituminous mix. Although the aggregate specific surface is needed to calculate the AFT of a bituminous mix, it cannot be precisely calculated using any well-defined methods. There are few highly empirical methods available to calculate specific surface, however, they are not well documented and are largely based on experience and engineering judgment (NASEM, 2011). This study utilized a simple and accurate relationship specified in NCHRP Report 567 and NCHRP Report 673 to calculate aggregate specific surface values consistent with traditional aggregate values (Christensen and Bonaquist, 2006; NASEM, 2011). This relationship is specified below:

$$S_s \cong \frac{P_{300} + P_{150} + P_{75}}{5} \quad [5.13]$$

Where,

P_{300}= Percentage of aggregate passing 300µm sieve

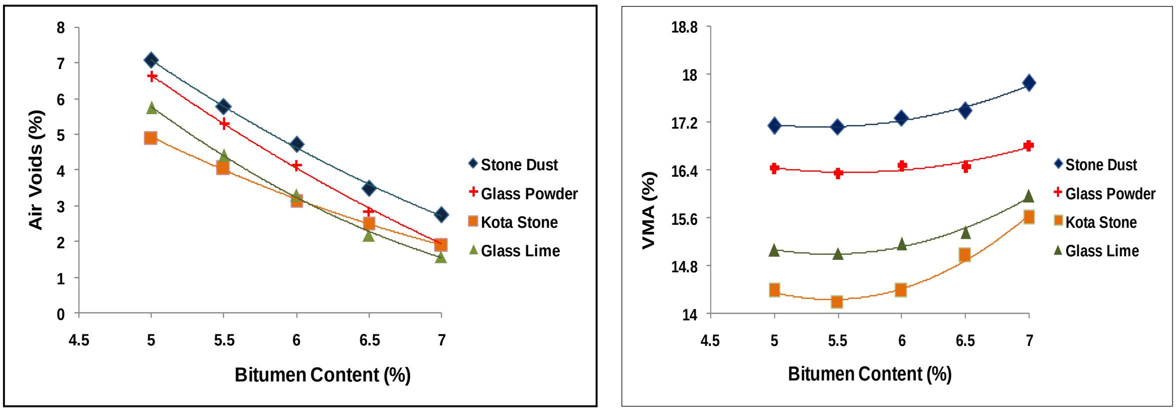
P_{150}= Percentage of aggregate passing 150µm sieve

P_{75}= Percentage of aggregate passing 75µm sieve

S_s= Aggregate specific surface (m^2/kg)

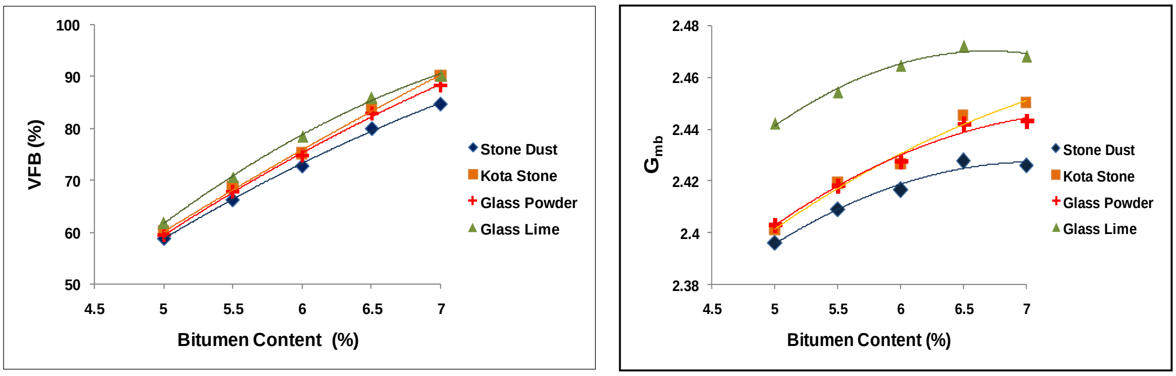
5.6 Analysis of Results

This section discussed the variation of various Marshall properties with the filler type and contents. The variation of various properties of bituminous mixes along with the bitumen contents is stated in Figures 5.3-5.7. As stated before, the optimum bitumen content (OBC) is determined as bitumen content corresponds to 4% air voids. After determination of OBC, a total of 48 specimens (3 for each mix) was casted and their average values are stated in Tables 5.4-5.7.



