Influence of Aggregate Gradation and Degree of Compaction on Air Voids in Bituminous Concrete Mixes

Anand Kumar[1*], Ankita kumari[2], Chandra Shekhar Verma[3], Amit Kumar[4], Dhananjay Kumar[5], Sushant Kumar[6]

[1*]Assistant Professor, Government Engineering College Sheikhpura, City-Sheikhpura, Bihar-811105,
Email id- kranand228@gmail.com Department of Science Technology and Technical Education, Government of Bihar, India
[2]Assistant Professor, Government Engineering College Sheikhpura, City-Sheikhpura, Bihar-811105,
Email id- ankita.dstte@bihar.gov.in, Department of Science Technology and Technical Education, Government of Bihar, India
[3]Assistant Professor, Government Engineering College Sheikhpura, City-Sheikhpura, Bihar-811105,
Email id- csverma.dstte@bihar.gov.in, Department of Science Technology and Technical Education, Government of Bihar, India
[4]Assistant Professor, Government Engineering College Nawada, City-Nawada, Bihar-805111,
Email id -amit357.dstte@bihar.gov.in, Department of Science Technology and Technical Education, Government of Bihar, India
[5]Assistant Professor, Sitamarhi Institute of Technology Sitamarhi, City-Sitamarhi, Bihar-843302,
Email: dhananjay.ce@sitsitamarhi.ac.in, Department of Science Technology and Technical Education, Government of Bihar, India
[6]Assistant Professor, Sitamarhi Institute of Technology Sitamarhi, City-Sitamarhi, Bihar-843302,
Email: sknilesh1996@gmail.com, Department of Science Technology and Technical Education, Government of Bihar, India

Abstract
The amount of air void influences the performance of bituminous mixes. The arrangement of aggregates is instrumental in understanding the framework of air voids. So, it becomes essential to study the particle size distribution of aggregates and compaction effort given in the preparation of the mix. Literature suggests that the aggregate properties, such as size, shape, and strength, have been studied to enhance the amount and distribution of air voids. The aim is to focus on the combined effect of aggregate gradation and compaction effort on the variation of air voids in bituminous concrete mixes. In this study, aggregates from two different sources namely Sheikhpura (Sh) and Mirza Chowki (Mc) is taken into consideration. Samples with varying gradation types were prepared under the same compaction effort and air voids corresponding to the mix of each gradation type were calculated. Now, samples are prepared by varying the compaction effort to each gradation type and air void is calculated. The observation suggests a significant reduction in air voids due to the initial increase in number of blows and this reduction in air void saturates at higher no. of blows and a comparatively lesser amount of air voids is found in denser gradation of aggregates. Mixes prepared with aggregates from Mc had comparatively lesser air voids for similar compaction efforts. The results are attributed to shape of Mc aggregates, due to which it breaks down upon compaction, resulting in a higher proportion of fine particles and reduced air voids for similar compaction efforts.

Keywords: Aggregate Gradation, Air voids, Bituminous mixes, Compaction effort

1. Introduction

Hot Mix Asphalt (HMA) pavement, in which aggregate is a major component, is globally used for flexible pavement construction. Significant presence of air voids influences the properties of bituminous mixes substantially. Air spaces between the compacted bitumen-coated aggregate particles were found in the air voids of bituminous mixes [1]. Air voids are the major controlling parameter to the durability like moisture-induced damage, aging, fatigue cracking, low temperature thermal cracking etc., of the mix [8,14-15]. Apart from the air voids, various other factors such as aggregate gradation, degree of compaction, method of compaction, aggregate shape characteristics, mixing temperature, and compaction temperature influence the durability in terms of moisture sensitivity to the bituminous mix [14,22].

The primary properties of aggregates that influence the bituminous mixes are aggregate gradation, aggregate strength, and aggregate shape [12-13]. The aggregate skeleton structure provides strength to bituminous mixes against externally applied loads. This is due to the connectivity of contact points, which primarily influences the bituminous mix. The internal skeleton structure of aggregate is influenced by aggregate gradation, morphological properties, and compaction effort [8-9,17,21]. The tensile strength and stiffness of bituminous mixes are significantly influenced by the strength and shape of aggregates, which in turn influence the performance of the mixes [1-2]. Particle shape as well as texture influences the performance of the mix [12,18]. When the aggregates are angular and rough rather than smooth and rounded, the performance of the mix improves because of improved packing, leading to better grain-to-grain transfer [3-4]. It is assumed that flat and elongated particles are fragmented during mixing and compaction, leading to reduced performance of the mix [7].

