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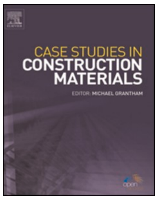

# A comparative analysis of engineering and economical suitability of bituminous mastics containing waste fillers

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ABSTRACT

This novel study focused on comparing the effect of waste glass powder (GP), waste-dried Kota stone slurry (KS), glass-hydrated lime composite (GL), and conventional stone dust (SD) fillers on the engineering and economical performance of bituminous mastics. Bituminous concrete mixes incorporating the fillers mentioned above at multiple proportions (4%, 5.5%, 7.0%, and 8.5% by weight) were prepared and characterized. The filler-bitumen ratio corresponding to each bituminous mix was determined and used to design its corresponding bituminous mastic. The rheological characteristics of bituminous mastics were compared by investigating their engineering performance against rutting, fatigue, and long-term ageing, using a series of sophisticated tests, namely multiple stress creep and recovery (MSCR), linear amplitude sweep (LAS), and ageing index (AI) analysis, respectively. It is inferred that an increase in filler volume concentration in the bituminous mastics leads to its enhancement in resistance against rutting and long-term ageing. More specifically, GL mastics outperformed in terms of rutting and ageing resistance, followed by GP, KS, and SD mastics. Considering fatigue resistance, SD mastics indicated higher fatigue life than the mastics prepared with waste fillers. In terms of economic performance, using a higher amount of fillers in mastics tends to reduce the cost-benefit ratio (C/B). In particular, utilizing GL mastic seems to deliver better engineering performance in a more economical manner, followed by GP, KS, and SD. These inferences were further validated using statistical analysis, confirming the significant influence of filler type and filler content over the analyzed engineering parameters.

## 1. Introduction and research background

Bituminous concrete mix is globally recognized as one of the widely used pavement materials in the surface course of a flexible pavement. It is a heterogeneous composite which primarily includes mineral aggregates, fillers, and bitumen. Fillers are the finest aggregate particles (passing through the No. 200 sieve (75 μm)) within the bituminous composite [1]. Filler, in combination with bitumen, forms bituminous mastic which coats over the aggregates in the bituminous mixes. The physical properties and chemical attributes of filler, along with its quantity in the mastic, modify mastic's viscosity and consistency, thereby influencing the overall

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**Table 1**
A review of past studies on the use of waste fillers in bituminous mixes.

| Reference | Filler Type | Filler-Bitumen Ratio | Properties | | | | |
|---|---|---|---|---|---|---|---|
| | | | Rutting | Fatigue | Ageing | Cost Analysis | Statistical Analysis |
| Cardone et al. [17] | Limestone and Basalt | 1.2 | ✓ | ✓ | × | × | × |
| Motamedi et al. [18] | Limestone | 1.0 | ✓ | ✓ | × | × | × |
| Das and Singh [19] | Basalt, Hydrated lime, and Nano-hydrated lime | 0.6, 0.8, 1.0, and 1.2 | × | ✓ | × | × | ✓ |
| Wei et al. [20] | Steel slag and Limestone | 0.3 | ✓ | ✓ | ✓ | × | × |
| Martinez et al. [21] | Natural limestone, Hydrated lime, Portland cement, Steel slag, and Blast furnace slag | 1.25 | ✓ | ✓ | × | × | × |
| Khateeb et al. [22] | Waste stone, sawdust and Limestone | 0.05, 0.10, 0.20, and 0.30 | ✓ | ✓ | × | × | × |
| Russo et al. [23] | Bottom ash and Limestone | 0.2 and 0.7 | ✓ | × | × | × | × |
| Wei et al. [24] | Iron ore tailing and Limestone | 0.6, 0.8, 1.0, and 1.2 | ✓ | × | × | ✓ | × |
| Varveri et al. [25] | Wigro 60 K, Quartz, Granite, and Bestone | 1.0 | × | × | × | ✓ | × |
| Wang et al. [26] | Hard andesite, Hard basalt, Hard basalt, Soft caliches, Hard dolomite, Soft dolomite, Fly ash Type C, Blast furnace slag, Hard granite, Hard granite, Siliceous gravel quartzite, Soft granite, Soft granite, Hydrated lime, Hard limestone, and Soft limestone | 1.0 | ✓ | × | × | × | ✓ |
| Present Study | Glass Powder, Kota Stone, Glass-Hydrated Lime Composite, Stone Dust | 0.66 – 2.00 | ✓ | ✓ | ✓ | ✓ | ✓ |

performance of bituminous mixes [2–6]. The fillers having higher porosity [7], lower specific gravity [8], and finer particle size [9] improved the rutting resistance of bituminous mastics. Fillers such as hydrated lime that contain strong bases like CaO and $Ca(OH)_2$ also act as antioxidants and antistripping agents. This could led to the enhancement of moisture and ageing resistance of bituminous mastics and mixes [10]. Although, an increase in filler content in the mastic improved its stiffness and rutting resistance, however, an excessive filler may also deteriorate bituminous mixes' fatigue resistance and workability due to the increased brittleness and viscosity of mastics [3,4,11,12]. Hence, it is imperative to analyze the nature and concentration of filler over the engineering properties of bituminous mastics. This need for detailed analysis is becoming more crucial since researchers are now focusing on the sustainable utilization of waste materials like bauxite residue [13], brick dust [14], glass powder [15], and coal fly ash [2] as fillers in bituminous mixes, which exhibit unique traits. Additionally, a recent study [16] has also observed that using composite fillers (a combination of two or more fillers) in bitumen could enhance the performance of bituminous mastics. Hence, intending to further understand the behavior of bituminous mastics, the current study analyzes the influence of bituminous mastic comprising waste materials (Glass Powder (GP) and Kota Stone dust (KS)) and Glass - Hydrated Lime (GL) composite filler. The GP and KS are fine-grained waste products obtained from the glass and dimensional stone industry, where they are produced in a slurry form at the time of cutting and polishing of glass panes and limestone slabs. The rheological behavior of mastics and their resistance towards rutting distress, fatigue cracking, and long-term ageing were analyzed and compared with conventional bituminous mastic prepared with stone dust (SD) filler.

The quantity of filler in the bituminous mastic is expressed in filler-bitumen ratio. The filler-bitumen ratio for any mastic is the ratio of the weight of filler in the bituminous mix and the weight of optimum bitumen content (OBC) of the bituminous mix [1]. This study analyzed the bituminous concrete mixes prepared with GP, KS and SD fillers at four filler content (4%, 5.5%, 7%, and 8.5% (by weight)). Marshall mix design procedure was adopted for finding the OBC of the bituminous mixes. Based on these calculated OBC values, the filler-bitumen ratio of mastics was decided, and mastics were prepared. The details of the mix design and the volumetrics are further elaborated in subsequent sections.

### 1.1. Research significance

The available research on the engineering and economic suitability of bituminous mastics containing waste fillers is limited, and its scope is also constrained. Additionally, the critical characterization of the fillers considered in the present study has not been covered with enough rigor. As per the author's knowledge, none of the studies comprehensively elaborated the laboratory inferences on the rutting, fatigue, ageing, cost, and statistical analysis carried out on bituminous mastics with different waste fillers (as compiled and illustrated in Table 1).

The present study covered a detailed understanding of the engineering and economic suitability of different waste fillers, particularly in bituminous mastics. The rheological properties of mastics were initially assessed at intermediate and higher temperatures using a Dynamic Shear Rheometer (DSR). Subsequently, the resistance of bituminous mastics against rutting, fatigue, and long-term ageing was assessed using Multiple Stress Creep and Recovery (MSCR), Linear Amplitude Sweep (LAS), and Ageing Index (AI) analysis, respectively. This comparative experimental and parametric study addresses both the economic and statistical inferences based on the

**Table 2**
Physical properties of aggregate and bitumen.

| Material | Property | Specification | Results | Requirements |
|---|---|---|---|---|
| Aggregates | Aggregate Impact Value in % | IS:2386 - Part IV[27] | 11.10 | Maximum 24 |
| | Los Angeles Abrasion Value in % | IS:2386 - Part IV[27] | 13.40 | Maximum 30 |
| | Combined Flakiness and Elongation Index | IS: 2386 - Part I[28] | 21.30 | Maximum 35 |
| Bitumen | Viscosity at 60°C in poise | IS 73: 2013[29] | 2692 | 2400–3600 |
| | Penetration Value at 25°C in dmm | | 62 | 50–70 |
| | Softening Point in °C | | 51.5 | Minimum 47 |

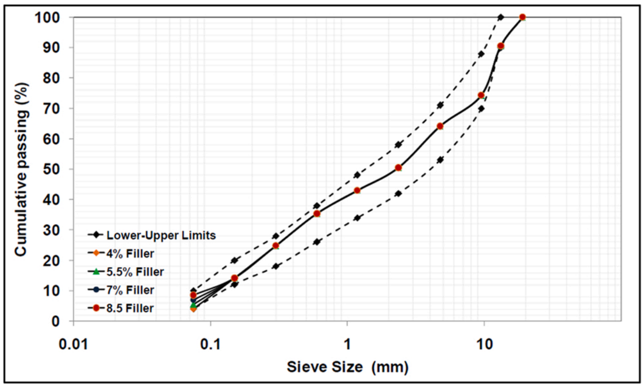


**Fig. 1.** Design aggregate gradation.

rheological test parameters (MSCR and LAS results). This was done to assess the significance of waste fillers for road infrastructure. It is expected that the procedure and analysis conducted in this study would aid in envisaging the influence of different waste fillers (individual and composite) and their desired quantities on the engineering performance of bituminous mastics. Further, it would help the policymakers, stakeholders, contractors, and construction engineers select the optimum filler content for preparing bituminous mixes, considering the cost-benefit ratio.

