

Feasibility Research on Coal Gasification Slag Used as a Filler in Asphalt Mastic

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Abstract

To explore the feasibility of using coal gasification slag (CGS) as a substitute for limestone filler (LF) in asphalt mastic, six representative CGS powders and one commonly used LF were selected. The physicochemical properties of the CGS powders and the rheological properties of the corresponding asphalt mastics were investigated, and an economic evaluation was conducted. Through comparative analysis of the high- and low-temperature rheological properties of the asphalt mastics at a fixed filler-to-binder (F/B) ratio of 1.0 by mass, low-carbon gasification slag generated by the pulverized-coal process (coded as LCPGS) was identified as the preferred raw material, achieving the optimal balance between high- and low-temperature properties. Compared with LF asphalt mastic, LCPGS asphalt mastic (LCPGS-AM) showed a 19.4% higher $G^*/\sin\delta$ at 64 °C, while m/S value at -12 °C was only 2.2% lower. Based on the rheological and fatigue-resistance properties of LCPGS-AMs with different F/B ratios, a suitable F/B range of 30%–40% by volume was determined, which can serve as a reference for asphalt mastic and mixture design. Complete replacement of conventional LF with LCPGS can reduce material cost by approximately 56.3%, yielding significant economic benefits. The preliminary performance and economic analyses indicate that the use of CGS powder as an alternative filler in asphalt mixtures is feasible.

Keywords: coal gasification slag; physicochemical properties; asphalt mastic; rheological properties; filler-to-binder ratio; cost analysis

21 1. Introduction

22 Mineral filler is an essential component of an asphalt mixture because it combines with asphalt binder to form the mastic
23 phase responsible for bonding, void filling, and load transfer. Its particle size, volume fraction, specific surface area, pore structure,
24 morphology, and mineral composition regulate asphalt–filler interactions and therefore influence the high-temperature stability,
25 low-temperature cracking resistance, and fatigue performance of asphalt mixtures [1–4]. Conventional filler, also referred to as
26 mineral powder, is commonly produced by grinding limestone. As highway construction and maintenance continue to expand,
27 consumption of this non-renewable material increases the demand for quarrying and grinding, with associated cost, dust, energy, and
28 ecological burdens [5–7].

29 To address the shortage of natural stone resources and environmental protection issues, industrial solid wastes have conse-
30 quently been investigated as substitutes for limestone filler. Recent examples include fly ash, coal-liquefaction residue, coal gangue,
31 steel slag, red mud, tailings, calcium carbide slag, phosphogypsum, flue-gas desulfurization ash, waste shells, and incineration
32 bottom ash [5, 8–19]. These materials can improve mastic stiffness, resistance to permanent deformation, adhesion, or fatigue per-
33 formance while reducing the demand for natural mineral resources. Their effects, however, depend strongly on composition, particle
34 morphology, surface area, pore structure, and dosage. Feasibility therefore cannot be established from improvement in a single
35 high-temperature index; high-temperature, low-temperature, and fatigue responses must be considered together.

36 Coal gasification slag (CGS) is an industrial solid waste generated during coal gasification in the modern coal chemical in-
37 dustry. Depending on the gasifier and separation process, it is discharged as coarse slag or fine slag with markedly different particle
38 sizes, residual carbon contents, glassy phases, and pore structures [20–23]. The comprehensive utilization of CGS remains limited,
39 and storage and landfilling are still common disposal routes, occupying land and posing potential risks to soil and water environments
40 [20]. Its inorganic fraction is generally rich in SiO_2 , Al_2O_3 , CaO , and Fe_2O_3 and contains amorphous aluminosilicates and residual

carbon [20–24]. After appropriate grinding, these mineral and physical characteristics provide a basis for its use as an asphalt mastic filler, although source-to-source variability makes screening essential.

Research on the use of CGS in pavement materials has covered subgrade, base-course, cementitious, and asphalt-mixture applications [20, 25]. Previous studies demonstrated the possibility of incorporating fine CGS into asphalt mixtures [26]. Wang et al. evaluated the temperature-sweep and multiple-stress creep-recovery (MSCR) responses of CGS mastics and reported improved resistance to high-temperature shear deformation but a possible low-temperature penalty [27]. Song et al. evaluated the rheological and self-healing behavior of asphalt mastics containing coarse or fine CGS at limestone-filler replacement ratios of 10–50% and also conducted a cost analysis [28], while Ding et al. related residual-carbon characteristics to the microwave-heating response of CGS mastic [24]. However, existing studies have focused on only one or a few CGS sources and/or a limited set of performance indicators. To date, no study has systematically compared different CGS types under standardized particle-size conditions and subsequently optimized the filler-to-binder ratio based on multiple performance criteria and economic cost assessment.