For the formation of a mix like bituminous concrete, aggregate must be adequately distributed in terms of particle size. According to previous studies aggregate structure in asphalt mixes are greatly influenced by aggregate gradation (well-graded, gap-graded, uniformly-graded), Physical & Chemical properties, Shape (flat & elongated, angular, cubical & rounded), texture (smooth & rough) and type of method & effort of compaction [14-15,24]. Many researchers have found the leading role of aggregate gradation on volumetric properties of bituminous mixes [11,16,20] and pavement performances [5,19,21]. Aggregate gradation dominantly affects the durability, rutting & cracking resistance and volumetric properties of the bituminous mix. Hence, it is essential to pay careful attention on the gradation of aggregates, which also ensures the successful performance of the mix during the entire service life [10]. The internal structure of aggregates controls the air void present and, in turn, the performance of bituminous mixes.

The novelty of this paper lies in its detailed investigation of the relationship between aggregate gradation and air voids in bituminous concrete mixes, emphasizing the influence of compaction effort. By utilizing aggregates from two different sources, the study offers unique empirical insights into how gradation affects air void distribution under varying compaction conditions. The application of polynomial modelling to represent these relationships enhances our understanding of saturation trends at higher compaction levels. This research fills a critical gap in the literature, providing significant implications for the design and optimization of asphalt pavement materials by paying attention on the air voids. Air void has significant effect on performance of the mix such as ageing, fatigue cracking etc.

Literature suggests that the correlation between aggregate properties and air void structure was limited. This study, therefore, is conducted to understand this correlation.

As the study suggests that air voids are influenced by several parameters like Aggregate gradation, compaction effort, shape, mineralogy etc and out of them aggregate gradation is important. Therefore, it would be meaningful to determine the effect of aggregate gradation on air voids under same compaction effort. The study is conducted by considering aggregates from two different sources namely Sheikhpura (Sh) district in Bihar, India and Mirza Chowki (Mc) in Sahib Ganj district, Bihar, India respectively. Aggregate impact value (AIV), crushing strength, Los Angeles Abrasion (LAA), Specific gravity, and Flakiness & Elongation index value (FI and EI) are determined to evaluate the quality of aggregates for both the sources. Bitumen was obtained from Barauni refinery and is tested for consideration of mix design. Marshall mix design was performed for identifying the optimum bitumen content for bituminous concrete of grade 2 (BC-II) as it is widely used in India for the preparation of surface coarse. It is a dense-graded mix which is designed for high volume of roads and it is recognized for its durability, performance and longevity under real-world conditions. For further testing four different aggregate gradations were designed like for Sheikhpura source of aggregate it is named as ShH1, ShH2, ShL1, ShL2 and for Mirza Chowki source of aggregate it is named as McH1, McH2, McL1, McL2. Further samples are prepared and tested by following the Marshall Mix Design Method. Further air voids are calculated for finding out the correlation with the particle size distribution of aggregates. Keeping in mind that compaction effort plays a major role to study the nature of variations of air voids. Therefore, some specified variations in compaction effort are subjected on all samples to quantify the amount of air voids. Hence, Samples of each gradation were prepared by providing the 20, 30, 40, 50, 60 and 75 number of blows subsequently and their respective air voids are calculated. Thereafter, evaluation was done to determine the correlation of aggregate gradation and compaction effort with air voids.

2. Materials and Methods

2.1 Aggregates

Aggregates were obtained from two sources: Sheikhpura district, in Bihar, and Mirza Chowki in Sahib Ganj district, Jharkhand, India. The nominal maximum aggregate of size 13.2 mm, 4.75 mm, and stone dust is used. Physical properties of aggregates such as aggregate crushing value (ACS), aggregate impact value (AIV), Combined Flakiness and Elongation Index (F&EI), Los Angeles Abrasion (LAA) Test, Specific Gravity (SG) test were determined by various testing methodologies as given in Indian standard code (i.e. IS code) as and corresponding test results findings are reported in table 1, and their comparison chart in figure 1. The aggregate obtained from Sheikhpura was observed to be siliceous sandstone in nature, whereas the aggregate from Mirza Chowki was basaltic in nature.

Table 1: Aggregates from Sh and Mc and their Physical Properties

Tests	Codal Provision	Sheikhpura (Sh)	Mirza Chowki (Mc)	Limits
Aggregate Crushing Strength (ACS) Test	IS: 2386 (Part IV) – 1963.	14.84%	12.34%	Max. 30%
Aggregate Impact Value (AIV) Test	IS: 2386 (Part IV) – 1963.	11.38%	9.74%	Max. 24%
Combined Flakiness and Elongation Index (F&EI)	IS: 2386 (Part I) – 1963	28.26%	31.12%	Max. 35%
Los Angeles Abrasion (LAA) Test	IS: 2386 (Part IV) – 1963	16.54%	13.64%	Max. 30%