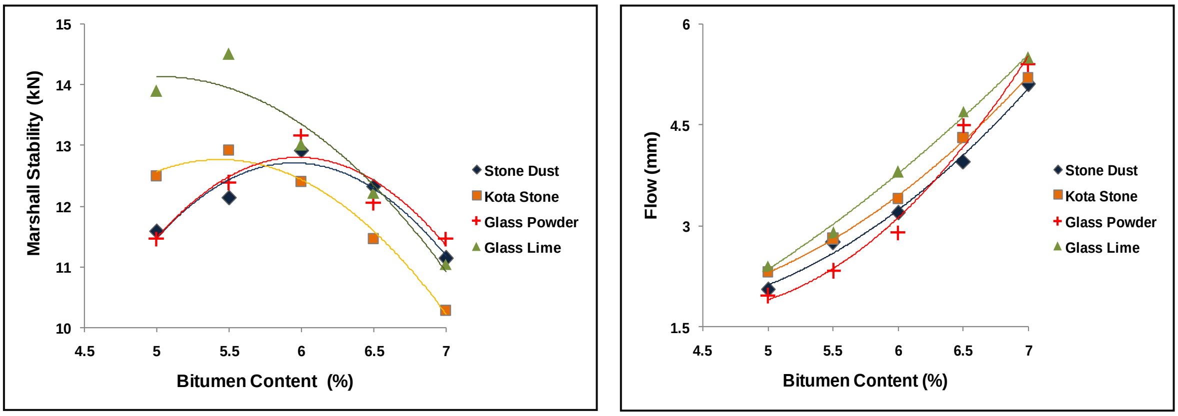
(a) Air voids versus bitumen content

(b) VMA versus bitumen content



(c) VFB versus bitumen content

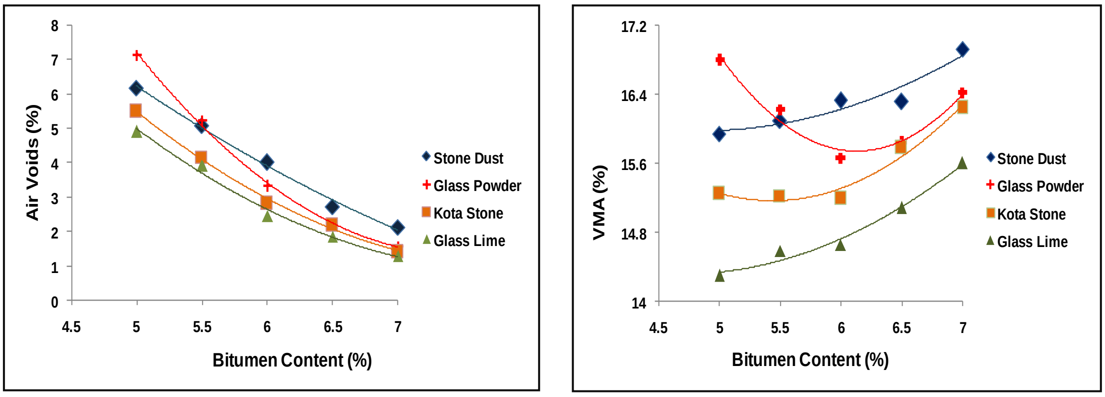
(d) G_{mb} versus bitumen content



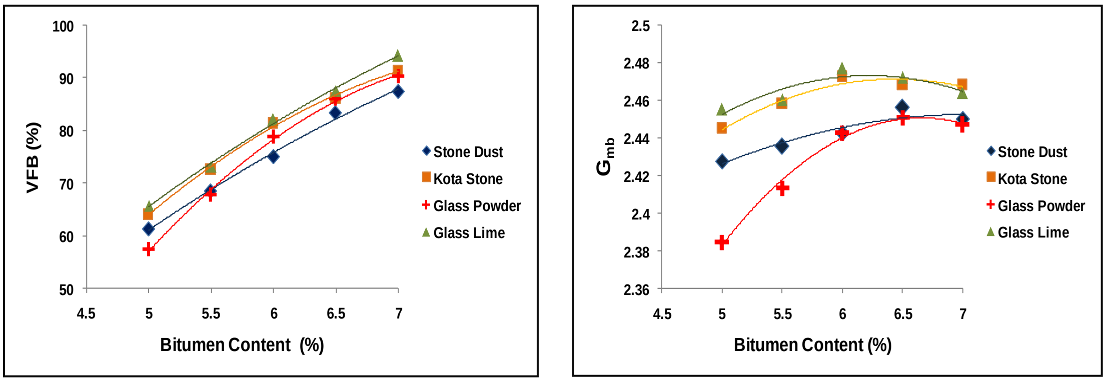
(e) Marshall stability versus bitumen content