To address this gap, six representative CGS powders and one conventional limestone filler (LF) were first used to prepare seven asphalt mastics at a fixed filler-to-binder (F/B) ratio of 1.0 by mass. Their rheological properties were investigated by means of dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests and the CGS powder with the best overall performance balance was identified. For the selected CGS powder, the high- and low-temperature rheological properties and fatigue characteristics of asphalt mastics with different F/B ratios were then investigated using DSR, multiple-stress creep-recovery (MSCR), BBR, and linear amplitude sweep (LAS) tests, and an appropriate F/B range was recommended. Finally, technical performance and economic cost were considered together to assess the feasibility of replacing limestone filler with CGS powder. The overall research framework is shown in Fig. 1. This study provides a technical basis for extending the use of sustainable pavement materials, particularly alternative fillers for asphalt mixtures.

61 **2. Materials and Methods**

62 *2.1. Raw Materials*

63 A Penetration Grade 70# paving asphalt binder was used. Its basic properties were tested in accordance with the Standard Test
64 Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG 3410–2025) [29] and the results are listed in Table 1,
65 all of which satisfied the technical requirements for paving asphalt in Technical Specifications for Construction of Highway Asphalt
66 Pavements (JTG F40–2004)[30].

67 The fillers comprised six CGSs and one limestone filler (LF). The six gasification slags were: (1) pulverized coal gasification
68 coarse slag and fine slag, coded as PCGCS and PCGFS; (2) coal-water slurry gasification coarse slag and fine slag, coded as WCGCS
69 and WCGFS; and (3) two low-carbon-content gasification slags produced by pressurized gasification units using the pulverized coal
70 process and the coal-water slurry process, coded as LCPGS and LCWGS, respectively. The basic physical properties of the fillers
71 were measured as per Test Methods of Aggregate for Highway Engineering (JTG 3432–2024) [31], and the results, together with
72 residual carbon contents, are listed in Table 2.

73 *2.2. Preparation of CGS Powders*

74 The particle sizes of the six raw CGS samples did not satisfy the mineral filler requirements specified in JTG F40-2004 [30].
75 The samples were therefore ground separately using a planetary ball mill. To ensure that the fillers and their corresponding mastics
76 could be compared on a consistent basis, the particle size distribution of each CGS powder was controlled to match that of LF as
77 closely as possible. Based on preliminary laboratory grinding tests, the grinding time for each CGS powder was determined with the
78 objective of achieving the same median particle size D50 (the particle size corresponding to 50% passing) as that of the LF. After
79 grinding, nitrogen adsorption–desorption was used to determine specific surface area, average pore diameter, and total pore volume;

80 scanning electron microscopy (SEM) was used to examine particle morphology; X-ray diffraction (XRD) was used to identify the
81 main mineral phases; and X-ray fluorescence (XRF) was used to determine the major oxide composition.

82 2.3. Asphalt Mastic Preparation

83 As shown in Fig. 1, the asphalt mastics were prepared under two scenarios. In Stage II, according to the range of F/B ratio
84 specified in JTG F40-2004[30], a fixed filler-to-binder ratio of 1.0 by mass was selected to prepare the mastics, with the main purpose
85 of selecting the optimal CGS powder through analysis of the rheological properties of various asphalt mastics. In Stage II, for the
86 selected CGS powder, asphalt mastics were prepared with different F/B ratios to investigate the variation in rheological properties
87 with F/B ratio and to determine an appropriate F/B ratio range. To eliminate the effect of the density difference between CGS and LF,
88 the filler-to-binder volume (F/B_v) ratio was defined as the ratio of filler volume to binder volume and denoted by F/B_v = 10%, 20%,
89 30%, 40%, and 50%. The mass-to-volume conversion was calculated as follows:

$$F / B_v = \frac{m_f / \rho_f}{m_b / \rho_b} \times 100\% \quad (1)$$

90 where m_f and m_b are the masses of filler and binder, respectively, and ρ_f and ρ_b are their respective apparent densities.

91 The preparation procedure for asphalt mastic was as follows: First, CGS powders and LF were dried in an oven at 105 °C for
92 over 4 h until constant mass was achieved. Subsequently, a predetermined amount of 70# asphalt was heated to 150–160 °C, and the
93 dried fillers were gradually added into the hot asphalt according to the designed F/B ratio. Finally, the mixture was continuously
94 sheared and stirred using a small electric mixer at a rotational speed of 1000 r/min for more than 30 min until the asphalt mastic
95 became thoroughly homogeneous and no visible air bubbles appeared on its surface. Corresponding to the fillers used, the prepared
96 asphalt mastics were coded as PCGCS-AM, PCGFS-AM, WCGCS-AM, WCGFS-AM, LCPGS-AM, LCWGS-AM and LF-AM,
97 respectively.