Specific Gravity (SG)Test	IS: 2386 (Part III) – 1963.	2.74	2.71	2.4 to 2.9
Soundness test (Sodium Sulphate Test)	IS 2386 (Part V)	10%	8%	Max.12%

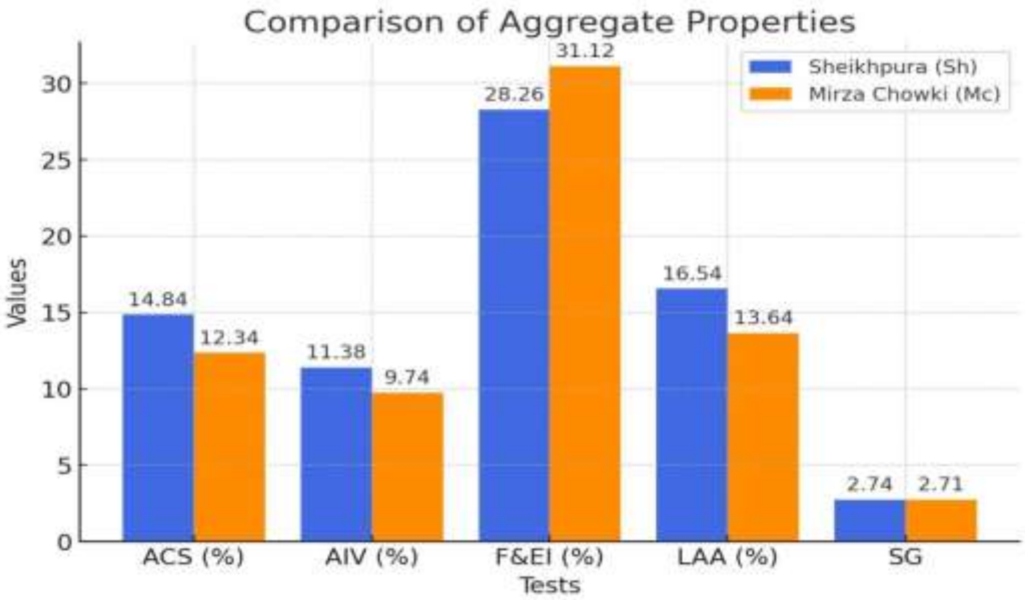


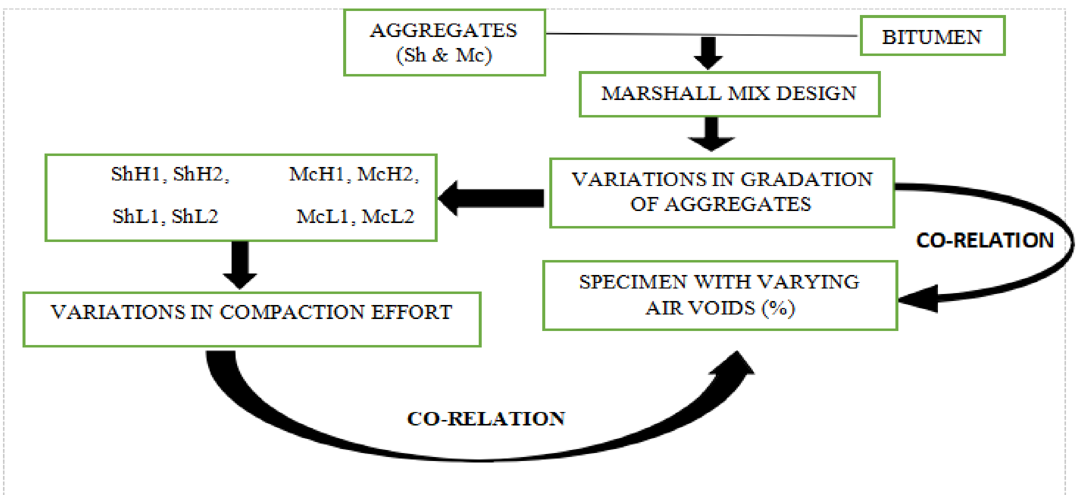
Fig. 1: Comparison chart of aggregate test results for Sheikhpura (Sh) and Mirza Chowki (Mc).