(f) Flow versus bitumen content

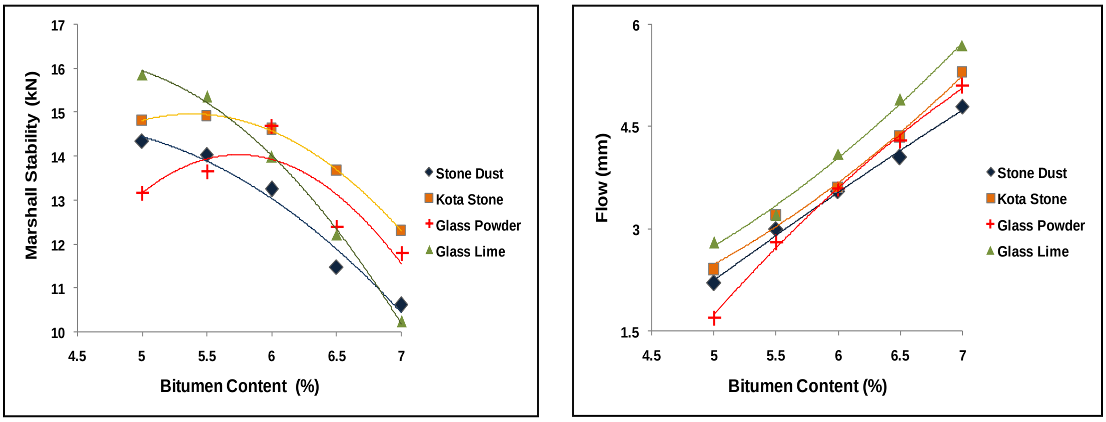
Figure 5.3 Marshall and volumetric properties of mixes with 4% filler



