



Evaluation of different porous asphalt gradations based on aggregate packing and stiffness parameters

Gummadi Chiranjeevi¹ · S. Shankar¹

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Abstract

Aggregate gradation is crucial for understanding how porous asphalt responds to traffic loading. A porous asphalt mixture is a particle size distribution that permits infiltration of the runoff storm water due to its voids content. The current study investigates the unbound aggregate blend packing conditions concerning density and stiffness characteristics. A gradation-based framework to analyze the susceptibility and durability of asphalt mixtures with various aggregate gradations is empirically evaluated by maintaining a constant source for both the aggregates and the binder; the laboratory experiment was intended to isolate the impact of aggregate gradation. The effort involved testing and packing studies for considering two gradations for the eleven various asphalt mixtures. Marshal Method of mix design was carried out, and tests like indirect tensile strength (ITS), tensile strength ratio (TSR), Cantabro test, and drain down test (min and max binder content) were conducted. Results indicate that the testing procedure impacts how the porous asphalt mixture responds to loads. According to the design criteria, the TSR value for both gradations exceeds 80%. The 9.5 mm and 4.75 mm fractions affect the mixture's strength, and a correlation is shown between the Marshall stability and ITS as well as the TSR and wet IDT. The findings demonstrate that filler material significantly affects the air void content and stability of the skeleton and that gradations, particularly fractions with 4.75 to 2.36 mm, impact the performance of porous asphalt mixtures. These pavement kinds help reduce drainage issues, replenish the subsurface layers, and enhance vehicle safety.

Keywords Porous pavement · Aggregate packing · Stability · Cantabro · Air void · Stiffness

Background

It is anticipated that the continued population growth and urbanization will potentially add 2.5 billion people to the world's urban population by 2050 [1]. This trend presses the extension of urban areas and accompanying impermeable surfaces. To recharge the groundwater, a porous asphalt surface course satisfies the criteria for absorptive capacity in the range of 16–22%; PAM has higher air voids. Besides the fines being removed to increase the empty area, porous asphalt is similar to ordinary pavements. [2–4]. Standard hot mix porous asphalt does not have the maximum fine aggregates. [5]. In recent years, porous mixes have gone up the

multi-fold to reduce road-based noise and stormwater runoff problems. PAM has a structure of interconnected open pores that allow water to infiltrate through it [6]. Moreover, there is hardly any water film on the porous asphalt surface in the rain because of its excellent drainage capacity. Several guidelines must be followed to achieve a higher percentage of air voids. A higher rate of air voids can be attained by using the aggregate selection procedure as an effective strategy. According to estimates, the porous asphalt mixture contains more than 80% aggregate particles with a size bigger than 2 mm. [7–11].

Porosity is related to the volumetric characteristics of aggregate packing, whereas coordination number is utilized to describe the mechanical characteristics of PAM's aggregate packing. One element that affects how asphalt mixes are packed is the form characteristics of the aggregates. [4–13]. A porous course is defined by the National Asphalt Pavement Association (NAPA, 2008) as having connected voids of 16% or less and a pavement thickness of 50 mm to 100 mm. The mechanism of a porous mixture is influenced

✉ Gummadi Chiranjeevi
gc720028@student.nitw.ac.in

S. Shankar
ss@nitw.ac.in

¹ Transportation Division, Department of Civil Engineering,
National Institute of Technology, Warangal 506004, India

by a wide range of elements, including the binder's characteristics and the packing of dry aggregates. [9–17]. Dry packing research uses varied shapes of coarse aggregates exposed to packing capacity and less than 10% of fine aggregates. [11]. However, The high effective air void content and the larger size of aggregate structure depending on the bonding of granular material adhesion force leads to several mechanical deficiencies, particularly the life span concerning due to ravelling effect and ageing effect of bitumen.[18]. The size distribution is critical to the performance of porous asphalt pavement [7]. PAM consists of a very small proportion of fine aggregates, forming interconnected void space that provides permeability characteristics that can withstand repeated traffic. The minimum void space of porous asphalt is 16% compared to 2–3% for conventional asphalt pavement [19, 20]

The durability assessment of PAM is primarily based on the Cantabro loss test developed in the 1990s in Spain. The Cantabro test is recommended to consider the resistance to disintegration effect of surface course distress like raveling [17, 21, 22]. Drain down is another problem for PAM mixtures because of its open gradation. PAM blends omitting the fines or less percentage in the gradation. Additives reduce drain-down loss in a binder, and aggregate structure and stiffness parameters improve [23, 24].

As stated previously, most studies used the AASHTO T283 TSR value to assess the moisture susceptibility of PAM. As a result, an effort has been made in the current study to examine the mechanical properties of TSR parameters, and their connections to specific other parameters, such as dry IDT and Marshall Stability conditioned samples, as well as wet IDT versus TSR [25–28]. The gradation, binder, and compaction play a key role in varying the air voids in the mix [29]. A few studies have investigated the effect of different aggregate sizes and types, variations in the aggregate-asphalt ratio, and compaction efforts on the strength and permeability of porous asphalt surface courses [30]. Also, the density studies mainly focused on the interlocking properties of mixture gradation [30–32]. The current

study evaluates the loss of packing density, dry rodded packing density, loose air voids, and compacted air voids for each gradation band. Several trial gradations were used to determine the bulk densities. Furthermore, cantabro, drain down parameters, and other end stiffness parameters are considered for this study. Apart from previous studies, this one uses gradations and a viscosity grading (VG30) binder that can withstand all temperatures.