2.2 Bitumen

VG-30 grade of bitumen was used as the binder for the preparation of the mix. The bitumen was taken from the Barauni refinery in Begusarai district of Bihar, India. Tests were performed to find out the physical properties to assess the quality and the results are furnished in Table 2

Table 2: Physical properties of Bitumen

Physical Properties	Test Method	Observed Value	Acceptable Limits
Penetration value	IS: 1203	60 mm	Min 45 mm
Softening point value	IS: 1205	48.5°C	Min 47°C
Specific gravity value	IS: 1202	1.02	0.97-1.02
Viscosity at 60°C in poise	IS: 1205	2972	2400-3600
Viscosity at 135°C in cst (min)	IS: 1205	368	Min 350
Solubility	IS: 1216	99.6%	Min 99%
Ductility at 25°C	IS: 1208	73	Min 50



Experimental Setup

3. Results and Discussions

3.1 Determination of Optimum Bitumen Content (OBC)

Marshall method of mix design was adopted and tested in accordance to MoRTH guidelines. Combined gradation is done to achieve desired value. The nominal maximum aggregate of size 13.2 mm, 4.75 mm and stone dust is used for blending. The aggregate gradation which was achieved after blending is given in Fig. 2

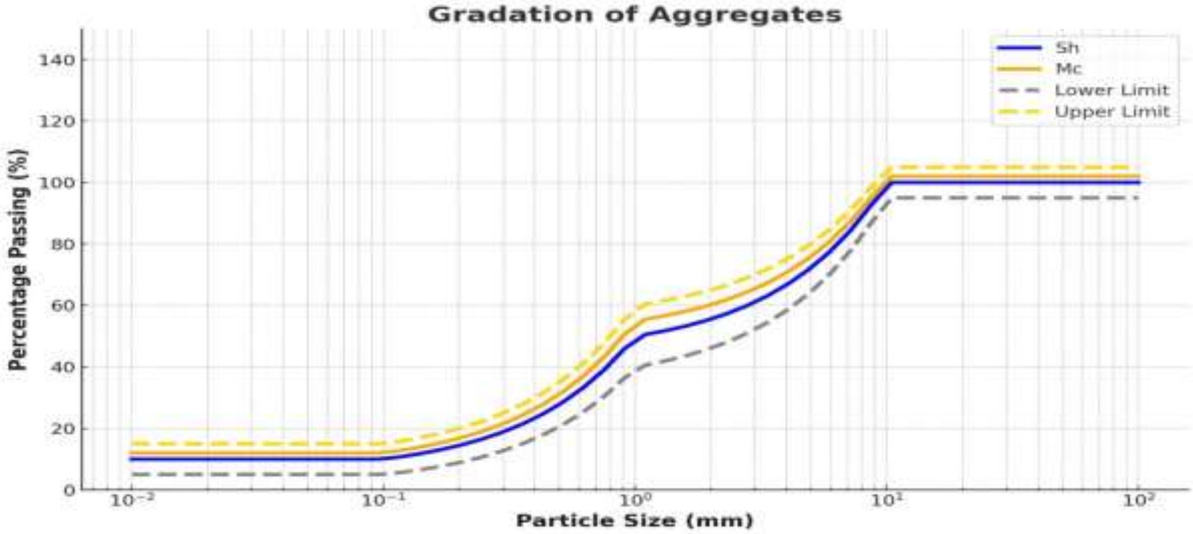


Fig. 2: Gradation of aggregates for Sheikhpura (Sh) and Mirza chowki (Mc)

Samples were prepared according to Marshall Mix Design. Optimum bitumen content is determined based upon the results obtained from various parameters of the mix such as stability, flow, bulk density, percentage air voids and percent voids filled with bitumen as guidelines furnished by MoRTH, which is provided under Table 4. Finally, The OBC of bituminous mix (BC II) for aggregates from Sheikhpura and Mirza chowki were determined to be 5.7% and 5.6% respectively.

Table 3: Marshall mix design parameters for determining Optimum Bitumen Content (OBC)

Source	Bitumen Content (%)	Stability (KN)	Flow (mm)	Bulk density (gm/cc)	Air voids (%)	Voids filled with Bitumen (%)
Sheikhpura (Sh)	5.25	10.3	2.4	2.33	7.2	61.1
	5.5	15	3	2.34	5.9	67.8
	5.75	17	3.3	2.36	4.2	76.4
	6	14.9	3.8	2.34	3.8	80
	6.25	13.7	3.9	2.32	3.6	84.4
Mirza chowki (Mc)	5.25	13.4	2.5	2.35	7.1	65.2
	5.5	14.4	2.5	2.37	5.4	70
	5.75	15	3.2	2.39	4.1	76.3
	6	13.7	4	2.36	3.6	78
	6.25	13.8	4.1	2.35	2.8	81.2

Table 4: Guidelines for Determining Optimum Bitumen Content (OBC) as per MoRTH

Properties	Designated Value
Air voids	3 to 5%
VFB	65 to 75%
Marshall stability	> 9.0 KN
Marshall Flow	2 to 4 mm

3.2 Gradation of aggregates for finding out the air voids

To assess the effect of aggregate gradation on air voids, four different gradations have been derived for each source of aggregate. For Sheikhpura and Mirza chowki sources of aggregate it is named as ShH1, ShH2, ShL1, ShL2 and McH1, McH2, McL1, McL2, respectively. Combined gradation of aggregate is done according to the specification of MoRTH. The data of the combined gradation of aggregate is furnished in Table 5 and the corresponding graph is plotted as shown in Figure 3.