(a) Air voids versus bitumen content (b) VMA versus bitumen content

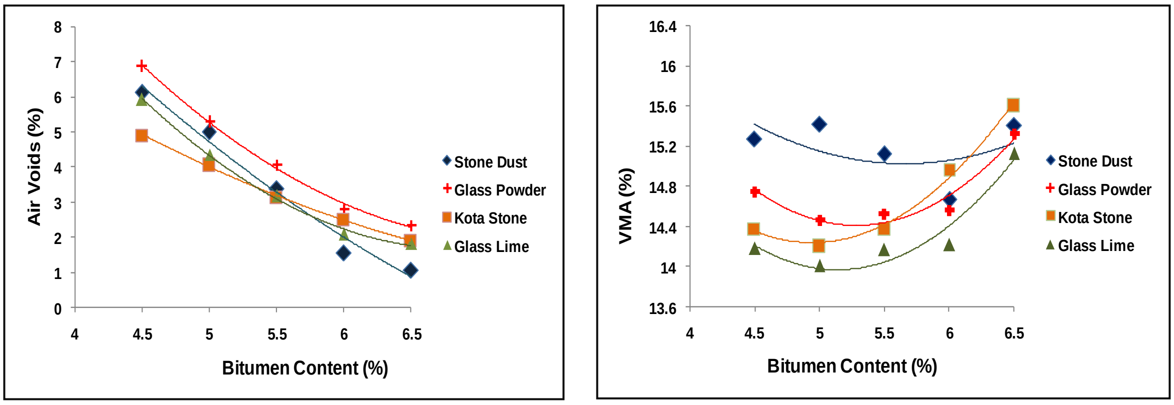


(c) VFB versus bitumen content (d) G_{mb} versus bitumen content

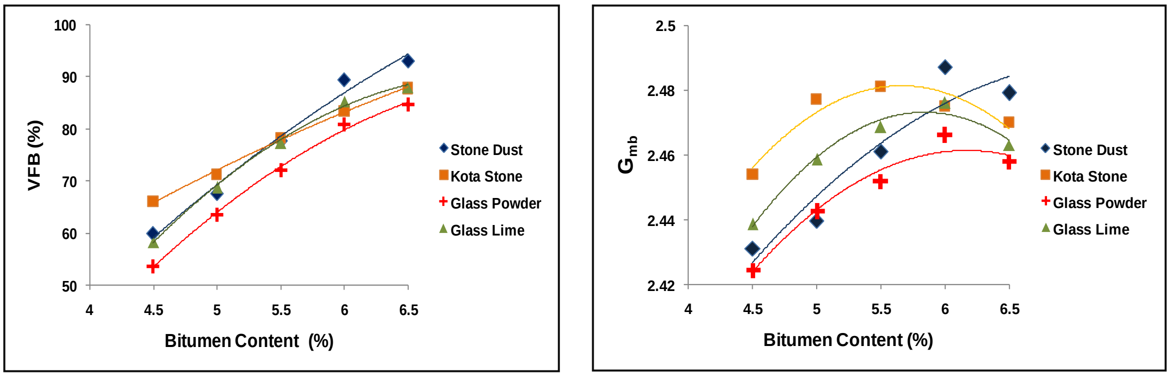


(e) Marshall stability versus bitumen content (f) Flow versus bitumen content

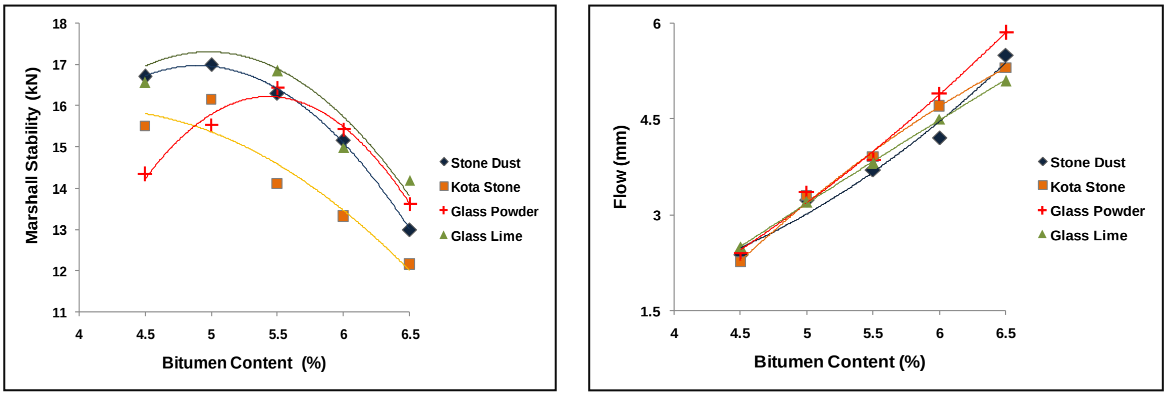
Figure 5.4 Marshall and volumetric properties of mixes with 5.5% filler