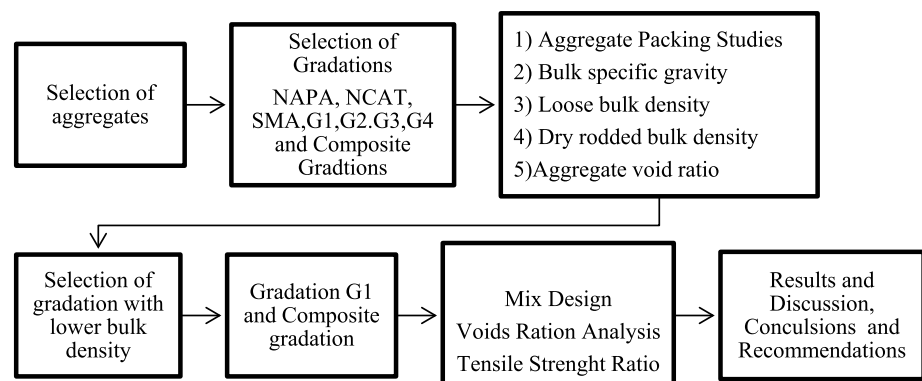
Current research need and methodology

The present study attempts to increase the performance of PAM using particle-packing theories, correlates the selected gradation following bulk densities by the Marshall Stability and flow values evaluation, and compares their tensile strength. The aggregate combinations are proportioned in such a way as to reduce packing density by increasing the void space. Figure 1 shows the research approach adopted in the current study.

Materials characterization

Eleven gradations were selected and blended based on the literature survey. Out of which, two trial gradations are considered, and aggregate packing studies were conducted for all the gradations to determine the bulk specific gravity, loose bulk density, and dry rodded bulk density. Gradation G1 and composite gradation were chosen from aggregate packing studies with various types of gradation bands taken from porous asphalt standard gradation suggested by the Federal Highway Agency (FHWA), National Center for Asphalt Testing (NCAT), and National Asphalt Pavement Association (NAPA). The aggregate packing studies selected the gradation with lower bulk density and higher air voids taken together skeleton band. Such types of two gradations perform a test procedure as per ASTM D7064. Mix design is carried out using the selected gradations with a VG30 binder. The physical properties of the binder, such

Fig. 1 Adopted research methodology



as penetration (0.1 mm, 100 g, 5 s), softening point, absolute viscosity at 60 °C (poise), and kinematic viscosity at 135 °C (Centistokes), are determined. The Optimum Bitumen Content (OBC) between 5.5% to 6.5% was considered in the present study as recommended by NAPA IS-115, NCAT, and FHWA for porous asphalt design criteria.

Aggregate gradation and binder used in the study

Air voids are primary and essential in designing porous asphalt pavement to ensure drainage capacity. In the early days, the porous pavements were designed at 15–18% of air voids, which has increased to 18–23% in recent years. Nevertheless, high air voids will raise versatile problems, such as low stability, strength, and poor durability. Since the Ministry of Road Transport and Highways (MoRTH, 2013) specifications did not provide any gradations for porous asphalt pavement, Stone Mix Asphalt (SMA) is used to compare aggregate packing studies. VG30 bitumen is used in the current study due to its thermal susceptibility. Fullers and Thomson described a maximum density gradation for a specific maximum aggregate size. Table 1 and Fig. 2 shows the different porous asphalt gradation in tabular form and graphical representation, respectively. Tables 2 and 3 show the current study's binder and aggregate properties adopted, respectively.

The most influential factor in the difference between NAPA (National Asphalt Pavement Association) and NCAT (National Center for Asphalt Technology) is 9.5 mm of aggregate sizes, up to 15% larger than NCAT. Furthermore, the aggregate size of 12.5 mm differs from that. The maximum coarser material quantity influenced the gradation and strength parameters. NAPA, NCAT coarse material is more expensive than SMA (Stone Matrix Asphalt). SMA fine material has a high content of up to 24%. In this case, the

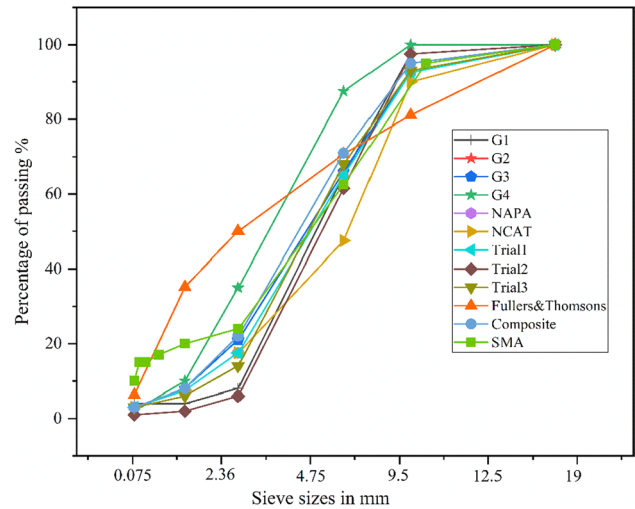


Fig. 2 Different gradations of porous asphalt pavement

SMA gradation influencing factors are 1.18 mm and 0.6 mm sizes. Porous asphalt gradation requires a higher void content in the gradation. Here, 1.18 and 0.6 mm porosity sizes influence SMA gradation.

Packing studies were conducted in several trials, but three gradations were selected based on their proximity to the results and ability to meet the porous design criteria. Two of them illustrated volumetric and mechanical characteristics.