Table 5: Combined gradations of aggregates

Sieve Size	SHEIKHPURA (Sh)				MIRZA CHOWKI (Mc)				MIDVALUE
	ShH1	ShH2	ShL2	ShL1	McH1	McH2	McL2	McL1	
19	100	100	100	100	100	100	100	100	100
13.2	99.02	96.12	91.4	91.11	100	96.2	94.48	91	95
9.5	84.36	83.28	76.4	74.29	85.29	80.97	77.88	73.6	79

4.75	68.45	63.98	61.54	57.12	69.54	66.28	61.02	55.4	62
2.36	56.68	53.47	47.35	44.98	56.48	52.4	48.3	45.36	50
1.18	44	42.21	40.86	38.56	45.36	42.68	39.77	37.58	41
0.6	35.12	33.4	30.48	29	36.98	35.54	31.56	27.41	32
0.3	27.04	24.58	22.21	20.68	26.45	23.4	22.4	19.68	23
0.15	19.5	16.25	12.96	12.35	19.86	17.02	15.4	13.54	16
0.075	8.32	7.21	6.93	5.12	9.65	7.85	6.93	6	7

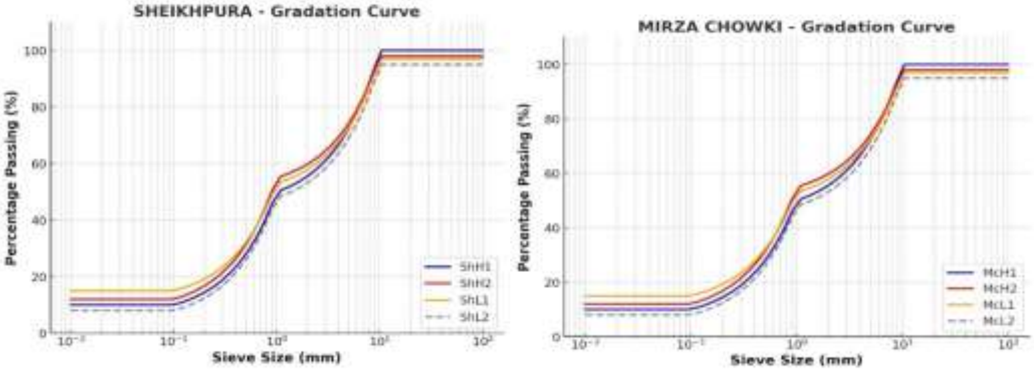


Fig. 3 Gradation graph for (a) Sheikhpura (Sh) (b) Mirza Chowki (Mc)

3.3 Calculation of Air voids

Again, Samples of each gradation of mixes have been prepared as according to the Marshall Method of Mix Design. The prime constituents such as coarse aggregates, fine aggregates, fillers and bitumen used in the bituminous concrete mix has been tabulated for evaluating the theoretical specific gravity (Gt) of the mix is calculated. Also, the bulk specific gravity of mix (Gm) is calculated by water immersion method. Finally, percentage air voids are calculated by using the formula Va = ((Gt - Gm) / Gt) * 100

The data obtained of the air voids have been furnished in Table 6, and their corresponding graph is presented as shown in Figure 4.