## 2. Materials and methods

### *2.1. Materials*

This investigation used dolomite aggregates (coarse and fine) and PG76 binder, and their physical properties are stated in Table 2. Fig. 1 presents the adopted aggregate gradation for the preparation of bituminous concrete mix. The waste fillers such as GP and KS were taken from the dump yard of a glass factory and dimensional stone industry located in the Indian cities of Bhopal and Kota, respectively. Similarly, conventional SD and HL were taken from a local supplier in Varanasi, India.

### *2.2. Filler characterization*

Specific gravities of all selected fillers were measured through a pycnometer following the guidelines specified in ASTM D854 [30]. Here specific gravity of fillers refers to their apparent specific gravity, which only includes the volume of aggregate particles in the calculation without including the volume of any capillary or pore filled with water after soaking for 24 h.

The particle size of fillers significantly influences the performance of bituminous mastics. Particle size distribution curves were constructed and analyzed using fineness modulus (FM) and particle mean size (D50).

Morphological analysis was done using scanning electron microscopy (SEM) to characterize the particle shape and surface texture. The photomicrographs of fillers were taken at different resolution levels to evaluate the geometric characteristics of various filler particles. However, the images corresponding to only 5000x magnification were shown here for brevity.

Filler porosity was calculated using the German filler test prescribed by National Asphalt Pavement Association [31]. The German filler test measures the amount of dried filler required to absorb 15 g of hydraulic oil until it loses its cohesion.

The mineralogy of the fillers also affects the interaction of bituminous mastic with the aggregates. Thus, predominant minerals present in the filler composition were identified using X-Ray Diffraction (XRD) technique.

It was emphasized earlier that the harmful clay in filler can expand in the presence of water, forming a barrier to adhesion between filler and bitumen, thus weakening the mix. Therefore, Methylene blue values (MBV) of filler were done to quantify the harmful clay content in fillers. EN 933–9 [32] was followed to analyze the MBV.

Table 3 demonstrates the characterization test results for the selected fillers. Some of the results are presented in Fig. 2 and Fig. 3.

**Table 3**
Characterization properties of waste fillers.

| Filler Property | Glass Powder (GP) | Kota Stone (KS) | Hydrated Lime (HL) | Stone Dust (SD) | Inferences |
|---|---|---|---|---|---|
| Specific gravity | 2.370 | 2.650 | 2.363 | 2.698 | KS and SD have higher specific gravity than GP and HL, thus yielding lower volume within the bituminous composite. |
| Methylene Blue Value (g/kg) | 1.25 | 3.75 | 0.25 | 3.25 | All the selected fillers exhibit lower MBV (<10), which inferred the existence of a lower percentage of harmful clay per unit weight of the material. |
| German filler value (g) | 75 | 97 | 35 | 85 | HL and KS exhibited the lowest and highest porosity/ fractional voids per unit weight, respectively. |
| Fineness modulus | 4.66 | 3.03 | 2.93 | 5.38 | SD and HL were the coarsest and finest filler, respectively. |
| D50(μm) | 19 | 09 | 09 | 21 | |
| Particle shape | Angular | Granulous | Sub-angular | Angular particles | The rough texture of the particles may adversely influence workability and result in high bitumen absorption. |
| Particle texture | Smooth | Rough | Rough | Smooth | |
| Primary Mineralogical Composition (XRD) | Quartz ($SiO_2$) | Calcite ($CaCO_3$), Quartz ($SiO_2$) | Portlandite ($Ca(OH)_2$), Calcite ($CaCO_3$) | Dolomite ($CaMg(CO_3)_2$) ,Quartz ($SiO_2$), Ertixite ($Na_2Si_4O_9$) | It was found that SD and HL filler comprises of dolomite and portlandite, respectively which imparts adequate bitumen adhesion owing to the presence of calcium-based water-insoluble mineral. |

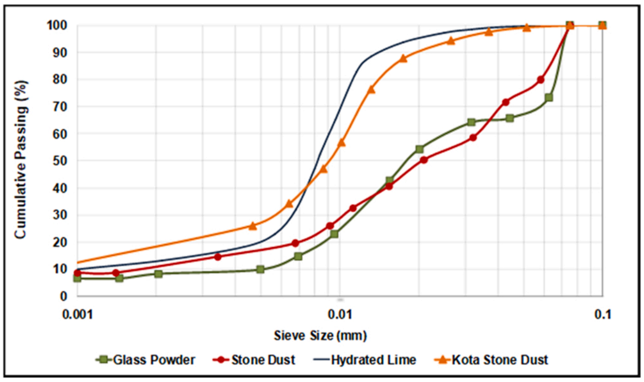


**Fig. 2.** Particle size distribution curves of selected fillers.

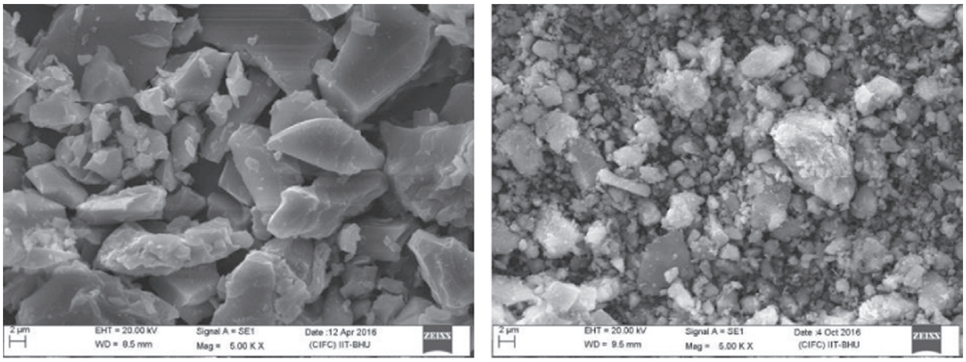
## 2.3. Designing of bituminous concrete mixes

### 2.3.1. Marshall and volumetric properties

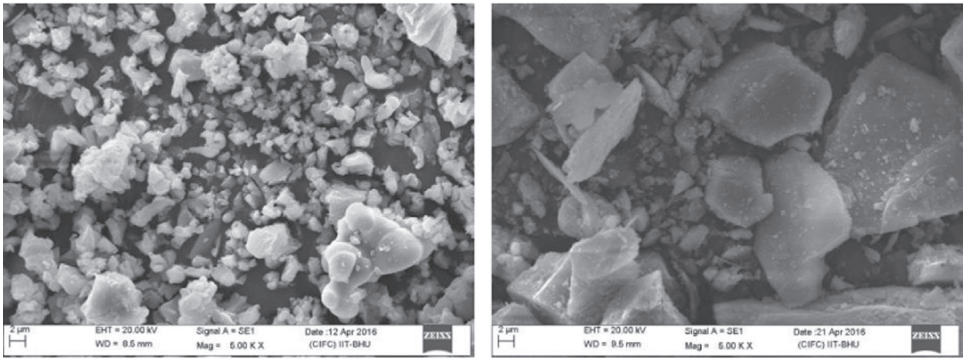
The Marshall mix design method, as specified in MS-2, was followed to measure the optimum bitumen content (OBC) for all bituminous mixes. As per the guidelines, the binder content corresponding to 4% air voids is considered as OBC [1,33]. The mix's aggregate gradation was selected per MoRTH specification, as illustrated in Fig. 1. The filler percentages were varied between 4%, 5.5%, 7%, and 8.5% by the weight of the aggregates in the mix. The increment of filler proportion in the mix was done by reducing the equal proportion of fine aggregates accordingly to satisfy the chosen gradation. The GL filler was designed by taking 2% hydrated lime in the respective filler proportion of the mix (4–8.5%) and assigning the balance part to GP. The 2% of hydrated lime is used in GL filler since it is the maximum permissible limit of HL recommended in Indian pavement design guidelines [1]. The average values of properties such as Marshall stability (MS), flow, voids in mineral aggregates (VMA), and voids filled with bitumen (VFB) have also been determined at OBC to ensure that mixes followed Indian design guidelines. The effective filler-bitumen ratios were calculated as per their individual OBC. These effective filler-bitumen ratios were used to prepare the bituminous mastics corresponding to each mix. The filler volume in each mastic was also determined as per Eq. 1.

$$V_f = \left( \frac{\frac{M_f}{G_f}}{\frac{M_f}{G_f} + \frac{M_b}{G_b}} \right) \times 100 \quad (1)$$

Where, $V_f$ is the volume fraction of filler in mastic (%), $M_f$ and $M_b$ are the mass of filler and bitumen in the mastic, respectively. $G_f$ and $G_b$ are the specific gravities of filler and bitumen, respectively.



(a) Glass Powder (b) Kota Stone



(c) Hydrated Lime (d) Stone Dust

**Fig. 3.** Morphology of selected fillers.

### *2.4. Designing and testing of bituminous mastics*

#### *2.4.1. Preparation and ageing of bituminous mastics*

The bituminous mastics were prepared by blending the bitumen and fillers as per the predetermined filler-bitumen ratio of corresponding bituminous mixes. A mechanical mixer, operated at a speed of 1600 rpm, was used for the blending process. The blending was done for 30 min at a temperature of 160 ± 5°C [23,34–38]. A part of the prepared mastic samples was subjected to short-term aged following ASTM D1754 guidelines [39]. As per the guideline, the bituminous mastics were kept over the revolving plate (5.5 ± 1 rpm) inside the draft oven at a controlled temperature of 163°C for a duration of 5 h. The short-term aged residue samples were then used for rheological testing at a high temperature (60°C). An accelerated performance test, such as the multiple stress creep and recovery (MSCR) test, was also carried out to assess the rutting characteristics of the bituminous mastics in short-term aged conditions.