The experimentation used in this study

The main objective of this study was to determine how different aggregate gradations used in an asphalt mixture affected the characteristics of porous asphalt. The porous

Table 1 Porous asphalt gradations

Sieve size (mm)	% of passing										
	G1	G2	G3	G4	NAPA	NCAT	Composite	SMA	Trial 1	Trial 2	Trial 3
19	100	100	100	100	100	100	100	100	100	100	100
13.2	–	–	–	–	–	–	–	95	–	–	–
12.5	97.5	93	99	100	92.5	90	95	–	96.5	97.5	93
9.5	65	66	95	87.5	65	47.5	71	62.5	59	61.5	68
4.75	8	21	33	35	17.5	17.5	22	24	8	6	14
2.36	4	8	10	10	7.5	7.5	8	20	5	2	6
1.18	–	–	–	–	–	–	–	17	–	–	–
0.6	–	–	–	–	–	–	–	15	–	–	–
0.3	–	–	–	–	–	–	–	15	–	–	–
0.075	4	3	3.5	2	3	3	3	10	1	1	3
DRUW	1.50	1.61	1.63	1.65	1.66	1.64	1.56	1.91	1.58	1.62	1.63
LUW	1.41	1.48	1.50	1.53	1.50	1.52	1.44	1.77	1.43	1.46	1.48
Air Voids (%)	43.2	39.1	38.3	37.6	37.2	37.9	41.3	27.7	40.2	38.7	38.3

Table 2 Physical properties of VG30 grade binder

Sl. No.	Test property	Obtained results	(IS:73–2018)
1	Absolute viscosity at 60 °C (poise)	2765	2400–3600
2	Kinematic viscosity at 135 °C (centistokes)	399	350 Min.
3	Penetration point 25 °C	50	45 Min.
4	Softening point (Ring and Ball °C)	53	47 Min.

Table 3 Properties of aggregates

Property	Obtained results	Specifications (MoRTH, 2013)	Test protocol
Bulk specific gravity	2.65	2.5–3.2	IS:2386-Part-3
Apparent specific gravity	2.66		
Water absorption (%)	0.13	< 2	IS:2386-Part-3
Aggregate crushing value (%)	22.0	< 30	IS:2386-Part-4
Aggregate impact value (%)	19.0	< 24	IS:2386-Part-4
Los angles abrasion (%)	25.0	< 30	IS:2386-Part-4
Flakiness index (%)	16.0	Max. 30	IS:2386-Part-1
Elongation index (%)	25.0		IS:2386-Part-1

**Fig. 3** Bulk density mould with open graded sample

asphalt pavement mix has undergone all performance-based testing, which is presented and discussed in this section.

Density of dry aggregates

This test method covers the determination of bulk density of aggregate in a compacted or loose condition and calculated voids between particles in fine, coarse, or mixed aggregates. This test method is applicable to aggregates not exceeding 125 mm (ASTM C29). In the current study, two band sizes were analyzed to calculate the bulk density of aggregate but considered the entire gradation band. Accordingly, test procedures are conducted for each size to know specific gravity and determine the aggregate interlocking air void content. Figure 3 shows the bulk density experiment setup.

Marshall stability

Five different binder contents were tested to find the ideal binder content. Gradation band is considered for each binder content; three compacted samples are prepared using the Marshall Mix design method in preparing all compacted specimens. It is to be noted here that if the proportions of the coarse aggregate, fine aggregate, and filler material must meet the applicable standards' criteria adopted. The procedure adopted is to prepare a sample of compacted bituminous mix, approximately 63 mm thick (height), 1200 g of aggregate and filler are needed; the aggregates are heated to a temperature of 175 to 190 °C. The required quantity of first trial bitumen is added to the heated aggregate and mixed properly after the bitumen is heated to a temperature between 121 °C and 138 °C. A specified number of blows are applied to compact the mixture. With the help of a sample, the extractor specimen has removed from the mould after a short while, and density and voids analyses were performed. Determination of void space for the mixture and skeleton is required for an open-graded course to perform this type of test. Air voids are calculated using Corelok. Equation 1. used to determine the air void content as presented below.

$$AV = \left(1 - \frac{G_{mb}}{G_{mm}} \right) \times 100 \quad (1)$$

The Core Lok system is an innovative product designed to determine apparent specific gravity and percent absorption

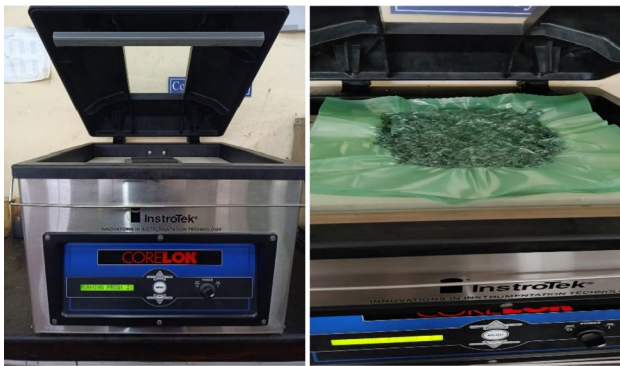


Fig. 4 Corelok for density analysis

of aggregates Figure 4 shows the experimental setup of corelok for density analysis. The apparent gravity and % absorption calculated by this method can then be used to determine bulk-specific gravity and saturated surface dry (SSD) weight of the aggregate by employing the already determined relationships. This system is designed for use with fine and coarse aggregates in specifically made puncture-resistant polymer bags; samples are automatically sealed. The Corelok technology has very high levels of accuracy and reproducibility when measuring densities.