Table 6: Types of gradation and their corresponding air voids

GRADATION NAME	ShH1	ShH2	ShL2	ShL1	McH1	McH2	McL2	McL1
AIR VOIDS (%)	4.2	4.56	4.71	5.32	3.94	4.27	4.38	4.78

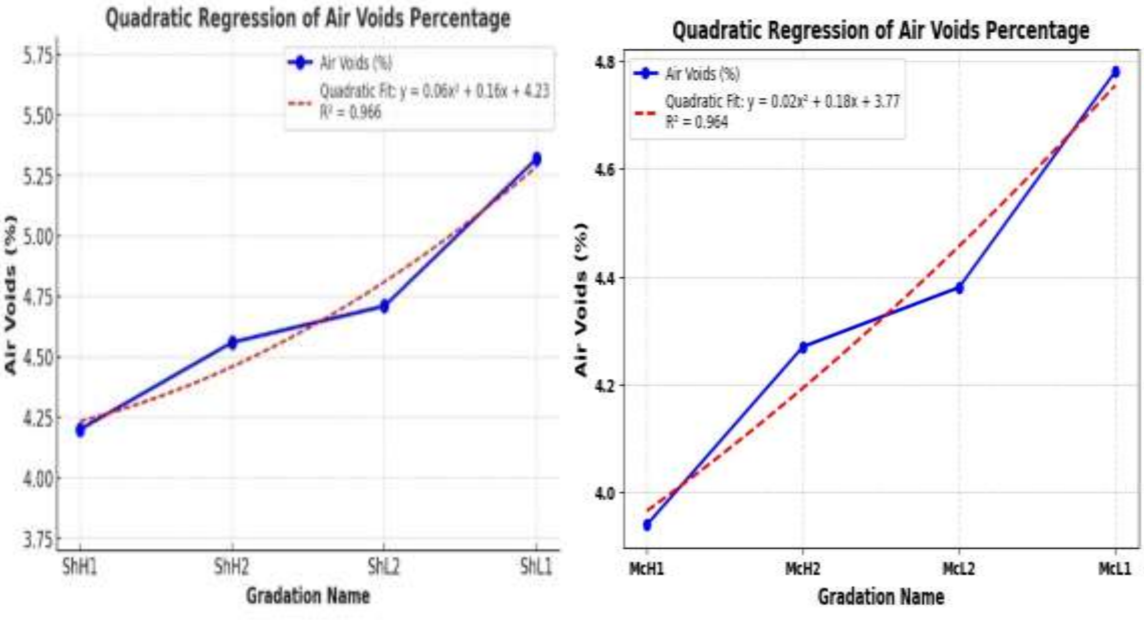


Fig. 4 Air voids in the mix corresponding to the different aggregate gradation

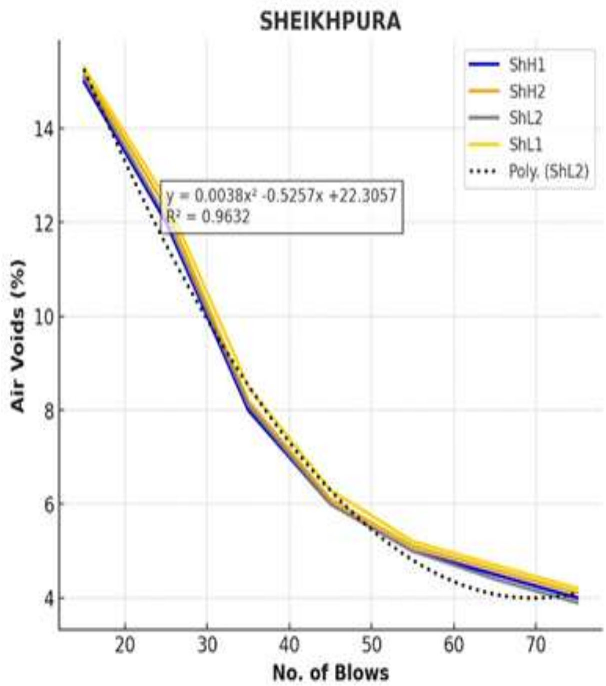
It was found that the graph in the figure 4 shown is a polynomial of degree 2 in nature for both the sources of aggregates having bituminous mix, and the R2 value close to 1 concretizes the relationship. The above relationship is between the gradation of aggregates and air voids in the corresponding bituminous mix.

3.4 Influence of aggregate gradation on air voids under variations in compaction effort

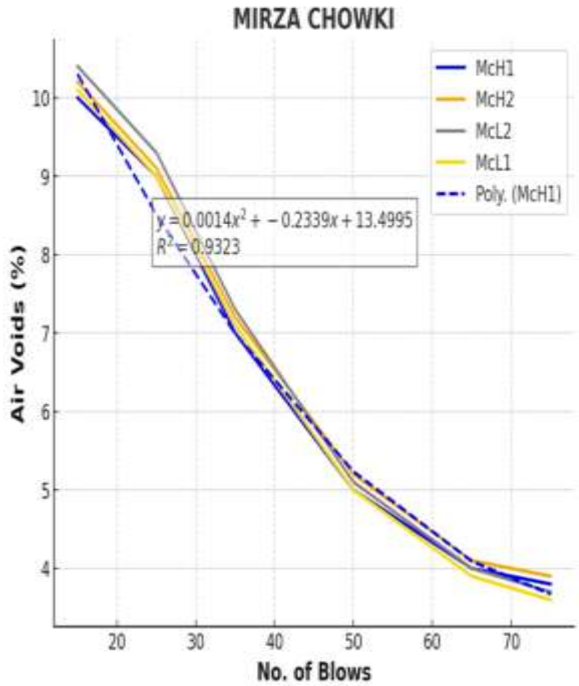
To evaluate the effect of variations in compaction energy on air voids in the mix, samples of each gradation type have been prepared by applying 20, 30, 40, 50, 60, and 75 no. of blows of the Marshall compaction hammer on both faces of the sample. A similar procedure is followed to determine the air voids in the mix. Data regarding the air voids of different grades of similar mix with the corresponding no. of blows are presented in Table 7, and their relationship is graphically shown in Figure 5. It was found that at initial stages the occupancy of air void is more but as soon as compaction energy increases aggregate starts to disintegrate successively. The broken aggregate particles occupy the voids which in turn reduces the amount of air voids in the mix. Such reduction in air void lead towards saturation, which can be easily identified from Table 7 that from 50 to 60 no. of blows there is minute change in air voids but in rest interval of no. of blows significant change in air void was found.