After evaluating performance at high temperatures, the prepared samples were subjected to long-term ageing and tested at an intermediate temperature (25°C). The long-term ageing of mastics was carried out using the method proposed by Behera et al. [40]. As per the method, the weight of short-term aged bitumen and mastic was determined to make a film thickness of 650 μm over a circular pan (140 mm diameter). Subsequently, the pans were kept in a draft oven at a temperature of 85°C for five days. The sample residue collected after long-term ageing was further tested at 25°C using DSR. In addition, a linear amplitude sweep (LAS) test was conducted to ascertain the resistance of long-term aged residue samples against fatigue cracking.

Rheological Properties of Bituminous Mastics.

The rheological properties (complex shear modulus and phase angle) of bituminous mastics were determined at intermediate temperature (25°C) and high temperatures (46–70°C) by carrying out a frequency sweep test. The test was performed following the AASHTO T315 specification [41], which specified the use of a dynamic shear rheometer (DSR) to assess the viscoelastic characteristics of bituminous mastics. A parallel plate geometry setup was employed with different spindle specifications based on the testing temperatures. A 25 mm diameter spindle with a 1 mm gap was used for testing at high temperatures, whereas an 8 mm diameter spindle having a gap of 2 mm was used for testing at intermediate temperatures. All the rheological tests were carried out under a linear viscoelastic (LVE) regime in a strain-controlled mode. The frequency was varied from 0.1 to 100 rad/s to understand the effect of frequency on the rheological parameters.

#### *2.4.2. Multiple stress creep and recovery (MSCR) test*

The MSCR test was carried out on short-term aged mastics at a temperature range of 46–70 °C. The test was conducted following

**Table 4**
Properties of bituminous mixes and mastics.

| Type of Filler | Filler Content (%) | Properties of Bituminous Mixes | | | | | Properties of Bituminous Mastics | | |
|---|---|---|---|---|---|---|---|---|---|
| | | OBC (%) | VMA (%) | VFB (%) | Marshall Stability (kN) | Flow (mm) | Abbreviations of Mastics | Effective Filler-bitumen ratio of mastic (by mass) | Volume fraction of filler in mastic (%) |
| Stone Dust | 4.0 | 6.20 | 17.02 | 74.22 | 12.22 | 3.43 | SD4 | 0.66 | 19.64 |
| | 5.5 | 5.95 | 16.21 | 74.43 | 13.99 | 3.62 | SD5.5 | 0.96 | 26.23 |
| | 7.0 | 5.38 | 15.31 | 74.79 | 15.96 | 3.50 | SD7 | 1.38 | 33.98 |
| | 8.5 | 5.34 | 14.70 | 72.01 | 16.58 | 3.22 | SD8.5 | 1.76 | 38.91 |
| Glass Powder | 4.0 | 6.03 | 16.51 | 74.85 | 12.98 | 3.38 | GP4 | 0.71 | 20.88 |
| | 5.5 | 5.81 | 15.96 | 73.92 | 13.46 | 3.18 | GP5.5 | 1.04 | 28.55 |
| | 7.0 | 5.48 | 14.85 | 72.97 | 14.93 | 3.37 | GP7 | 1.46 | 35.36 |
| | 8.5 | 5.26 | 14.23 | 72.27 | 14.52 | 2.95 | GP8.5 | 1.87 | 42.20 |
| Kota Stone | 4.0 | 5.96 | 16.83 | 74.79 | 12.65 | 3.37 | KS4 | 0.70 | 23.04 |
| | 5.5 | 5.53 | 15.33 | 72.54 | 14.42 | 3.15 | KS5.5 | 1.06 | 30.48 |
| | 7.0 | 4.98 | 14.27 | 73.84 | 15.60 | 2.95 | KS7 | 1.45 | 38.26 |
| | 8.5 | 4.89 | 14.07 | 72.13 | 16.34 | 2.90 | KS8.5 | 1.82 | 44.86 |
| Glass-Lime | 4.0 | 5.65 | 15.43 | 74.18 | 14.32 | 3.21 | GL4 | 0.77 | 24.53 |
| | 5.5 | 5.38 | 14.62 | 70.79 | 15.04 | 3.06 | GL5.5 | 1.15 | 32.67 |
| | 7.0 | 5.12 | 14.22 | 69.15 | 16.78 | 3.30 | GL7 | 1.60 | 40.30 |
| | 8.5 | 5.05 | 13.92 | 69.33 | 16.10 | 2.88 | GL8.5 | 2.00 | 45.88 |
| Requirements [1] | 4–10 | – | 14.00 (min) | 65–75 | 9.00 (min) | 2–4 | – | – | |

the guidelines specified in AASHTO T350 [42]. As per the specification, the rutting resistance depends on the value of accumulated strain and delayed elasticity. Each sample was tested with ten consecutive cycles at 0.1 kPa and 3.2 kPa stress levels. Each cycle undergoes one-second creep loading and a nine-second recovery period without any loading condition. As a result, two parameters, non-recoverable creep compliance ($J_{nR}$) and percentage recovery (%R), were calculated. Generally, the sample with lower $J_{nR}$ at 3.2 kPa stress indicates higher rutting resistance, whereas %R expresses the extent of elasticity in the mastics.

### 2.4.3. *Linear amplitude sweep (LAS) test*

The fatigue life was evaluated using an accelerated test, i.e., the LAS test. The test was carried out on long-term aged mastics at a temperature of 25 °C following AASHTO TP101 specification [43]. This test is based on the principle of visco-elastic continuum damage (VECD). It estimated the fatigue-resistant ability of mastic by applying cyclic loading at increasing amplitudes to accelerate the damage. The fatigue life ($N_f$) of mastics at several strain amplitudes (γ) is a function of damaged (A) and undamaged parameter (B), as shown in Eq. 2.

$$N_f = A(\gamma)^B \tag{2}$$

These parameters were determined using a two-step process wherein the first step involves a frequency sweep test trailed by an amplitude sweep test. The frequency sweep test (0.2–30 Hz) is carried out under the linear viscoelastic range to determine the undamaged material characteristic (α). The value of α is further used to compute undamaged parameter B ($B = -2\alpha$). The amplitude sweep test is done at a frequency of 10 Hz, with a linearly increased strain amplitude of 0–30%. This step was done to determine the A parameter using the VECD approach.

### 2.4.4. *Long-term ageing resistance*

The effect of ageing on binder and mastics' mechanical properties was assessed by calculating their Ageing Index (AI). AI was calculated for bitumen and mastics based on short-term and long-term aged complex shear modulus (G*), measured at 10 rad/s frequency and 25 and 64°C temperatures using Eq. 3. This parameter determines the rheological implication of ageing in binders and mastics. A higher value of AI signifies higher ageing susceptibility, which is not desirable.

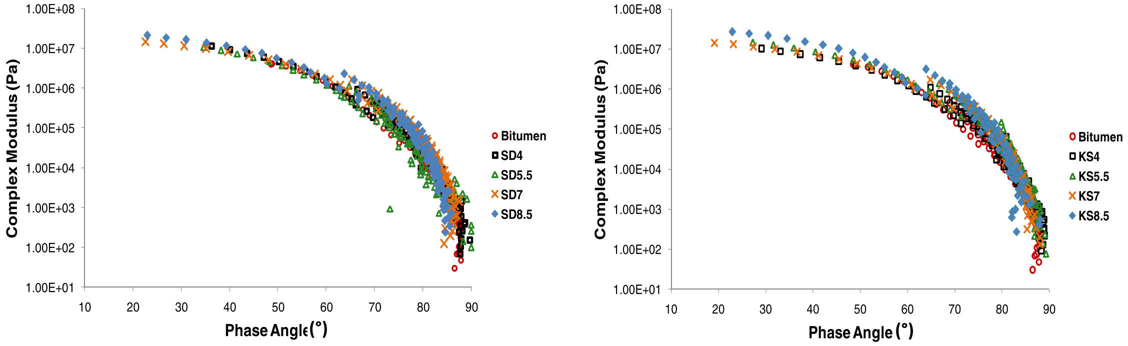
$$AI = \left(\frac{G^*_{LTA}}{G^*_{STA}}\right) \times 100 \tag{3}$$

Where, $G^*_{LTA}$ is the complex shear modulus of mastic subjected to long-term ageing and $G^*_{STA}$ is the complex shear modulus of mastic subjected to short-term ageing.

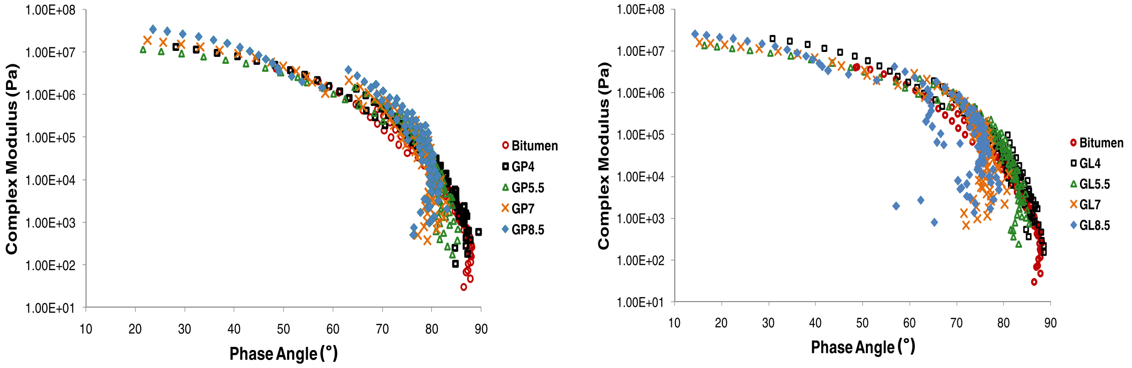
## 3. Results and discussion

### 3.1. *Marshall and volumetric properties*

In general, it was found that almost all the prepared bituminous mixtures passed the specified criteria of strength and volumetrics



(a) Black diagrams of SD mastics (b) Black diagrams of KS mastics



(c) Black diagrams of GP mastics (d) Black diagrams of GL mastics

**Fig. 4.** Black diagrams of bitumen and various bituminous mastics.

given in Indian standards (Table 4). Therefore, these waste materials can be used as filler material in a bituminous composite [1]. It has to be noted that the mixes prepared with GL at 8.5% filler content exhibit slightly lower VMA (13.9%) than the specified requirement (14%). The effective filler-bitumen ratio (by mass) for each mix was calculated (based on OBC and filler content), which was further used to prepare mastics corresponding to the mixes. The filler volume fraction in each mastic is calculated as per Eq. 1.