Marshall Stability is the sum of all the values (kN) resulting in specimen failure. The specimen is placed in a water bath heated to $60^{\circ} \pm 1^{\circ} \text{C}$ and left for 30 min to conduct the stability test. The Marshall stability testing equipment is used to load the sample until failure is reached at a constant rate of deformation of 5 mm/minute. Flow value is a measurement of the overall deformation, measured in units of 0.25 mm, that occurs under the highest load; 30 s is the maximum time that should pass between taking the sample out of the bath and finishing the test. The ideal binder content is chosen as the average binder content for the mix's maximum density, stability, and specified percent of air voids.

Drain down test

The drain-down test is conducted as per ASTM D 6390. A sample of the asphalt mixture to be tested is prepared in the laboratory or obtained from field production. The sample is placed in a wire basket on a plate or other suitable container of known mass. The sample, basket, and plate are placed in a force draft oven for one hour at a pre-selected temperature. At the end of one hour, the basket containing the sample is removed from the oven along with the plate and the mass of the plate or container containing the drained material, if any, is determined. By dividing the initial total sample weight by the final plate or container weight and subtracting



Fig. 5 Drain down loss before and after testing

the starting plate or container weight from the final plate or container weight, one can determine the amount of drain down using Eq. 2.

$$\text{Drain down loss (\%)} = \left(\frac{A - B}{C} \right) \times 100 \tag{2}$$

where,

A = Plate or container's final weight, in g.

B = Plate or container's initial weight, in g.

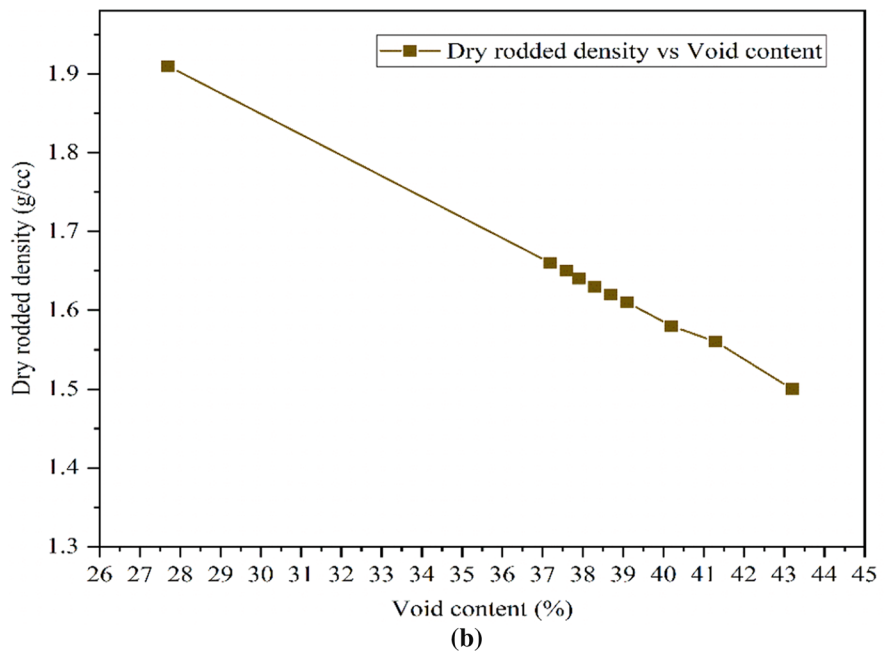
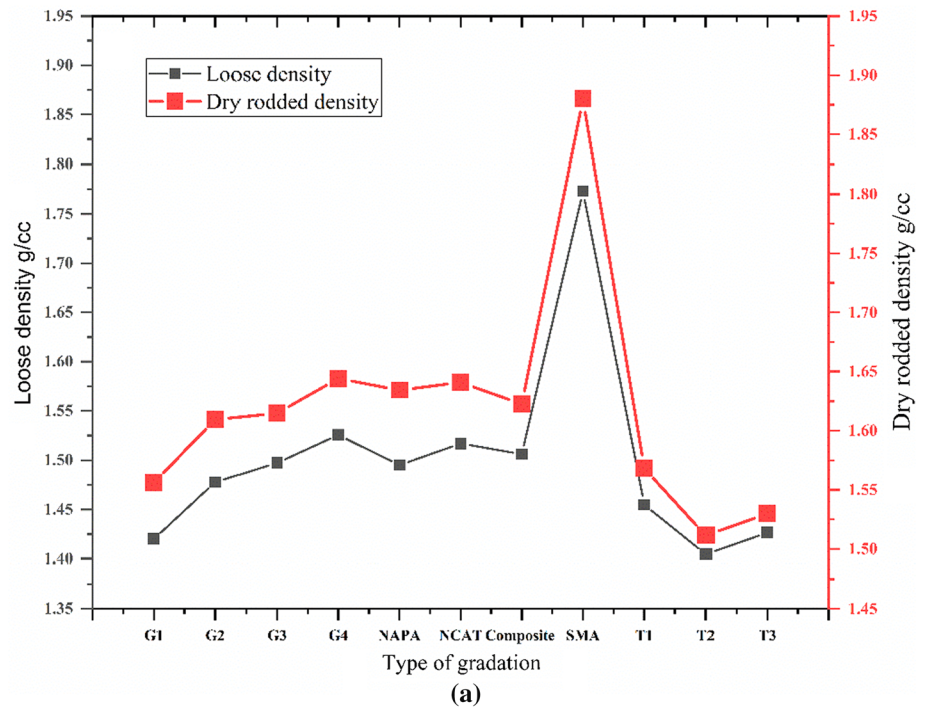
C = Initial weight of the entire sample, in g.

The test calculates the amount drained down at elevated temperatures 10% above the compaction temperature at 160 °C. Figure 5 illustrates the drain-down test procedure.