Table 7: Air voids of different gradations of mix with the corresponding no. of blows

NO. OF BLOWS	AIR VOIDS							
	ShH1	**ShH2**	**ShL2**	**ShL1**	**McH1**	**McH2**	**McL2**	**McL1**
20	14.84	15	15.12	15.5	9.78	10	10.2	10.58
30	11.3	12	12.14	12.54	8.64	8.85	9.42	9.75
40	7.36	7.5	7.85	7.9	5.02	5.15	5.6	5.95
50	6.23	6.5	6.94	7.36	4.53	4.95	5.1	5.47
60	6.1	6.32	6.78	7.15	4.37	4.87	5.04	5.28
75	4.2	4.56	4.71	5.32	3.94	4.27	4.38	4.78



(a) Sheikhpura



(b) Mirza Chowki

Fig. 5 Air voids of various gradation corresponding to no. of blows (a) Sheikhpura (b) Mirza Chowki

3.5 Impact of physical properties of aggregate on air voids in the mix on the account of same compaction effort

Almost same gradation of aggregates from Sheikhpura (ShH1) and Mirza chowki (McH1) sources have been taken. Physical properties in terms of Aggregate Compressive Strength Test (ACS), Aggregate Impact Value Test (AIV), Los Angeles Abrasion Test (LAA) and Soundness test indicates that aggregate from Mirza chowki source is comparatively higher in strength than Sheikhpura source that makes it more suitable for construction. Also, At the same compaction effort air voids in the mix prepared from Mirza chowki source (McH1) of aggregate is lesser than Sheikhpura source (ShH1) of aggregate, which can easily be identified in figure 6.