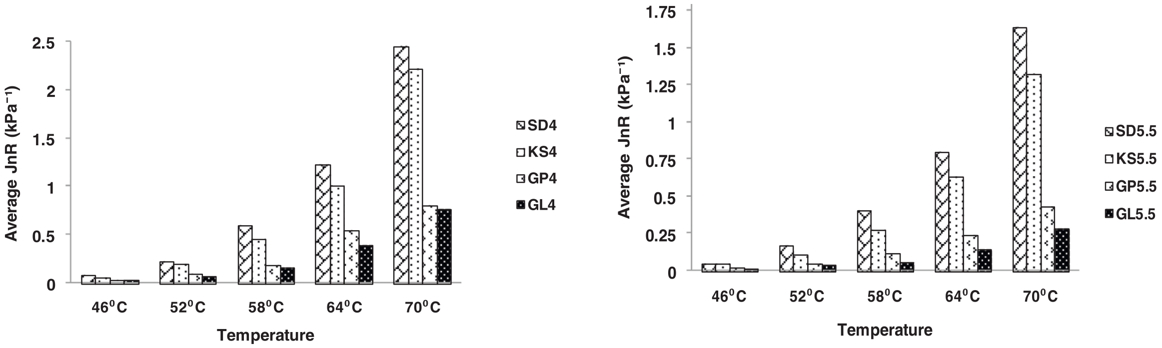
It can be observed that the MS of mixes increased with the filler content, which might be due to the toughening of bituminous mastic due to an increase in filler content and a corresponding decrease in OBC. However, a slight drop was observed in MS of GP and GL prepared with 8.5% filler content. The probable reason behind the reduction in MS is the adhesion loss in mastic due to higher silica content in filler composition and lower OBC. In general, it was found that GL mixes yield higher MS, followed by SD and GP mixes. The reason behind this behavior is the strengthening of bituminous mastic owing to the fineness of HL. However, the bituminous mixes comprising SD and KS at 8.5% filler content indicate the highest stabilities, followed by GL and GP mixes. This may be attributed to the high silica content in the glass, which lowers the adhesion in GP and GL mixes. Flow values of all mixes were found to be under the specified range. This verified that the application of waste fillers did not affect the plasticity and brittleness of the mix.

A reduction in OBC was evident with the increase in the quantity of filler, irrespective of their type (Table 4). This may be attributed to the bitumen "extender" characteristics of fillers, which signifies that a lower amount of bitumen is required with a higher quantity of filler in order to prepare the same amount of bituminous mastic for lubrication of aggregates in the bituminous mix [12,44]. Mixes containing KS and GL fillers displayed the highest tendency to act as bitumen extenders; thus, their mixes exhibited the lowest OBC. GP mixes also have lower OBC than SD mixes, which might be due to GP's lower specific gravity, enabling it to occupy a larger volume in the mix at the same weight proportion, thus leaving a lower volume for binder accumulation [45].

### 3.2. Discussion on rheological properties

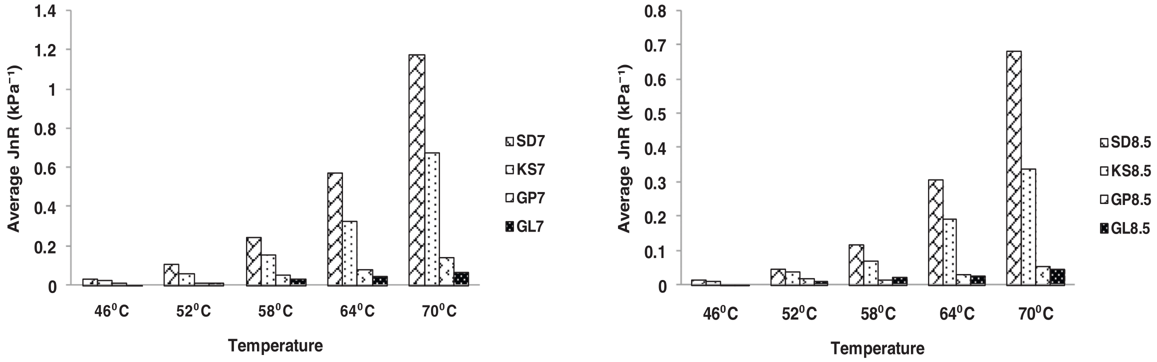
The rheological properties of short-term aged bitumen and mastics were determined using a frequency sweep conducted at intermediate (25°C) and high temperatures (46–70°C). The testing is done at the strains below the mastics' linear viscoelastic (LVE) limits. The black diagrams of various were plotted to analyze the variation amongst the rheological properties.

Several researchers [46–48] defined the black diagram as the plot of complex shear modulus versus the phase angle used to analyze the effect of ageing and the modification in bitumen and mastics. Black diagrams of various mastics were plotted in Fig. 4. The increase in filler concentration tends to shift the black curve upwards and left. This signified the increase in the complex shear modulus and decrease in phase angle with the increase in filler concentration in the mastic. The mastics prepared with GL displayed the highest complex shear modulus, followed by GP, KS, and SD. Also, GL mastic displayed the lowest phase angle, followed by GP, KS, and SD. The



(a) $J_{nR}$ values of mastics corresponding to 4% filler at 3.2 kPa stress

(b) $J_{nR}$ values of mastics corresponding to 5.5% filler at 3.2 kPa stress



(c) $J_{nR}$ values of mastics corresponding to 7% filler at 3.2 kPa stress

(d) $J_{nR}$ values of mastics corresponding to 8.5% filler at 3.2 kPa stress

**Fig. 5.** $J_{nR}$ values of bitumen and various bituminous mastics at 3.2 kPa stress.

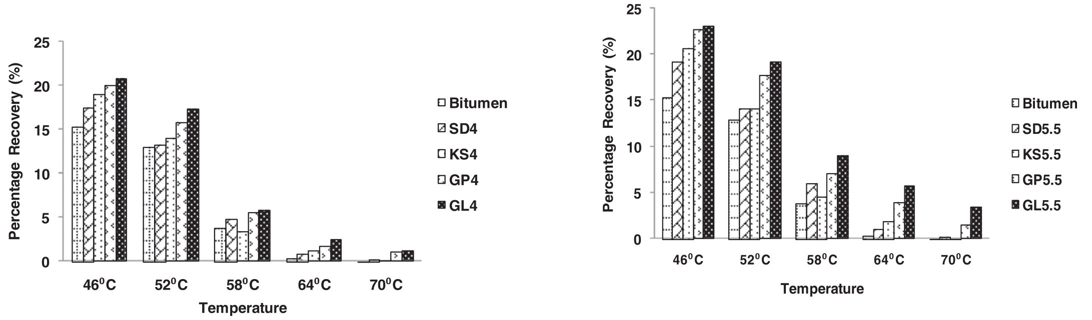
higher complex modulus in GL and GP mastics might be due to the reinforcement provided by filler particles due to their relatively higher volume concentration in these mastics [4,5]. Apart from the volumetric reinforcement, the higher complex modulus of GP and GL mastic might also be due to the angular nature of GP, which resulted in better interlocking amongst particles [6].

The black diagram of bitumen, SD, and KS mastics is smooth, signifying a consistent relationship between the complex modulus and phase angle of these mastics throughout the frequencies and temperature. This trend is expected since the analysis was performed in the linear viscoelastic region when the loading frequency and temperatures (time-temperature superposition) interdependency exists. However, black diagrams of GL and GP mastics don't exhibit simple smooth curves at higher filler concentrations (7% and 8.5%), especially at higher temperatures and lower frequencies. Previous studies [2,4] have theorized that stiffness in the mastic increases linearly up to a specific filler volume known as critical filler volume concentration. The further addition of the filler volume led to a non-linear and rapid increase in complex shear modulus. At this concentration, the filler particles get close enough and cause interaction, which exhibits a dramatic increase in the complex modulus [4]. GL and GP mastics especially experienced a higher increase in complex modulus and a higher drop in phase angle at higher filler concentrations (7% and 8.5%). Despite GP and HL having almost similar specific gravities, GL displayed a higher complex shear modulus due to the higher interaction of HL. This is attributed to its relatively finer size and calcium-based mineralogical composition, indicating strong interaction with bitumen.