Cantabro test

The Cantabro test determines the mass loss percentage in the samples, and the ravelling effect of such pavements is evaluated using the Cantabro test method. This test measures the breakdown of compacted samples utilizing the Los Angeles Abrasion (LAA), as shown in Fig. 9. The Cantabro loss indicates durability and relates to the quantity and quality of the asphalt binder. The methodology is used in several countries as a benchmark test for mix design practices. Marshall's mix compressed sample needs to be placed in an LAA machine without the customary steel charges, and they need to tumble for 330 revolutions in the drum. After the 330 revolutions, discard the loose material broken off the test specimen. Do not include any of this material in the weight. Weigh the test specimen and determine the Cantabro loss using Eq. (3) as given below. It is observed that the maximum amount of stone loss on fresh samples is 20%.

Fig. 6 a Dry loose density and dry rodded **b** Void content and rodded density of different gradations



$$\text{Cantabro loss(\%)} = \left(\frac{A - B}{A} \right) \times 100 \tag{3}$$

Indirect tensile strength test (ITS)

It is the preliminary test to characterize the stiffness of a bituminous mixture. Most frequently, the problem is to find if the specimens compaction type is used for ITS evaluation during the mix design phase. The test is carried

out as per AASHTO T312. Samples are mixed before being spread out to a thickness of 25 mm. The mixture is baked for two hours at 135 °C with 30 °C stirring intervals to retain conditioning. After two hours of cooling, the mixture is brought to room temperature. Following that, measure the thickness (t) and diameter (D) and conduct the maximum specific gravity (GMM) test following AASHTO T 209, as well as the bulk specific gravity (GMB) test AASHTO T166. Samples were sealed and stored for 24 h at a temperature of 18–30 °C, and then

they were heated in a water bath for 2 h at a temperature of 25–50 °C. Before performing a test as per AASHTO T283, use the vacuum saturation process to determine the degree of saturation percentage if saturation levels range from 70 to 80%. A tensile strength ratio (TSR) dry/conditioned subset value of 80% is acceptable for porous asphalt mix design.

Analysis and discussion of results

Bulk density for coarse and fine aggregate

The bulk density for coarse and fine aggregates is determined [33]. It is observed that Stone Matrix Asphalt (SMA) has more dry loose density and dry rodded density, as shown in Fig. 6a. Similarly, the loose and rodded air voids are less in SMA. It is a known phenomenon where the mixes with higher densities usually have lower air voids. The remaining gradations have an opposite trend where larger air voids and lower densities. Apart from the SMA, the remaining mixes have the same range of densities and void ratios.

The packing density ratio is considered while determining the initial value of density vs the increased value at each gradation band. Figure 7 illustrates how finer content affects packing density. Additionally, the finer proportion steadily grew in the gradation band, with a clear downward sign.

The porous asphalt mixtures were made by using one crushed granite aggregate source.

Each aggregate gradation's specific gravity void content for all aggregate sizes was measured as per [34]. Table 3 shows the different porous asphalt gradations.

The selection of particular gradation G_1 and composite gradations are based on the bulk density and void content. Bulk density is directly related to the hydraulic conductivity of porous asphalt mixture, and density impacts the skeleton's permeability and voids ratio. Figure 8 illustrates the characteristic behaviour aggregates concerning size and percentage of each size varying the density. Further stiffness parameters are evaluated for high void content and low rodded density of G_1 , composite gradation.

Density and void analysis for porous asphalt mix

Drain down and Cantabro test

The drain-down test is performed at two temperatures to determine the potential effect of plant and laboratory

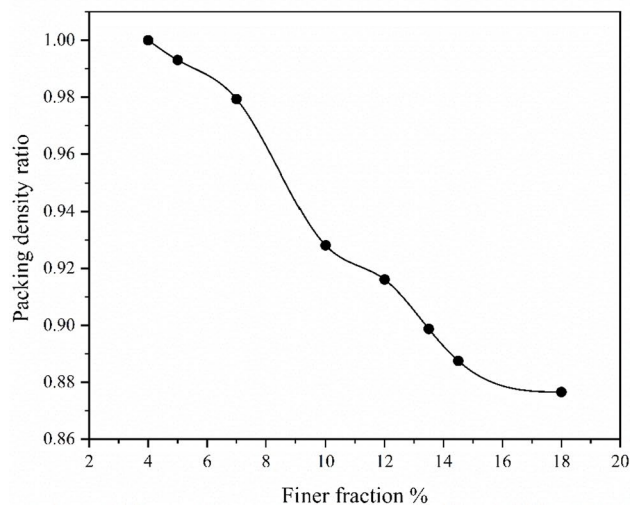
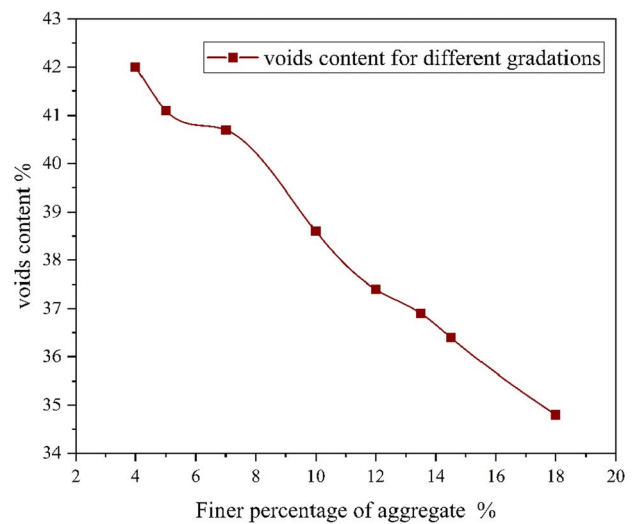