(a) Air voids versus bitumen content (b) VMA versus bitumen content

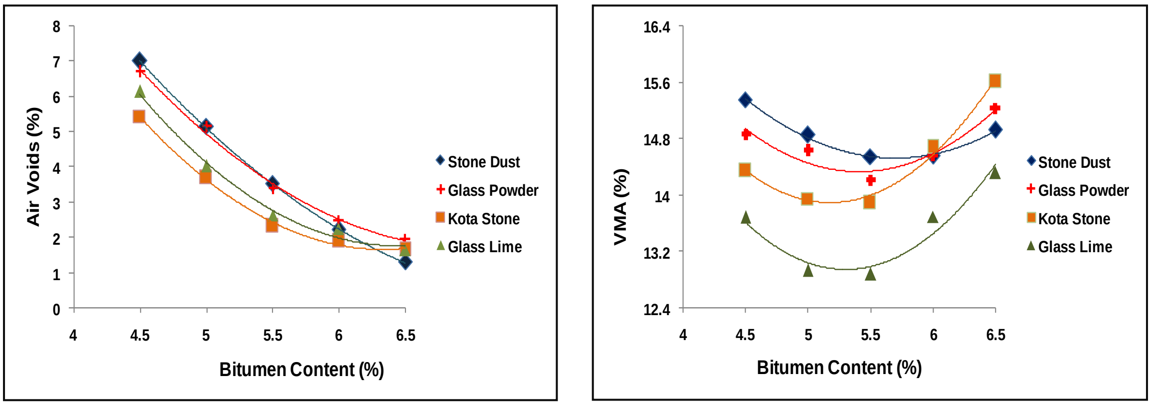


(c) VFB versus bitumen content (d) G_{mb} versus bitumen content

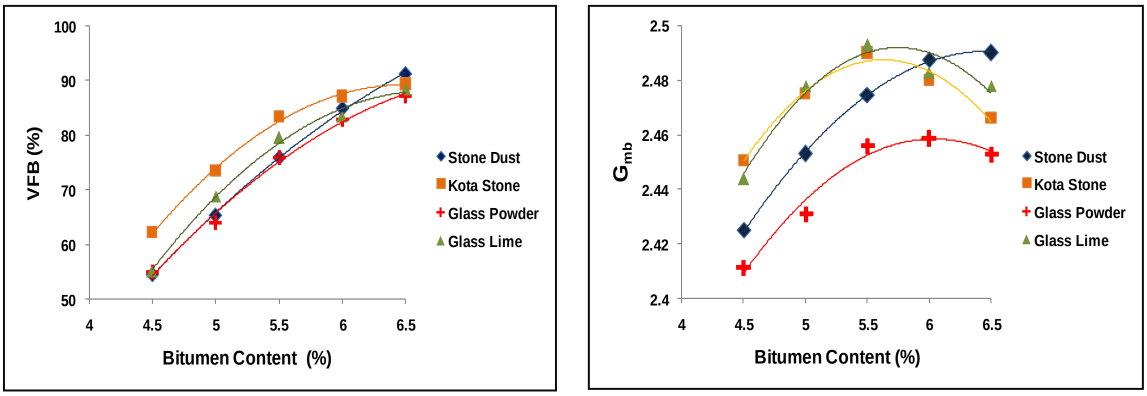


(e) Marshall stability versus bitumen content (f) Flow versus bitumen content

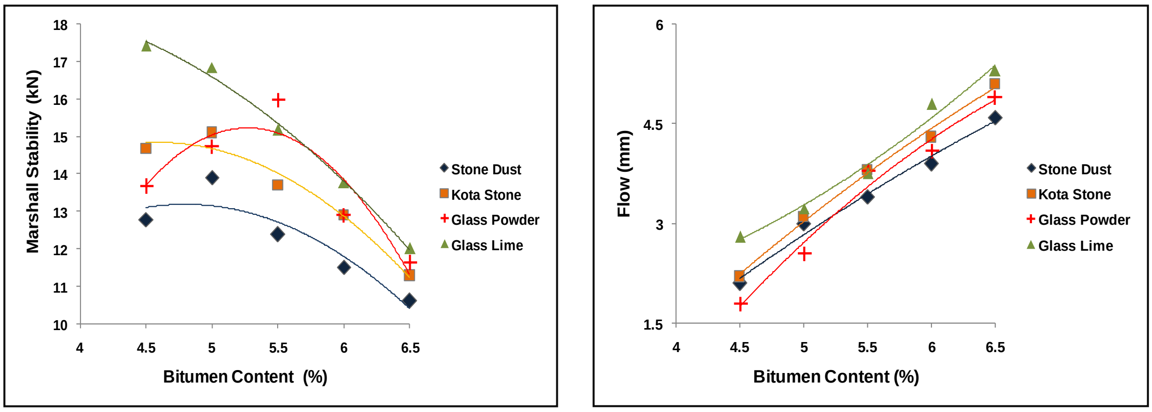
Figure 5.5 Marshall and volumetric properties of mixes with 7% filler



(a) Air Voids versus bitumen content (b) VMA versus bitumen content



(c) VFB versus bitumen content (d) G_{mb} versus bitumen content



(e) Marshall Stability versus Bitumen Content (f) Flow versus Bitumen Content

Figure 5.6 Marshall and volumetric properties of mixes with 8.5% filler

Table 5.4 Marshall properties of bituminous mixes with stone dust at OBC

Property	Filler content (%)			
	4.0	5.5	7.0	8.5
G_{mb}	2.430	2.444	2.453	2.466
VMA (%)	17.02	16.21	15.31	14.70
VFB (%)	74.22	74.43	74.79	72.01
OBC (%)	6.20	5.95	5.38	5.34
Marshall stability (kN)	12.22	13.99	15.96	16.58
Flow (mm)	3.43	3.62	3.50	3.22
Effective filler bitumen ratio	0.66	0.96	1.38	1.76
AFT (µm)	7.85	7.34	6.47	5.77

Table 5.5 Marshall properties of bituminous mixes with glass powder at OBC

Property	Filler content (%)			
	4.0	5.5	7.0	8.5
G_{mb}	2.427	2.431	2.441	2.448
VMA (%)	16.51	15.96	14.85	14.23
VFB (%)	74.85	73.92	72.97	72.27
OBC (%)	6.03	5.81	5.48	5.26
Marshall stability (kN)	12.98	13.46	14.93	14.52
Flow (mm)	3.38	3.18	3.37	2.95
Effective filler bitumen ratio	0.71	1.04	1.46	1.87
AFT (µm)	7.38	6.83	6.17	5.62

Table 5.6 Marshall properties of bituminous mixes with Kota stone at OBC

Property	Filler content (%)			
	4.0	5.5	7.0	8.5
G_{mb}	2.427	2.456	2.467	2.469
VMA (%)	16.83	15.33	14.27	14.07
VFB (%)	74.79	72.54	73.84	72.13
OBC (%)	5.96	5.53	4.98	4.89
Marshall stability (kN)	12.65	14.42	15.60	16.34
Flow (mm)	3.37	3.15	2.95	2.90
Effective filler bitumen ratio	0.70	1.06	1.45	1.82
AFT (µm)	7.78	6.55	5.92	5.49

Table 5.7 Marshall properties of bituminous mixes with glass-lime composite at OBC

Property	Filler content (%)			
	4.0	5.5	7.0	8.5
G_{mb}	2.448	2.457	2.455	2.452
VMA (%)	15.43	14.62	14.22	13.91
VFB (%)	74.18	70.79	69.15	69.33
OBC (%)	5.65	5.38	5.12	5.05
Marshall stability (kN)	14.32	15.04	16.78	16.10
Flow (mm)	3.21	3.06	3.30	2.88
Effective filler bitumen ratio	0.77	1.15	1.60	2.00
AFT (µm)	6.99	6.07	5.50	5.25

Filler type and its content significantly affected the properties of bituminous mixes at OBC. Marshall stability (MS) of the bituminous mixes indicated their ability to resist pressure along with horizontal and shear stresses caused by the imposed static and dynamic loads (Akbulut et al., 2012).