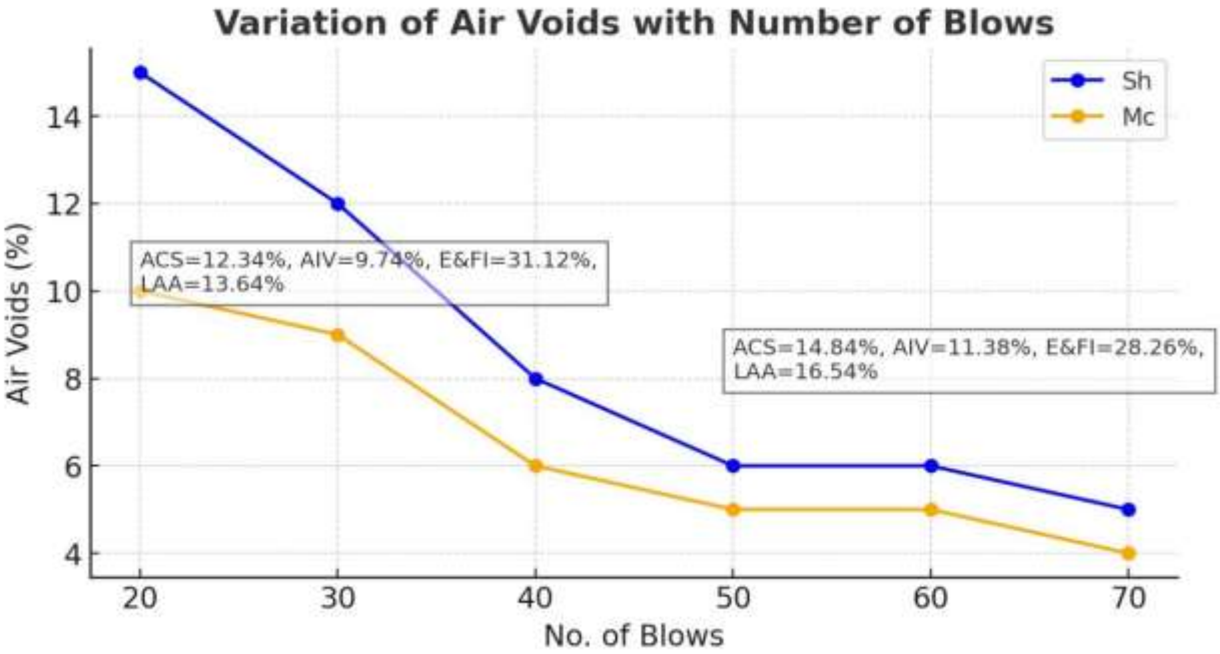


Fig. 6 Air Voids and no. of blows along with Physical Properties of Aggregate

3.6 Gradation of aggregates

The graph which is plotted on the upper side because of higher percentage passing through subsequent sieve size which means that it has the lowest percentage of coarse aggregate and highest percentage of fine aggregate while the graph which is plotted on the bottom most side because of comparatively lower percentage passing through its subsequent sieve size than any other which shows that it has the highest percentage of coarse aggregate and lowest percentage of fine aggregates. On the other hand, the graph which is in between these two boundaries have moderate amount of percentage passing of coarse as well as fine aggregates. Graph ShH1 and McH1 indicates the highest percentage of fine aggregates while graph ShL1 and McL1 indicates the lowest percentage of fine aggregates and rest of the graph shows the moderate percentage of fine as well as coarse aggregate. Since particle size distribution affects the demography of the mix.

3.7 Impact of particle size distribution on air voids

Result shows that the gradation graph ShH1 and McH1 have the highest number of fine aggregates which results into the lowest amount of air voids while gradation graph ShL1 and McL1 have the highest number of coarse aggregates which results into highest amount of air voids in the mix. Rest of the gradation graph contains in between air voids i.e. neither too high nor too low because of moderate combination of coarse as well as fine aggregates. For Sheikhpura source of aggregate the air void value ranges from 4.2 to 5.32% and for Mirza chowki source of aggregate the air void value ranges from 3.94 to 4.78 % for each gradation type. Definitely, Sheikhpura source of mix contains higher amount of air voids compared to the mix of Mirza chowki source for each type of gradation. But it is very similar variation of air voids for both mixes. The nature of variation of air void with percentage passing is polynomial of degree 2 for both source of aggregate and the above relationship is justified by R2 value which is close to 1.

3.8 Impact on air voids with variation in gradation of aggregates under different degree of compaction

The compaction effort was measured in terms of number of blows by Marshall compactor and corresponded to 20, 30, 40, 50, 60 and 75 number of blows. The air void (%) were determined for the compaction efforts and were plotted. After calculating the air voids for each gradation of mix corresponding to subsequent no. of blows it can clearly be seen that with increase in compaction energy, air voids in the mix decreases irrespective of type of gradation. The air voids of ShL1 & McL1 mix are highest and ShH1 & McH1 mix is lowest at any no. of blows because of ShL1 and McL1 gradation have the coarsest particle than any other gradation due to which it produces the highest amount of air voids while ShH1 and McH1 have the finest particles which possess the lowest amount of air voids. It was noticed that as initiating the compaction effort i.e. at low degree of compaction, air void starts decreasing rapidly because of available air void is maximum initially but on increase in compaction effort aggregate particle disintegrates and available air void is filled by broken aggregates. Furthermore, after a certain specific compaction effort the air voids value drastically decreases and finally comes to a saturation level even after increase in no. of blows. Reason is further increase in compaction effort causes the broken particles to settle in the air voids and its subsequent effect leads to saturation in air voids of the mix. The relationship between air voids and no. of blows was found to be polynomial of degree 2 and R2 value close to 1 justifies it. Also, it is observed that for the same compaction effort, the air void of mixes prepared with Sh aggregates is more as compared to Mc aggregates because Mc aggregates are flakier and more elongated compared to Sh aggregates. On application of compaction effort, it breaks down and resulting in a higher proportion of fine particles and reduced air voids for similar compaction effort.

4. Conclusions

The study suggested that air void content in bituminous mixes is governed more by aggregate shape and gradation than by mechanical strength properties. Coarse aggregate dominantly affects mechanical behaviour of bituminous mix, while fine aggregates play a role in defining the distribution of air voids [23]. Despite Mc aggregates exhibiting superior strength, their higher flakiness and elongation lead to particle breakage during compaction, reducing air voids. Increasing compaction effort significantly reduces air voids initially, followed by marginal decrease due to aggregate rearrangement limitations and particle disintegration [6]. Overall, optimal compaction is critical in defining the volumetric properties of asphalt mixes.

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Authors Contribution
Anand Kumar: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing, Supervision; Ankita Kumari: Conceptualization, Methodology, Data curation, Resources, Validation, Writing – original draft, Writing – review & editing; Chandra Shekhar Verma: Conceptualization, Formal analysis, Investigation, Validation, Supervision, Project administration; Amit Kumar: Conceptualization, Methodology, Investigation, Formal analysis, Resources, Validation, Writing – review & editing; Sushant Kumar: Formal analysis, Investigation, Data curation, Resources, Visualization, Writing – review & editing; Dhananjay Kumar: Formal analysis, Investigation, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing, Supervision, Project administration;
All authors have read and agreed to the published version of the manuscript.

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