Fig. 7 Packing theory concerning finer percentages on each band

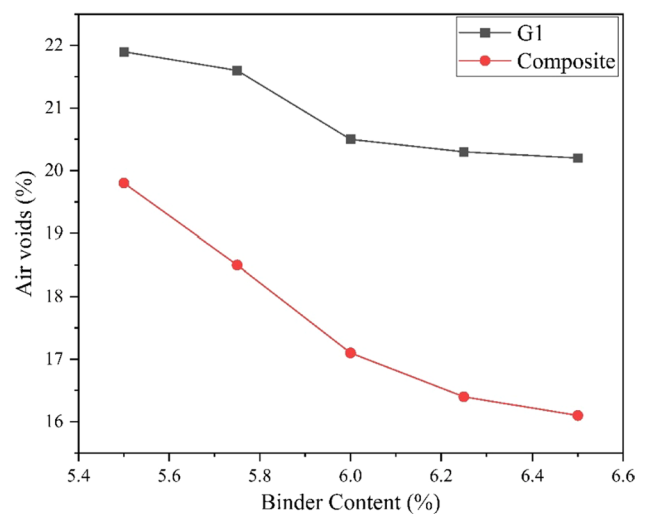


Fig. 8 % of voids for different bitumen content for porous asphalt pavement

temperatures. The drain down test is performed according to the ASTM D 6390 (1997) standard test method for determining drain down characteristics in un-compacted asphalt mixtures [23]. The test is applicable mainly for open-graded mixes. Figure 9 shows the drain down percentage at the minimum and maximum binder content. Composite Gradation has a lower drain down compared with Gradation G₁. This is because of zero fines content in the gradation G₁. Therefore, the Gradation G₁ requires filler materials or anti-stripping additives to attain maximum strength.

The cantabro test was performed to evaluate the durability of the PAM and the ravelling effect in the present mix. Figure 10 shows the test setup for the Cantabro test. Figure 11 illustrates the Cantabro loss for various gradations as a result of the Cantabro test. This is more in G1 and less in composite gradation due to omitting 0.075 mm. A maximum stone loss of 20% is specified for un-aged samples. The percentage loss of the material represents the mixture's durability. ASTM D7064-04 percentage of loss for the unaged sample was less than 20%.

Marshal stability and flow value

The specimens are immersed in a water bath at a temperature of 60 ± 1 °C for 30 min and tested at a constant rate of deformation of 5 mm per minute until failure.

Figure 12a, which displays the stability test results, (a) illustrates the link between the stability of porous asphalt pavement and the amount of asphalt binder present. It demonstrates that the stability value initially increases, reaching its maximum stability at a binder level of 5.5% for composite gradation and 6.0% for G1 Gradation. However, with adding more binder, the stability can get less stable. Lack of



Fig. 10 Cantabro test using LAA Machine

stability is caused by too much binder. Flow is a deformation condition of an asphalt mixture resulting from a load placed on the pavement's surface and measured in millimetres (mm). Figure 12b depicts the relationship between flow and binder content for all variations in porous pavement mixtures. The findings suggest that the flow might rise along with the amount of asphalt binder. All the Marshall mix design parameters are shown in Fig. 12c–e. The results show that the stability, unit weight, and VFB are more for the Gradation G₁, whereas VMA is less for gradation G₁. Similarly, when the binder content increases, the VMA decreases. In terms of flow values, there is no specific trend observed. This is because the percentage fines are more minor, and binder bond film capacity losses in gradation G₁.