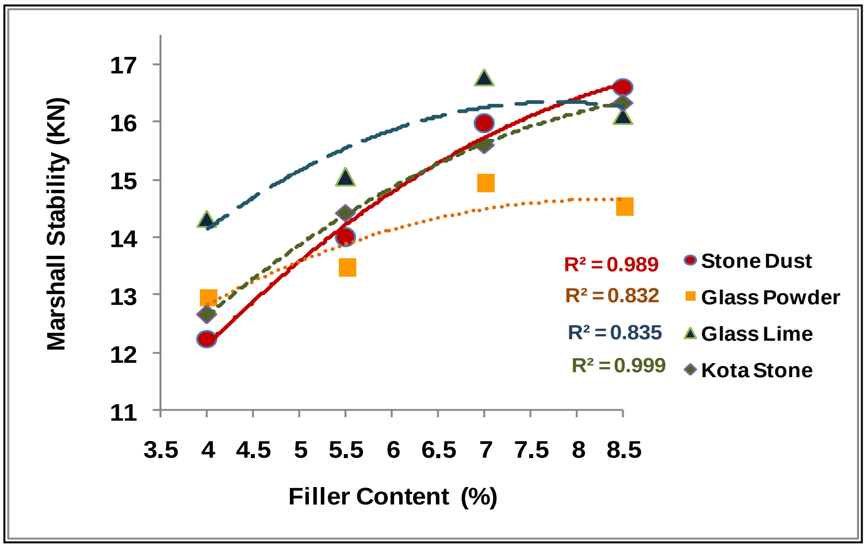


Figure 5.7 Variation of Marshall stability of bituminous mixes with filler contents

In this study, all mixes comfortably satisfied the minimum requirement of stability (9 kN) as specified in MoRTH (2013) specification. From Figure 5.7, it is observed that for all types of fillers, stability increased with the increase in filler content at lower percentages (4 and 5.5%). Improvement in the stability of bituminous mixes with filler content might be attributed to improvement in the strength of bitumen filler mastic due to the presence of higher filler content in the mix. Some previous studies (Akbulut et al., 2012; Anderson 1987; Brown et al. 1983; Tayebali et al., 1998) have also observed a similar trend. In the case of glass and glass - hydrated lime composite mixes, stability values increased up to 7% filler content and then marginal decline is observed at 8.5%. The marginal decrease in stability might be attributed to the loss of adhesion in the mixes due to high silica content in glass powder as well as due to their lower bitumen content. On the other hand, the stability values of Stone dust and Kota stone mixes increased up to 8.5% filler content. Both stone dust and Kota stone are calcium-based materials which have a predominance of dolomite and calcite in their composition and form a strong bond with bitumen. Hence their mixes managed to maintain their higher stabilities at higher filler contents too. In most of the cases, glass - hydrated lime mixes displayed maximum stabilities amongst all mixes. This might be due to the higher stiffening in glass - hydrated lime mastic due to the fineness (lower fineness modulus and D_{50} values) and higher porosity (lowest German filler value and higher Rigden voids) of hydrated lime. Interestingly, mineralogy of filler seemed to influence the stability of the mixes, as glass powder has the lowest stability in most of the cases. While conventional stone dust mixes are showing the highest stability values especially at higher filler contents. This aspect could be explored in detail in further studies.

Flow value of bituminous mix indicates the total deformation or strains in the Marshall specimen occurring during the application of load from zero to maximum value. It represents the plasticity and flow behavior of bituminous mixes which has a relationship with its internal friction (Arabani et al., 2017; Uzun and Terzi, 2012). As per MS-2 specifications, the flow values of bituminous mixes at OBC should lie in between 2-4 mm. The high flow value of mix displayed its plastic behavior while lower flow value signified its brittle behavior (Asphalt Institute 1997). The flow values of all mixes lied within this prescribed range (Tables 5.4-5.7). Although there is no well-defined trend observed between filler content and flow values of the mixes, some discernable observations can be made for flow values of different mixes. Clearly, in most cases, glass - hydrated lime mixes have the lowest flow values while stone dust has the highest flow values. Hence glass - hydrated lime composite seemed to increase the stiffness of bituminous mixes.