### *3.3. Discussion on rutting resistance*

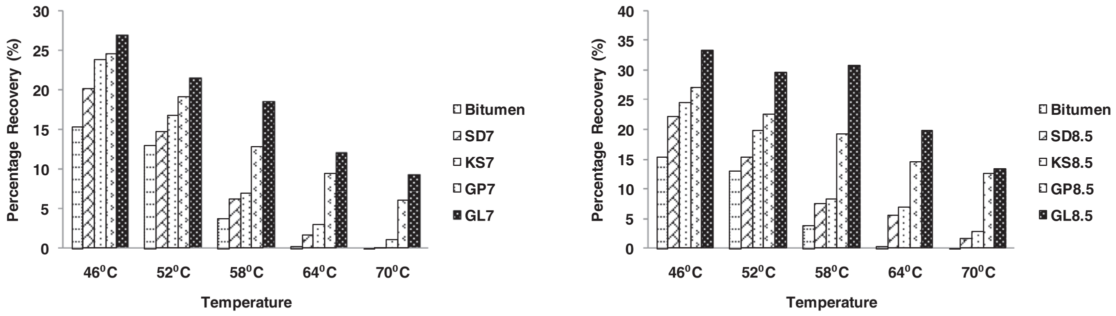
The $J_{nR}$ and %R values of bitumen and mastics at different temperatures and 3.2 kPa stress are shown in Figs. 5 and 6. In the case of both bitumen and mastics, $J_{nR}$ values increased with the increase in temperature, which is expected since bitumen behaves as a viscous liquid at higher temperatures and exhibits higher rutting. Adding filler volume decreases $J_{nR}$ values and increases bituminous mastics' rutting resistance. GL mastics displayed the highest rutting resistance, followed by GP, KS, and SD. Percentage recovery (%R) is used to characterize the elasticity of the bitumen and mastics (Fig. 6). The %R value of bitumen and mastics decreases with the increase in temperature. At a 3.2 kPa stress level, the bitumen displayed negligible recovery at higher temperatures. The inclusion of filler volume imparted the elasticity in the mastics, and hence %R was found to increase with the filler bitumen ratio. Similar to the $J_{nR}$ values, the % R values were higher for GL mastics, followed by GP, KS, and SD mastics.

The $J_{nR}$, diff values of bitumen and various mastics are reported in Table 5, which is used to assess their stress sensitivity. The



(a) %R values of mastics corresponding to 4% filler at 3.2 kPa stress

(b) %R values of mastics corresponding to 5.5% filler at 3.2 kPa stress



(c) %R values of mastics corresponding to 7% filler at 3.2 kPa stress

(d) %R values of mastics corresponding to 8.5% filler at 3.2 kPa stress

**Fig. 6.** %R values of bitumen and various bituminous mastics at 3.2 kPa stress.

**Table 5**
Average $J_{nR}$ diff values of bitumen and various bituminous mastics at 3.2 kPa stress.

| Type of Mastic | Average $J_{nR}$, diff values (%) | | | | |
|---|---|---|---|---|---|
| | 46°C | 52°C | 58°C | 64°C | 70°C |
| Bitumen | 13.76 | 16.00 | 20.43 | 26.18 | 33.36 |
| SD 4 | 10.51 | 8.96 | 16.35 | 13.88 | 24.28 |
| KS 4 | 7.43 | 13.53 | 12.16 | 17.49 | 18.89 |
| GP 4 | 3.76 | 5.47 | 6.68 | 13.94 | 15.75 |
| GL 4 | 6.67 | 8.90 | 1.74 | 20.23 | 8.80 |
| SD 5.5 | 5.86 | 12.01 | 8.54 | 12.76 | 15.31 |
| KS 5.5 | 6.52 | 1.76 | 7.00 | 15.42 | 20.58 |
| GP 5.5 | 12.89 | 14.50 | 14.73 | 18.77 | 16.33 |
| GL 5.5 | 4.61 | 17.21 | 24.04 | 21.14 | 24.99 |
| SD 7 | 3.57 | 5.53 | 8.44 | 14.36 | 21.85 |
| KS 7 | 4.25 | 7.20 | 4.52 | 10.28 | 21.98 |
| GP 7 | 9.43 | 12.66 | 14.29 | 8.10 | 8.49 |
| GL 7 | 1.54 | 1.78 | 9.52 | 8.99 | 2.45 |
| SD 8.5 | 1.71 | 4.26 | 8.14 | 14.68 | 27.96 |
| KS 8.5 | 1.57 | 5.65 | 7.37 | 9.78 | 16.56 |
| GP 8.5 | 4.65 | 5.49 | 15.79 | 1.22 | 0.77 |

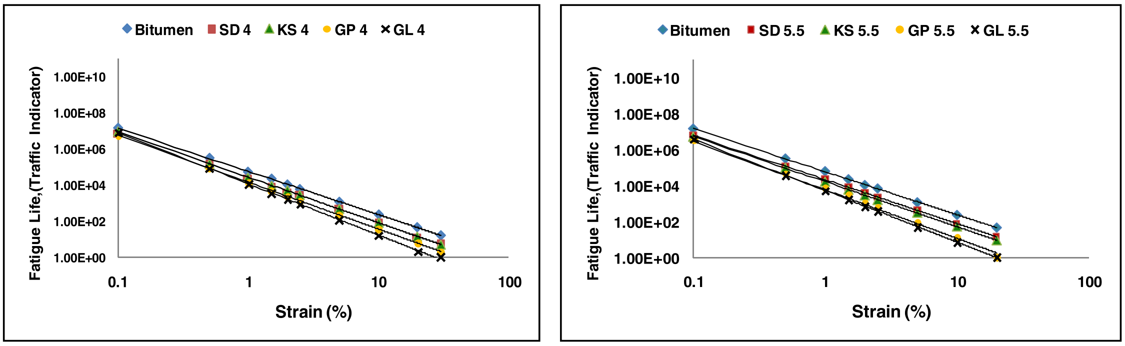
continuous increase in $J_{nR}$, diff values with the temperature reflected the increase in stress sensitivity of the bitumen and mastics with the increase in temperature. However, at higher temperatures, GP8.5, GL7, and GL8.5 mastics deviated from this trend. This might be due to the higher filler volume concentration in these mastics, which inhibit the viscous behavior of bitumen at a higher temperature. This phenomenon needs further exploration and can be a part of a future study.

### *3.4. Discussion on fatigue resistance*

The fatigue damage parameters and fatigue life equation obtained after the damage analysis of bitumen and mastics are shown in Table 6. The fatigue life of bitumen and mastics depend on the parameters ‘α’ and ‘A’. A higher value of ‘A′ and a lower value of ‘α’ is

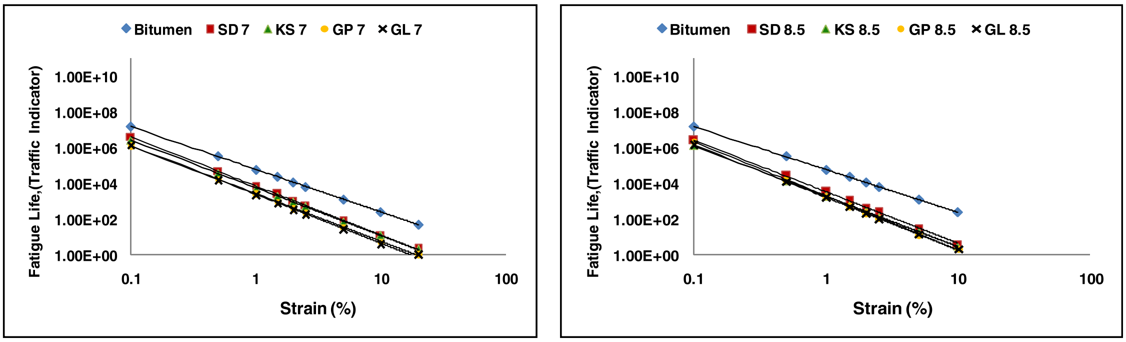
**Table 6**
Fatigue damage potential and corresponding fatigue life.

| Type of mastic | α | A | B | $N_f = A(\gamma_{max})^B$ |
|---|---|---|---|---|
| Bitumen | 1.200 | 57830 | -2.401 | $N_f = 57830(\gamma_{max})^{-2.401}$ |
| SD 4 | 1.257 | 23700 | -2.514 | $N_f = 23700(\gamma_{max})^{-2.514}$ |
| GP 4 | 1.301 | 13900 | -2.602 | $N_f = 13900(\gamma_{max})^{-2.602}$ |
| KS 4 | 1.263 | 27990 | -2.526 | $N_f = 27990(\gamma_{max})^{-2.526}$ |
| GL 4 | 1.427 | 11690 | -2.854 | $N_f = 11690(\gamma_{max})^{-2.854}$ |
| SD 5.5 | 1.231 | 20580 | -2.462 | $N_f = 20580(\gamma_{max})^{-2.462}$ |
| GP 5.5 | 1.363 | 6754 | -2.725 | $N_f = 6754(\gamma_{max})^{-2.725}$ |
| KS 5.5 | 1.256 | 16500 | -2.513 | $N_f = 16500(\gamma_{max})^{-2.513}$ |
| GL 5.5 | 1.436 | 4958 | -2.872 | $N_f = 4958(\gamma_{max})^{-2.872}$ |
| SD 7 | 1.383 | 7374 | -2.766 | $N_f = 7374(\gamma_{max})^{-2.766}$ |
| GP 7 | 1.348 | 2560 | -2.695 | $N_f = 2560(\gamma_{max})^{-2.695}$ |
| KS 7 | 1.336 | 5511 | -2.671 | $N_f = 5511(\gamma_{max})^{-2.671}$ |
| GL 7 | 1.390 | 2289 | -2.780 | $N_f = 2289(\gamma_{max})^{-2.780}$ |
| SD 8.5 | 1.448 | 3261 | -2.896 | $N_f = 3261(\gamma_{max})^{-2.896}$ |
| GP 8.5 | 1.537 | 1852 | -3.073 | $N_f = 1852(\gamma_{max})^{-3.073}$ |
| KS 8.5 | 1.418 | 1837 | -2.836 | $N_f = 1837(\gamma_{max})^{-2.836}$ |
| GL 8.5 | 1.484 | 1606 | -2.968 | $N_f = 1606(\gamma_{max})^{-2.968}$ |



(a) Fatigue life of mastics corresponding to 4% filler at different strain levels

(b) Fatigue life of mastics corresponding to 5.5% filler at different strain levels



(c) Fatigue life of mastics corresponding to 7% filler at different strain levels

(d) Fatigue life of mastics corresponding to 8.5% filler at different strain levels

**Fig. 7.** Fatigue life of values of bitumen and various bituminous mastics at different strain amplitudes.

necessary to ensure superior resistance to fatigue damage. The fatigue life of bitumen and mastics are shown in Fig. 7. The bitumen displayed the highest value of 'A′ and lowest value of 'α' and exhibited the highest fatigue life at all strain levels. In general, the increase in filler content increases 'α' and decreases 'A′ parameter, irrespective of mastic type. The difference in fatigue life of mastics is not predominant at lower strain levels; however, at higher strain levels, the difference in fatigue life is noticeable, especially in the case of mastic corresponding lower filler concentration (4% and 5.5%).