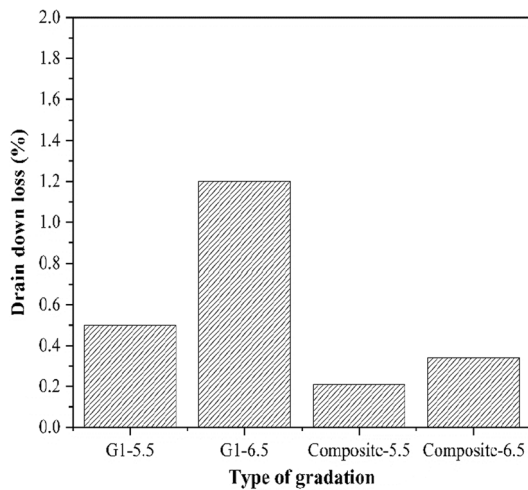


Fig. 9 Drain down test for the gradations G1 and composite

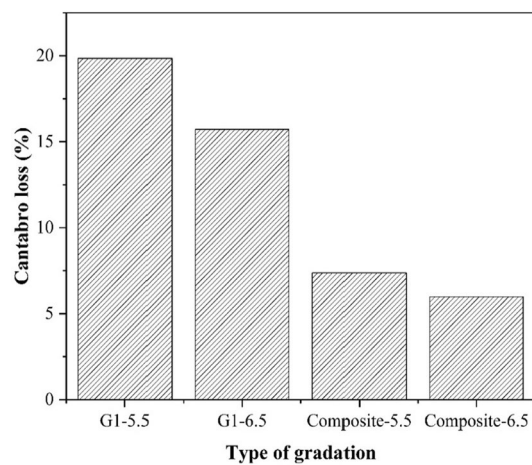


Fig. 11 Results of Cantabro loss test for different gradations

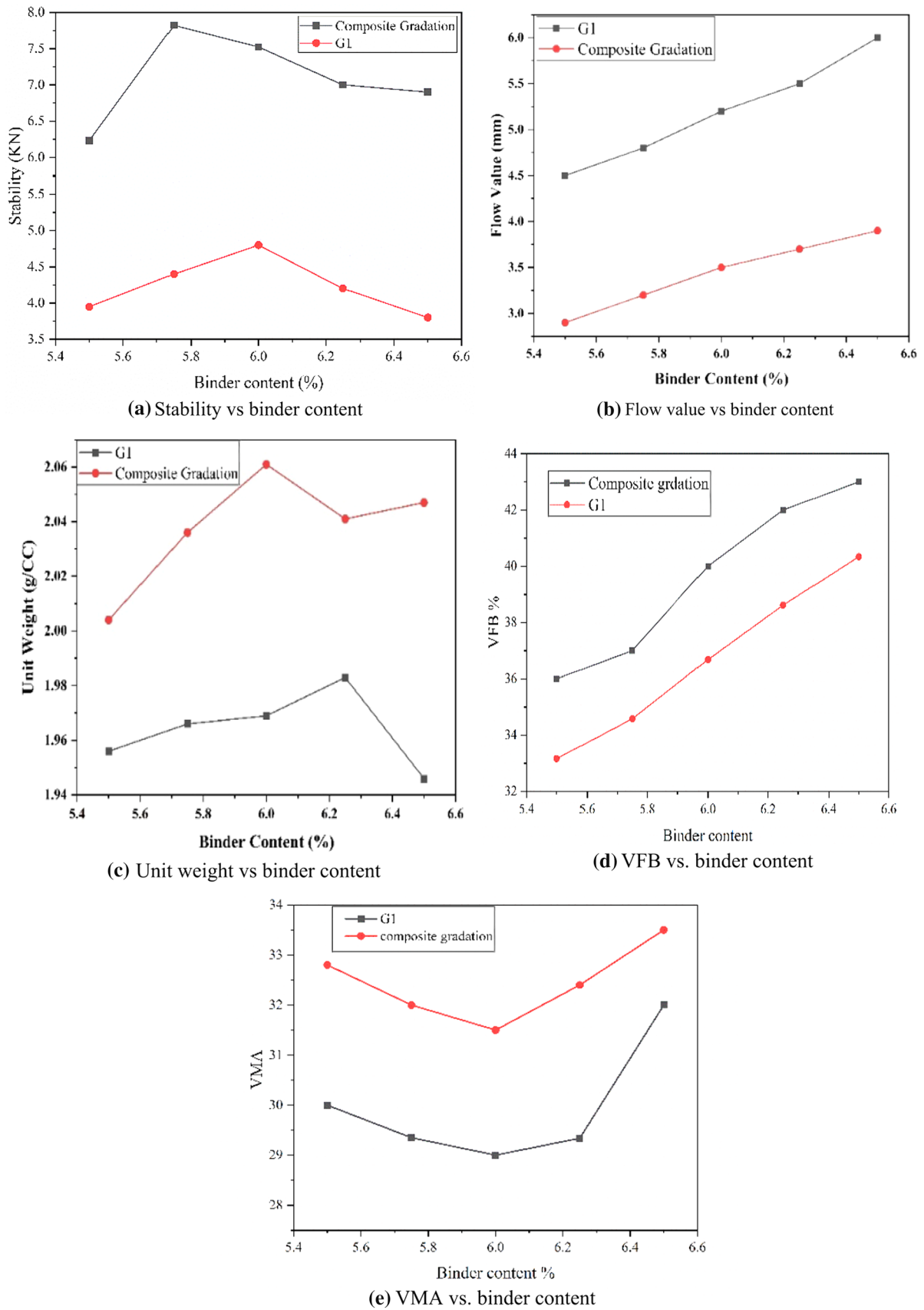


Fig. 12 Marshall mix properties of porous asphalt pavement

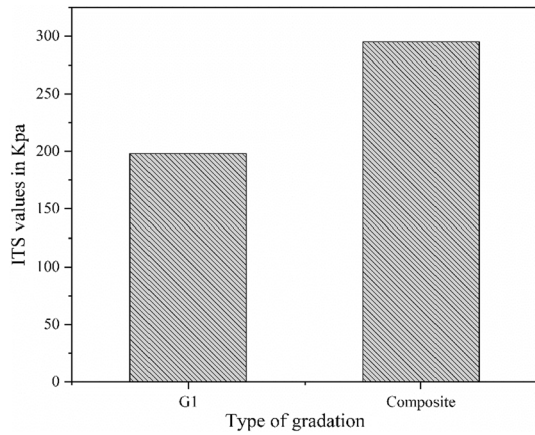


Fig. 13 Indirect tensile strength values for Two Gradations

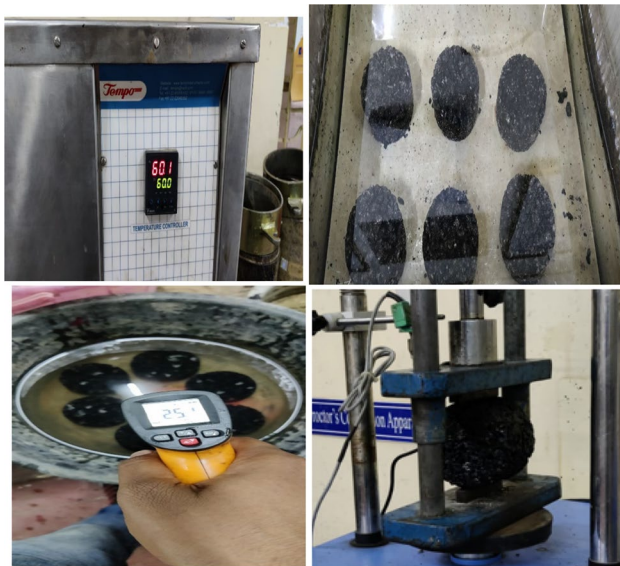


Fig. 14 TSR test sample images for Wet IDT test

Indirect tensile strength

The indirect tensile strength is performed on the specimens of size 100 mm in diameter and the height of 63.5 ± 2 mm. The results of the ITS for G₁ and composite gradation are shown in Fig. 13. From the observations, the composite gradations have a higher ITS value than the G₁. Aggregate sizes of 9.5 mm and 12.5 mm influence porous asphalt mixtures. Figure 14 illustrates TSR test sample images for wet IDT test.