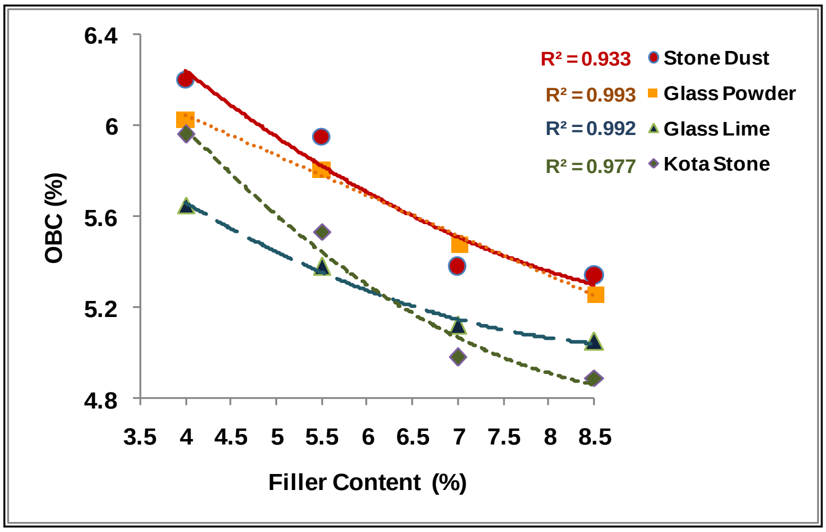


Figure 5.8 Variation of OBC of bituminous mixes with filler contents

OBC of bituminous mixes influences their durability against moisture and aging. Several studies discussed that the OBC of bituminous mixes are influenced by several parameters of fillers such as particle size, gradation (Chen et al., 2011a), surface texture (Bocci, 2018; Chen et al., 2011a; Chen et al., 2011b), surface area (Zulkati et al., 2012), shape (Chen et al., 2011a; Sharma et al., 2010), porosity (Arabani et al., 2017; Chandra and Choudhary, 2013), and specific gravity (West and James, 2005; Korayem et al., 2018) etc. In most of the cases, a specific factor has a higher dominance over other factors to influence OBC of the mix. Similar results have also been reported in this study. The variation of OBC for different mixes with filler content is shown in Figure 5.8. In all cases, OBC decreases with the increase in filler content. In bituminous mixes, aggregates are coated with bituminous mastic rather than with bitumen alone. Hence, mastics with higher filler content require lesser amount of bitumen to make the same amount of mastic for lubrication of aggregates in the mix (Huang et al., 2007). This is known as bitumen “extender” function of filler in the mixes. This trend is in agreement with that observed in the previous studies (Akbulut et al., 2012; Chandra and Choudhary 2013; Huang et al., 2007; Sharma et al., 2010). The filler particles have particle size finer than AFT, display a greater tendency to show bitumen extender behaviour. The AFT of all mixes at OBC is stated in Tables 5.4-5.7. AFT also followed the trend similar to OBC and decreased with the increase in filler contents for all mixes. If a uniform AFT of 6μm is considered in all mixes, then hydrated lime and Kota stone have highest percentages of materials finer than 6μm (as determined from their particle size distribution curves), thus they display higher tendency to act as bitumen extender. Mixes containing Kota stone and glass - hydrated lime fillers have followed this trend and thus exhibited the lowest OBC amongst all mixes. Kota stone is the second finest filler after hydrated lime and it also has the least porosity amongst all fillers. Due to these two parameters, it displayed bitumen extender action which might result in the formation of mixes with lowest OBC at higher filler contents (7 and 8.5%). It is interesting to see that despite hydrated lime having high porosity, glass - hydrated lime composite filler mixes displayed the lowest OBC at lower filler contents (4 and 5.5%). Since hydrated lime is the finest filler amongst all mixes, it displays the highest tendency amongst all fillers to act as bitumen extender and thus reducing their OBC. Hydrated lime and glass powder also have lower specific gravities than stone dust and Kota stone and thus occupied larger volume in the mix at same weight proportion. This leaves lower volume for bitumen accumulation in the mixes which reduces their OBC (Korayem et al., 2018; West and James, 2006). It is also interesting to see that despite having lower individual specific gravities, a combination of glass powder and hydrated lime form mixes with higher bulk specific gravities at lower filler contents (4 and 5.5%). Hence it can be assumed that higher Rigden voids in hydrated lime don't negatively affect the workability or densification of the mixes. Glass powder mixes also have lower OBC than conventional stone dust mixes, which also might be due to the lower specific gravity of glass powder. Hence it can be said that mixes containing waste materials as fillers can be considered economical due to their lower bitumen consumption.