The SD mastics indicated the highest fatigue life, followed by KS, GP, and GL mastics, irrespective of the strain levels. It was evident

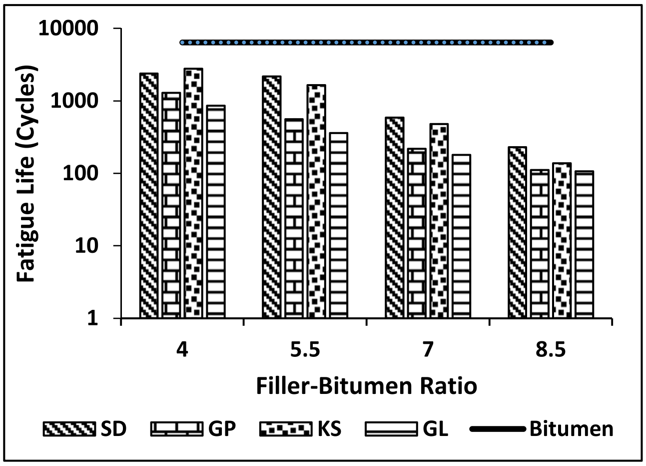


**Fig. 8.** Fatigue life of bitumen and various mastics at 2.5% Strain.

**Table 7**
Complex shear modulus at different ageing conditions and test temperatures.

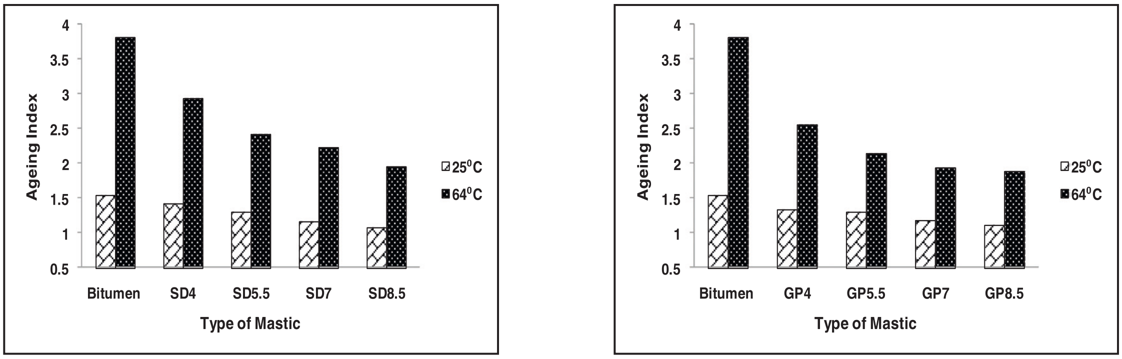
| Complex shear modulus of bitumen and mastics (kPa) | | | | |
|---|---|---|---|---|
| Type of conditioning | Short-term ageing | | Long-term ageing | |
| Testing temperature | 25°C | 64°C | 25°C | 64°C |
| Type of mastic | | | | |
| Bitumen | 1129 | 5.76 | 1738 | 22.07 |
| SD 4 | 1562 | 12.98 | 2334 | 38.16 |
| SD 5.5 | 2971 | 16.42 | 3892 | 39.74 |
| SD 7 | 4530 | 19.81 | 5300 | 44.17 |
| SD 8.5 | 8034 | 31.23 | 8757 | 61.52 |
| GP 4 | 3259 | 18.93 | 4399 | 48.65 |
| GP 5.5 | 4778 | 23.52 | 6211 | 50.56 |
| GP 7 | 8002 | 34.33 | 9442 | 66.94 |
| GP 8.5 | 11672 | 53.32 | 12956 | 100.77 |
| KS 4 | 2559 | 15.75 | 3582 | 46.93 |
| KS 5.5 | 3964 | 19.87 | 4916 | 48.48 |
| KS 7 | 5312 | 26.00 | 6746 | 49.92 |
| KS 8.5 | 10848 | 39.98 | 10956 | 69.16 |
| GL 4 | 4356 | 23.10 | 5576 | 51.05 |
| GL 5.5 | 8991 | 30.55 | 10429 | 60.49 |
| GL 7 | 11252 | 45.45 | 12602 | 75.01 |
| GL 8.5 | 13335 | 62.16 | 14402 | 101.70 |

that the mastics with higher filler volume content underwent brittle failure at higher strain amplitude. This can also be observed by analyzing the slope between the fatigue life and strain amplitude (Fig. 7). The fatigue life of GL and GP mastics decreased steeply at higher strain levels (typically after 2.5%), which suggested their higher strain susceptibility. However, it can also be seen that mastics prepared at higher filler levels (7% and 8.5%) exhibited the same rate of decrease in fatigue life, as shown in Fig. 7. It can be implied that the strain susceptibility of mastics decreased for those with higher filler volume. The fatigue life of mastics was compared at 2.5% of strain level using the relationship given in Table 6 and Fig. 8.

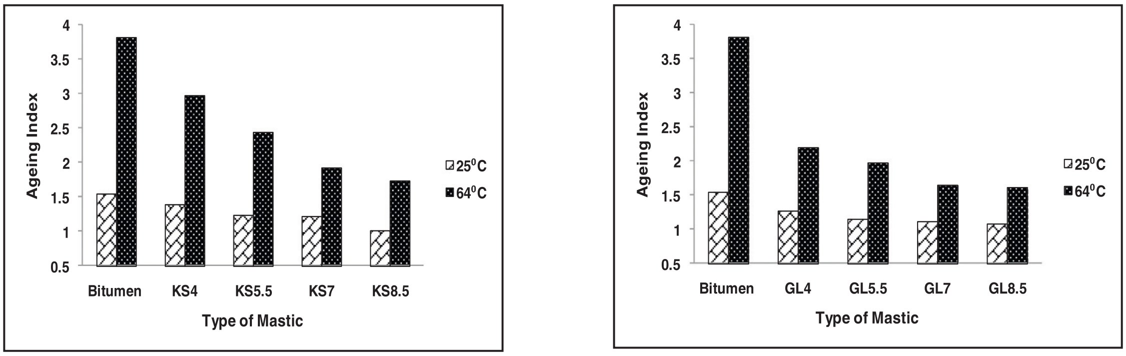
### *3.5. Discussion on long term ageing resistance*

The G* values of the bitumen and mastics at both temperatures are shown in Table 7. It can be seen that ageing tends to increase the G* of both bitumen and mastics. This increase in the stiffening is due to the oxidation of lighter components of bitumen (saturates and aromatics) to the heavier fractions (resins and asphaltenes) [49]. This resulted in the transformation of the visco-elasticity of bitumen to elasticity which increased G* values. Hence the AI of bitumen and mastics can't be lower than unity.

The AI of bitumen and mastics are shown in Fig. 9. It can be seen that bitumen exhibited higher age hardening at both temperatures than the mastics and has higher AI. In addition, the age hardening of the mastics was found to reduce with the increase in filler concentration at both temperatures. The ageing of the mastic depends not only on the fillers' physical characteristics but also on their molecular interaction with the bitumen. The increase in the filler volume fraction in the mastic with the simultaneous decrease in bitumen volume fraction tends to decelerate the age hardening of the bitumen in the mastic. The presence of the fillers in the mastic



(a) AI of SD mastics at 25 and 64°C (b) AI of GP mastics at 25 and 64°C



(c) AI of KS mastics at 25 and 64°C (d) AI of GL mastics at 25 and 64°C

**Fig. 9.** AI of bitumen and various bituminous mastics at 25 and 64°C.

imparts impermeability to the oxygen diffusion, which reduces the oxidation of bitumen. As the filler volume fraction increases in the mastic, the oxygen molecules are required to take a more tortuous path in the bitumen, which inhibits bitumen oxidation and hinders the rise in its stiffness [50].

The mastics prepared with GL displayed the lowest AI and exhibited lower sensitivity to ageing followed by GP, KS, and SD mastics. GL mastics have the highest filler volume fraction and thus prevent oxygen diffusion and maintain the mastic's softening. Although GP mastics have a similar volume fraction, it indicates higher AI than GL. This might be because GL consists of hydrated lime, which is also widely recognized to display anti-ageing bitumen due to the acid-base reaction between the polar molecules of the bitumen and the hydrated lime surface [10,51]. Thus, the additional decrease in the AI for GL mastics might be due to the addition of filler bitumen interaction between hydrated lime and bitumen [52]. It is also interesting to notice that despite having a relatively lower filler volume fraction, KS 8.5 mastic displayed lower AI than GP 8.5. This might be due to the alkaline nature of KS, which interacts well with the bitumen due to its acidic nature and prevents bitumen oxidation [51]. The ageing susceptibility of bituminous mastics accelerates with the increase in testing temperatures, and AI at 64°C was always higher than that at 25°C. Mastics tested at 64°C displayed much higher fluidity than the mastics at 25°C. This might have resulted in relatively free movement of filler in the mastic, resulting in higher filler-filler and filler bitumen interaction, which may increase their ageing susceptibility. This aspect needs to be explored further in future studies.