Tensile strength ratio

The observed TSR values for porous asphalt mixtures without additives have higher TSR values of more than 80%.

Table 4 Wet IDT statistical analysis of gradation type

Type of Gradation	G ₁	Composite
Count	9.0	9.0
Minimum	121.31	183.91
Maximum	169.51	239.52
Quartile 1	121.31	183.91
Quartile 3	169.51	239.52
Mean	137.59	217.42

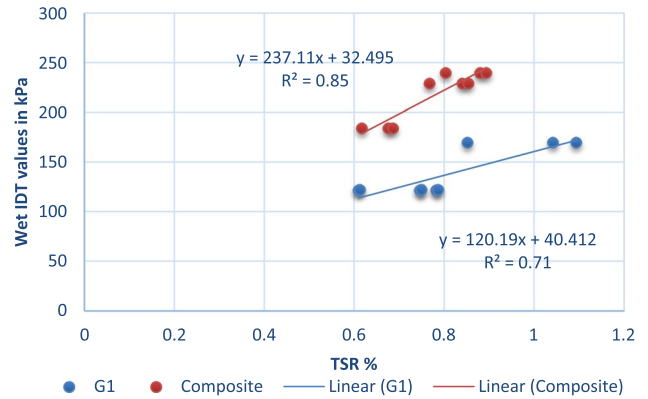


Fig. 15 Comparison of Wet IDT versus TSR with linear correlation trend line

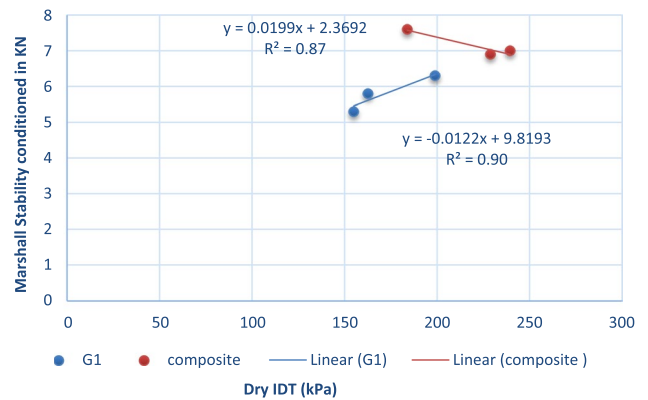


Fig. 16 Comparison of Marshall stability with dry density

A large amount of asphalt binder in the porous mixes may give more adhesion or cohesion between the binder and the aggregate. The TSR and wet IDT strength of the two gradations are shown in Fig. 15. It is observed that the TSR values are proportional to the wet IDT strength. This implies that a higher TSR value may guarantee better moisture damage

resistance. The selected gradations show a strong correlation between TSR and wet IDT.

Statistical analysis for the two gradations is shown in Table 4. The observations show a significant difference between the G_1 and composite gradation types. The strength of the composite gradation is higher than the G_1 gradation.

Dry IDT versus Marshall stability of conditioned samples

A relationship is established between ITS and Marshall stability of the porous asphalt pavements, as shown in Fig. 16. Here, three criteria affect the skeleton porous asphalt sample: temperature, gradation, and binder. The temperature range varies in each situation; the gradation effect on the fine and coarser fractions. From the observations, the dry density and the marshall stability are correlated positively for the G_1 gradation and negatively for the composite gradation. Binder oxidation and stripping mechanism correlate with each other.

Conclusions

The present work has studied the effect of gradation on porous asphalt mixture prepared with VG30. The following are the specific conclusions drawn from the study as presented below:

- The application of porous asphalt pavements might be advanced without sacrificing their coefficient of permeability by using a continuous update skeleton, a balanced aggregate to binder ratio, and a balanced aggregate size.
- The porous asphalt course is mainly influenced by aggregate gradation. The aggregate gradation band consists of 100% of 19 mm downsized aggregates and requires less quantity of 4.75 mm passing aggregates like 2.36 mm, and 0.075 mm for adequate permeability.
- Gradation G_1 has higher air voids compared to composite gradation. Here, the percentage of fines and filler materials is 8–10% (G_1), and the composite gradation percentage of fines and filler material is 18 to 22%.
- Composite gradation performs well. Here, gradation G_1 stone loss is high for un-aged samples. Here, gradation G_1 fails in the drain down test and exceeds the maximum range.
- Gradation G_1 porosity is high, and stability values depend upon aggregate gradation, the skeleton of the sample, binder content, mixing temperatures, etc.
- The G_1 gradation's ideal binder content (OBC) is 5.92%, whereas the composite gradation's OBC is 5.75%. The design criteria of porous asphalt mix design

considerations are satisfied by the tensile strength ratio for both gradations.

Recommendations and future scope

Future scope of the study, one can conduct permanent deformation characteristics and durability assessment in wet and dry processes for aged and unaged binders by using the Cantabro test and develop life/strength prediction models using soft computing methods for rutting of porous asphalt mixes.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Authors declare that present work performed as per ethical standards of institute. This manuscript has not been published in whole or in part elsewhere and not currently being considered for publication in another journal.

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