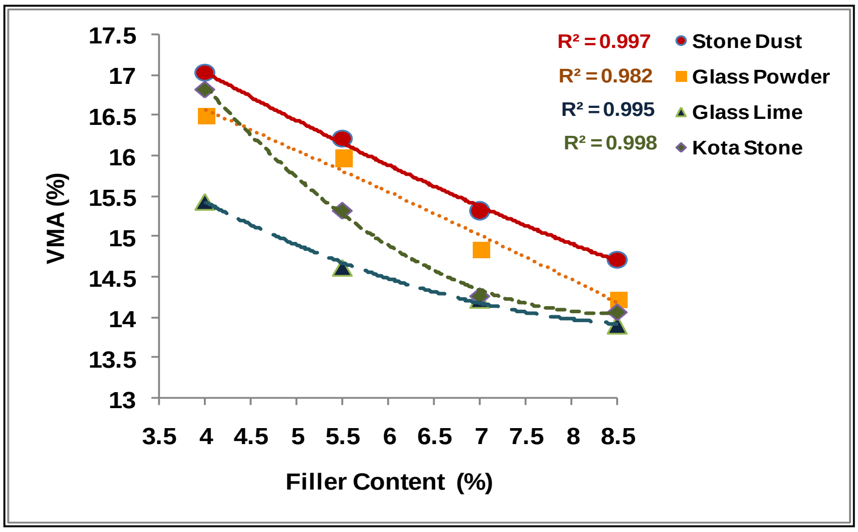


Figure 5.9 Variation of VMA of bituminous mixes with filler contents

VMA is the volume of inter-granular void space in between aggregates of the compacted mix. It occupies air voids and the bitumen that is not absorbed by the aggregates (Akbulut et al., 2012; Arabani et al., 2017). Similar to the OBC, VMA of all mixes were also decreased with the increase in filler content (Figure 5.9). Apart from the glass - hydrated lime mix prepared with 8.5% filler, all mixes fulfilled the minimum requirement of VMA specified in Indian specification. So for utilization of glass lime filler at higher concentration, the altering of aggregate gradation can be done to increase the VMA in the mix. However, since it was not in the scope of the study, it was avoided here and could be considered as future scope of the study. In general, stone dust mixes were found to have highest VMA followed by glass powder, Kota stone, and glass - hydrated lime mixes. The void filled with bitumen (VFB) is termed as the percentage of VMAs that is occupied by bitumen. VFB values of all mixes were found to be within the prescribed limits (65-75%). In most of the cases, the VFB values of mixes containing waste fillers were found to be lower than the conventional stone dust filler mixes. A previous study (Kutuk-Sert and Kutuk, 2013) has inferred that the mixes having lower VFB values may perform better in regions having hot climates due to lower bleeding possibilities in them. Hence incorporation of waste filler might be beneficial for the mixes having hotter climates. The effective filler-bitumen ratio of all mixes is stated in Table 5.4-5.7. It is the ratio of the effective bitumen (P_{be}) and filler contents in the mixes by weight. Several design specifications prescribed effective filler bitumen ratio should be in the range of 0.6-1.2 to ensure adequate stiffness and avoid excessive brittleness of the bituminous mixes (Asphalt Institute 2014; MoRTH, 2013). However, German mix design specification (Asphalt-StB 07, 2007) have allowed filler bitumen ratio to be as high as 1.8. In this study, for the selected gradation, all mixes have fulfilled the requirements of filler-bitumen ratios specified by MoRTH (2013) at lower filler contents (4 and 5.5%). The effective filler bitumen ratios determined at OBC for all mixes were taken into consideration to further preparation and analysis of bituminous mastic in the subsequent chapters.

5.7 Summary

The chapter presented the investigation on the designing of bituminous concrete mixes containing four types of fillers (stone dust, glass powder, Kota stone, and glass - hydrated lime composite) added at four different filler contents (4.0, 5.5, 7.0 and 8.5%) using Marshall mix design method. In general, mixes containing waste fillers displayed satisfactory Marshall properties prescribed by MoRTH (2013) specifications. However, glass - hydrated lime mixes prepared at 8.5% filler displayed marginally lower VMA value than the suggested limits. The Marshall stability of bituminous mixes was found to increase with the filler content up to 7% (glass and glass - hydrated lime mixes) and 8.5% (stone dust and Kota stone mixes). The fineness and calcium mineral content of filler seemed to influence the stiffness and adhesion of mastics which subsequently affect the Marshall stability of the bituminous mixes. The OBC and VMA of bituminous mixes decreased with the increase in the filler content which was attributed to bitumen extender behaviour shown by fillers in the mixes. The glass - hydrated lime and Kota stone filler formed the mixes with lowest OBC at lower (4 and 5.5%) and higher (7 and 8.5%) filler contents respectively. The fineness, specific gravities and porosity of the fillers are three major parameters affecting the OBC of mixes. The conventional stone dust filler mixes have higher OBC than waste filler mixes and it can be considered uneconomical in this aspect. The VFB and flow values of all mixes were also found to be well within the prescribed limits.