### 3.6. *Cost benefit analysis*

The inferences of the present study support the application of waste fillers to achieve desirable/appreciable performance. However, there is a need to adjudicate the change in the cost-benefit ratio (C/B) for their direct implementation of road infrastructure. Thus, a simple approach proposed in past literature [34,35] was adopted to analyze the C/B for the bituminous mixtures based on their performance at the mastic level. To calculate the C/B ratio, the cost of materials such as coarse aggregate, fine aggregate, stone dust and bitumen were taken from Central Public Work Department (CPWD), India [53]. It should be noted that the cost of waste fillers was assumed to be zero, as it was directly obtained from the dump yards. However, the processing or laboring charge of waste fillers was taken into account during the final calculation. It was taken as 0.5% of the total cost of material, as per the suggestion reported in a past study. In the present study, the material cost, required to construct a 1 kilometer of 2 lane pavement surface course, was determined. The cost analysis carried out in this study does not incorporate the expenditure incurred for transportation, workmanship, and machinery, as the construction technique is the same for conventional and waste filler-inclusive bituminous pavements. After preparing the data inventory, the procedure demonstrated in a previous study [54] was adopted to calculate the construction cost of surface

**Table 8**
Quantity of ingredients and cost analysis of various bituminous mixes.

| Bituminous Mix | Surface course thickness (mm) | OBC (% of total weight of mixes) | Bitumen quantity (ton/km) | Coarse aggregate quantity (m3/km) | Fine aggregate quantity (m3/km) | Stone dust quantity (m3/km) | Waste filler quantity (m3/km) | Hydrated lime quantity (ton/km) | Cost of material (INR/km) | Cost of processing (0.5% of material cost) (INR/km) | Final cost (INR/km) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material Rate [53] | | | INR 39570/ton | INR 1350/m3 | INR 1350/m3 | INR 1400/m3 | 0 | INR 2900/ton | | | |
| SD 4 | 57 | 6.20 | 64.09 | 123.11 | 192.73 | 13.42 | 0 | 0 | 29,96,115 | 0 | 29,81,081 |
| SD 5.5 | 50 | 5.95 | 54.12 | 108.94 | 166.14 | 16.33 | 0 | 0 | 25,35,602 | 0 | 25,35,602 |
| SD 7 | 46 | 5.38 | 44.91 | 101.28 | 150.36 | 19.33 | 0 | 0 | 21,43,901 | 0 | 21,43,901 |
| SD 8.5 | 45 | 5.34 | 43.82 | 99.65 | 143.90 | 23.09 | 0 | 0 | 20,95,111 | 0 | 20,95,111 |
| GP 4 | 54 | 6.03 | 58.87 | 116.72 | 182.73 | 0 | 14.49 | 0 | 27,33,731 | 13,669 | 27,47,400 |
| GP 5.5 | 49 | 5.81 | 51.43 | 106.37 | 162.22 | 0 | 18.16 | 0 | 23,97,847 | 11,989 | 24,09,836 |
| GP 7 | 45 | 5.48 | 44.58 | 98.48 | 146.20 | 0 | 21.39 | 0 | 20,94,322 | 10,472 | 21,04,794 |
| GP 8.5 | 44 | 5.26 | 41.86 | 96.82 | 139.81 | 0 | 25.54 | 0 | 19,75,908 | 9880 | 19,85,788 |
| KS 4 | 55 | 5.96 | 59.22 | 118.99 | 186.28 | 0 | 13.21 | 0 | 27,55,416 | 13,777 | 27,69,193 |
| KS 5.5 | 48 | 5.53 | 48.53 | 106.19 | 161.94 | 0 | 16.21 | 0 | 22,83,541 | 11,418 | 22,94,959 |
| KS 7 | 44 | 4.98 | 39.86 | 97.97 | 145.44 | 0 | 19.03 | 0 | 19,05,680 | 9528 | 19,15,208 |
| KS 8.5 | 43 | 4.89 | 38.21 | 95.84 | 138.40 | 0 | 22.61 | 0 | 18,28,182 | 9141 | 18,37,323 |
| GL 4 | 50 | 5.65 | 51.31 | 109.51 | 171.44 | 0 | 6.80 | 16.11 | 24,56,272 | 12,281 | 24,68,553 |
| GL 5.5 | 47 | 5.38 | 45.96 | 103.65 | 158.07 | 0 | 11.26 | 15.25 | 22,16,271 | 11,081 | 22,27,352 |
| GL 7 | 44 | 5.12 | 40.80 | 97.26 | 144.38 | 0 | 15.09 | 14.31 | 19,82,291 | 9911 | 19,92,202 |
| GL 8.5 | 42 | 5.05 | 38.34 | 92.80 | 134.00 | 0 | 18.72 | 13.65 | 18,62,926 | 9315 | 18,72,241 |

**Table 9**
Actual and normalizes values of various bituminous mastics.

| Mastics | %R | $J_{nR}$ | NV-%R | NV-$J_{nR}$ | A | B | NV-A | NV-B |
|---|---|---|---|---|---|---|---|---|
| SD 4 | 0.78 | 1.23 | 0.04 | 1.00 | 23700 | 2.51 | 0.85 | 0.818093 |
| SD 5.5 | 0.94 | 0.80 | 0.05 | 0.65 | 20580 | 2.46 | 0.74 | 0.801171 |
| SD 7 | 1.70 | 0.57 | 0.09 | 0.46 | 7374 | 2.77 | 0.26 | 0.900098 |
| SD 8.5 | 5.45 | 0.31 | 0.27 | 0.25 | 3261 | 2.90 | 0.12 | 0.942402 |
| GP 4 | 1.72 | 0.55 | 0.09 | 0.44 | 13900 | 2.60 | 0.50 | 0.84673 |
| GP 5.5 | 3.91 | 0.24 | 0.20 | 0.20 | 6754 | 2.73 | 0.24 | 0.886756 |
| GP 7 | 9.47 | 0.08 | 0.48 | 0.07 | 2560 | 2.70 | 0.09 | 0.876993 |
| GP 8.5 | 14.55 | 0.03 | 0.73 | 0.03 | 1852 | 3.07 | 0.07 | 1 |
| KS 4 | 1.10 | 1.02 | 0.06 | 0.83 | 27990 | 2.53 | 1.00 | 0.821998 |
| KS 5.5 | 1.82 | 0.64 | 0.09 | 0.52 | 16500 | 2.51 | 0.59 | 0.817768 |
| KS 7 | 2.99 | 0.33 | 0.15 | 0.27 | 5511 | 2.67 | 0.20 | 0.869183 |
| KS 8.5 | 6.94 | 0.19 | 0.35 | 0.16 | 1837 | 2.84 | 0.07 | 0.922877 |
| GL 4 | 2.47 | 0.39 | 0.12 | 0.32 | 11690 | 2.85 | 0.42 | 0.928734 |
| GL 5.5 | 5.77 | 0.15 | 0.29 | 0.12 | 4958 | 2.87 | 0.18 | 0.934592 |
| GL 7 | 12.11 | 0.05 | 0.61 | 0.04 | 2289 | 2.78 | 0.08 | 0.904653 |
| GL 8.5 | 19.88 | 0.02 | 1.00 | 0.02 | 1606 | 2.97 | 0.06 | 0.965831 |
| HM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 10**
Average benefit obtained using waste fillers at different filler contents.

| Mastics | %R/$J_{nR}$ | Benefit 1 (%R/$J_{nR}$) | A/B | Benefit 2 (A/B) | Average benefit |
|---|---|---|---|---|---|
| SD 4 | 0.04 | 1.00 | 1.04 | 1.00 | 1.00 |
| SD 5.5 | 0.07 | 1.85 | 0.92 | 0.89 | 1.37 |
| SD 7 | 0.18 | 4.69 | 0.29 | 0.28 | 2.49 |
| SD 8.5 | 1.10 | 28.16 | 0.12 | 0.12 | 14.14 |
| GP 4 | 0.19 | 4.96 | 0.59 | 0.57 | 2.76 |
| GP 5.5 | 0.99 | 25.34 | 0.27 | 0.26 | 12.80 |
| GP 7 | 7.22 | 184.10 | 0.10 | 0.10 | 92.10 |
| GP 8.5 | 27.29 | 695.60 | 0.07 | 0.06 | 347.83 |
| KS 4 | 0.07 | 1.71 | 1.22 | 1.18 | 1.44 |
| KS 5.5 | 0.18 | 4.49 | 0.72 | 0.70 | 2.59 |
| KS 7 | 0.57 | 14.42 | 0.23 | 0.22 | 7.32 |
| KS 8.5 | 2.25 | 57.23 | 0.07 | 0.07 | 28.65 |
| GL 4 | 0.39 | 10.01 | 0.45 | 0.43 | 5.22 |
| GL 5.5 | 2.40 | 61.28 | 0.19 | 0.18 | 30.73 |
| GL 7 | 15.13 | 385.58 | 0.09 | 0.09 | 192.83 |
| GL 8.5 | 51.77 | 1319.58 | 0.06 | 0.06 | 659.82 |

courses prepared with different fillers. Azzam and Al-Ghazawi [55] have suggested a similar procedure for comparing the cost of bituminous mixes, prepared with standard and waste materials. The surface layer thickness and material composition, required for various bituminous mixtures were determined through a mechanistic-empirical approach, specified in IRC 37 [56]. A similar approach/protocol was detailed/followed in a previous study conducted by the authors [54] for other waste filler-inclusive bituminous mixtures. Hence, the procedure has not been detailed here for brevity. The cost comparison was done by taking a conventional bituminous mixture prepared with stone dust at 4% filler content (SD 4).

Table 8 shows the cost of construction corresponding to different bituminous mixtures. In the case of the SD mix, the increase in SD in the mix from 4% to 8.5% has resulted in a cost reduction of up to 30%. GL mixes were found to be the most economical at lower filler contents (4% and 5.5%), followed by KS, GP, and SD mixes. On the other hand, KS mixes exhibited the lowest material cost at higher filler contents (7% and 8.5%), followed by GL, GP, and SD mixes. Amongst all mixes, KS 8.5 was found to be the most economical, which displayed significant savings of about 39% compared to the conventional SD 4 mix. Since bitumen is the most expensive ingredient, the cost reduction in different mixes was attributed to the saving in bitumen consumption.

In general, a cost-effective bituminous mixture does not necessarily deliver favorable performance. Thus, a simple cost framework proposed by [57,58] was applied to find the best candidate in terms of lower cost and superior performance. As different rheological performance tests, such as MSCR for rutting and LAS for fatigue, were carried out, the output of the same tests can be used to assess the C/B ratio. %R and $J_{nR}$ from MSCR were used to ascertain the benefit at 64 °C (where rutting is more prevalent). In contrast, LAS test parameters such as A and B were studied to calculate the benefit at 25 °C (prevalent fatigue temperature). Two ratios, i.e., %R/$J_{nR}$ and A/B, were determined to understand the benefit of different bituminous mastics. The high values of these ratios would offer comparatively better rutting and fatigue performance. As these performance parameters have different units and ranges of magnitudes, data normalization was done before the analysis. Eq. 4 was used to evaluate the normalized value (NV) of the MSCR and LAS test data. In general, the normalized value ranges from 0 to 1. However, the use of 0 in the denominator exhibit undefined values. To overcome this issue, a hypothetical bituminous mastic (HM) was defined with 0 value corresponding to different performance parameters such as

**Table 11**
Cost benefit ratio and corresponding rank.

| Mastics | Cost per km | Cost ratio (C) | Benefit ratio (B) | C/B | Rank (Cost) | Rank (C/B) |
|---|---|---|---|---|---|---|
| SD 4 | ₹ 29,81,081.00 | 1.00 | 1.00 | 1.00 | 16 | 16 |
| SD 5.5 | ₹ 25,35,602.00 | 0.85 | 1.37 | 0.62 | 13 | 14 |
| SD 7 | ₹ 21,43,901.00 | 0.72 | 2.49 | 0.29 | 8 | 11 |
| SD 8.5 | ₹ 20,95,111.00 | 0.70 | 14.14 | 0.05 | 6 | 7 |
| GP 4 | ₹ 27,47,400.00 | 0.92 | 2.76 | 0.33 | 14 | 13 |
| GP 5.5 | ₹ 24,09,836.00 | 0.81 | 12.80 | 0.06 | 11 | 8 |
| GP 7 | ₹ 21,04,794.00 | 0.71 | 92.10 | 0.01 | 7 | 4 |
| GP 8.5 | ₹ 19,85,788.00 | 0.67 | 347.83 | 0.00 | 4 | 2 |
| KS 4 | ₹ 27,69,193.00 | 0.93 | 1.44 | 0.64 | 15 | 15 |
| KS 5.5 | ₹ 22,94,959.00 | 0.77 | 2.59 | 0.30 | 10 | 12 |
| KS 7 | ₹ 19,15,208.00 | 0.64 | 7.32 | 0.09 | 3 | 9 |
| KS 8.5 | ₹ 18,37,323.00 | 0.62 | 28.65 | 0.02 | 1 | 5 |
| GL 4 | ₹ 24,68,553.00 | 0.83 | 5.22 | 0.16 | 12 | 10 |
| GL 5.5 | ₹ 22,27,352.00 | 0.75 | 30.73 | 0.02 | 9 | 6 |
| GL 7 | ₹ 19,92,202.00 | 0.67 | 192.83 | 0.00 | 5 | 3 |
| GL 8.5 | ₹ 18,72,241.00 | 0.63 | 659.82 | 0.00 | 2 | 1 |

A= 0, B= 0, %R= 0, and $J_{nR}$= 0. This technique led to non-zero values of the actual bituminous mastics considered in this study. The use of hypothetical binder and their corresponding values was specified by Saboo et al. [57,58]. Table 9 shows the normalized value of all the considered performance parameters.

$$Normalized \quad Value = \frac{(parametric \quad value - Minimum \quad (parametric \quad values))}{(Maximum \quad (parametric \quad values) - Minimum \quad (parametric \quad values))} \tag{4}$$

Next, the relative ratios (%R/$J_{nR}$) and (A/B) were calculated using SD 4 as a reference mastic, as demonstrated in Table 10. It should be noted that the value of HM was neglected while calculating the relative benefits. The final C/B was evaluated using 50% weightage to rutting and fatigue distresses. Therefore, the relative values corresponding to both ratios were averaged and are illustrated in the last column of Table 10.

The cost of construction (as shown in Table 8) and the benefit value were compiled to determine the C/B ratio corresponding to each bituminous mastics. These values are shown in Table 11. It should be noted that the value of SD 4 was taken as unity as all the C/B was relative to SD 4 as it is taken as the reference mastic in the present study.

Generally, a lower C/B is desirable for bituminous mixtures with lower cost and favorable performance. All the bituminous mastics prepared from waste fillers not only performed superior but were also found to be cost-effective, as indicated by lower C/B. These observations are independent of filler content. Interestingly, C/B decreased with the increase in filler content, irrespective of the filler type. However, the ranking of C/B is a function of filler type. In particular, at 8.5% filler content, GL filler was found to be the best candidate (as indicated by lower C/B), followed by GP, KS, and SD. A similar ranking of C/B was observed in other filler contents. Overall, all the bituminous mastics, prepared with different waste fillers, were better than SD 4 in terms of cost and performance.

Table 11 also shows the ranking of different fillers and their respective filler content based on the construction cost and C/B ratio. Surprisingly, the ranking of bituminous mastics, as per the construction cost, differed from the rank obtained by analyzing C/B. Needless to say, the analysis of C/B was more justifiable than the direct calculation of construction cost. This supports the statement that lower cost does not necessarily offer better performance [59]. The ranking of C/B, evaluated in this study, was primarily based on the results obtained in this study. The rank/trend may change by incorporating any other variable or change in any result. However, the process remains the same for analyzing the C/B of bituminous mixtures prepared with different materials.

Based on the above discussion, it can be stated that the utilization of selected waste fillers not only aids in providing an alternative to conserve natural resources but also leads to the construction of cost-effective bituminous pavement. However, selecting filler type and filler content is a critical research challenge that requires further investigation on a macro level.

### *3.7. Statistical analysis*

A two-way analysis of variance (ANOVA) was done to understand the statistical relationship between the independent and dependent variables. Independent variables are filler type and filler content, whereas dependent variables include %R, $J_{nR}$, A, and B parameters. F-calculated of the dependent variables and the p-value were compared with the respective F-critical and assumed confidence level (i.e., $\alpha = 0.05$). F-calculated is the ratio of the mean square of a variable in question to the mean square of each parameter, whereas p-value indicates the probability value of the occurrence of any data under the null hypothesis. In general, if F-calculated < F-critical, and the corresponding p-value > α, the null hypothesis is rejected, implying that the relationship between the independent and dependent variables is not statistically significant. In the present study, two-way ANOVA was done to assess the significance of filler type and filler content on bituminous mastics' rutting and fatigue performance.

Table 12 shows the results of two-way ANOVA for all the performance parameters. As evident, both filler type and filler content significantly affect the performance of bituminous mastics. However, the effect of filler content was found to be more pronounced, as indicated by lower p-value, compared to the p-value corresponding to filler type. This observation was consistent for all the test

**Table 12**
Results of two-way ANOVA.

| Dependent Variable | Independent Variable | F-calculated | p-value | F-critical |
|---|---|---|---|---|
| %R | Filler type | 7.18335 | 0.00921 | 3.86255 |
| | Content | 10.8931 | 0.00237 | 3.86255 |
| $J_{nR}$ | Filler type | 22.5155 | 0.00016 | 3.86255 |
| | Content | 25.5817 | 0.000097 | 3.86255 |
| A | Filler type | 5.27573 | 0.02254 | 3.86255 |
| | Content | 16.3171 | 0.00055 | 3.86255 |
| B | Filler type | 4.92092 | 0.02719 | 3.86255 |
| | Content | 9.0979 | 0.00435 | 3.86255 |

parameters. The extent of reduction in p-value is dependent on the performance parameter. Considering rutting performance, the effect of filler type was more dominant for $J_{nR}$ value (p-value = 0.00016) as compared to %R value (p = 0.00921). A similar trend was observed for the filler content, where the p-value corresponding to $J_{nR}$ and %R was calculated to be 0.000097 and 0.00237, respectively. In the case of LAS test results, both filler type and filler content were more effective for causing the variation in the value of parameters A and B. Comparison of the p-value for LAS test parameters shows that the variation caused by filler type and filler content was more significant for parameter A rather than parameter B.

## 4. Conclusions

All bituminous concrete mixes delivered Marshall and volumetric properties equivalent/superior to the conventional SD mixes. The increase in filler content led to the simultaneous enhancement in MS, whereas an inverse trend was observed in the case of OBC. In particular, bituminous mixes prepared with GL filler displayed the lowest OBC's, as well as the highest MS. Using waste fillers in place of conventional fillers also improved the engineering performance of bituminous mastics. The rutting resistance increased with the filler-bitumen ratio, where GL and GP mastics displayed the highest rutting resistance, followed by KS and SD mastics. Similarly, the ageing resistance of mastics prepared with GL was superior to the other counterparts. However, caution should be implied while using GL in higher quantities as it may increase mastics' brittleness and reduce fatigue resistance. The SD mastics indicated the highest fatigue resistance, followed by KS, GP, and GL mastics. The cost-benefit ratio analysis validated the economic feasibility of waste fillers, as their implementation in optimum quantity lowers the cost and imparts superior engineering performance to flexible pavements. From the perspective of sustainability, using waste fillers could be a step toward the safe disposal of significant quantities of waste materials and conserving a significant amount of conventional resources around the globe.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

No data was used for the research described in the article.

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