98 2.4. Test Methods

99 2.4.1. Physical and Morphological Characterization of Fillers

100 The particle size distributions of the CGS powders and LF were determined using a laser particle-size analyzer in accordance
101 with GB/T 19077–2024 [33]. The surface morphologies of the six CGS powders were observed by scanning electron microscopy
102 (SEM) in accordance with JY/T 0584–2020 [34]. Nitrogen adsorption–desorption tests were conducted using a surface-area and
103 pore-size analyzer. Before testing, the samples were degassed at 120 °C for 8 h. The BET specific surface area was determined in
104 accordance with GB/T 19587–2017 [35], while the average pore diameter and total pore volume were obtained from the nitrogen
105 adsorption–desorption data.

106 2.4.2. Mineralogical and Chemical Characterization of Fillers

107 The mineral phases of the six CGS powders were characterized by X-ray diffraction (XRD) in accordance with JY/T 0587–
108 2020 [36]. The major chemical compositions of LF and the six CGS powders were determined by X-ray fluorescence (XRF) in
109 accordance with JY/T 0569–2020 [37].

110 2.4.3. DSR Temperature Sweep

111 The dynamic shear rheometer (DSR) tests were performed in accordance with JTG 3410–2025, Method T 0628–2011 [29]. In
112 Stage II, temperature-sweep tests were conducted from 46 to 76 °C at 6 °C intervals on LF-AM and the six CGS mastics prepared at
113 F/B = 1.0 by mass. In Stage III, the rutting parameter $G^*/\sin\delta$ was tested at 64 °C for the asphalt mastics with selected CGS powder at
114 F/B_v ratios of 10%, 20%, 30%, 40%, and 50%. As this small-strain index does not fully represent deformation under repeated
115 loading, high-temperature resistance to deformation assessment also incorporated the MSCR results [2, 3].

116 2.4.4. MSCR Test

117 The multiple-stress creep-recovery (MSCR) test was performed using the same DSR employed for the temperature-sweep
118 tests. It was conducted in Stage III. Testing was performed at 60 °C according to JTG 3410–2025, Method T 0647–2025 [29]. The
119 performance indices included percent recovery R , nonrecoverable creep compliance J_{nr} , and stress sensitivity $J_{nr\text{diff}}$.

120 2.4.5. Low-Temperature BBR Test

121 The bending beam rheometer (BBR) tests were conducted at –12 °C according to JTG 3410–2025, Method T 0627–2011 [29].
122 The performance indices included creep stiffness S and creep rate m . Because S and m may yield inconsistent rankings, m/S was used
123 as the primary comprehensive criterion for their combined evaluation; a larger m/S indicates better low-temperature performance
124 [38].

125 2.4.6. LAS Test

126 The linear amplitude sweep (LAS) test was performed using the DSR in Stage III. Testing was conducted at 25 °C according
127 to JTG 3410–2025, Method T 0648–2025 [29]. The indices included peak stress, damage-transition behavior, and predicted fatigue
128 life N_f calculated at design strain levels of 3% and 5%.

129 2.5. Economic Cost Analysis

130 To simplify the calculation of economic benefits, only the material cost saved by replacing LF with CGS powder was considered in
131 this study; all other material costs and the costs of mixing, transporting, and compacting asphalt mixtures are assumed to be identical.
132 A 1 km-long two-way four-lane expressway was taken as an example. The asphalt surface course consists of a 4-cm-thick SMA-13
133 upper layer, a 6-cm-thick AC-20 intermediate layer, and an 8-cm-thick AC-25 lower layer. The filler dosage is taken as 6% by weight
134 of the asphalt mixture. The relevant basic parameters are shown in Table 3.

135 The material unit cost is the sum of the processed price, which includes costs such as material extraction and processing, and the
136 transportation cost, as shown in Eq. (2).

$$137 \qquad C = P + D \cdot F_r \qquad (2)$$

138 where C is the material unit cost of filler, CNY/t; P is the processed price of the filler, CNY/t; D is the transport distance, km; and F_r
139 is the freight rate per unit mass and distance, CNY/t·km.

140 **3. Results and Discussion**

141 *3.1. Grinding Characteristics and Particle-Size Standardization*

142 Based on the median particle size (D50) of LF as the target, the required grinding times for LCPGS, LCWGS, WCGCS,
143 PCGCS, PCGFS, and WCGFS were 40, 22, 10, 7, 6, and 5 min, respectively. The grinding time generally decreased with increasing
144 residual carbon content, indicating that the higher-carbon CGS samples were easier to grind. The cumulative particle-size distribution
145 curves (Fig. 2) of the six CGS powders exhibited similar shapes and showed only small differences at representative particle sizes.
146 Their particle-size distributions were therefore considered essentially equivalent. This standardization minimized the influence of
147 particle-size differences on subsequent comparisons of mastic properties, enabling the observed performance differences to be at-
148 tributed primarily to filler composition, surface characteristics, and pore structure.

149 *3.2. Physicochemical Characteristics of the CGS Powders*

150 Following the composition-to-structure characterization sequence, the six CGS powders were characterized in terms of
151 chemical and mineralogical composition, particle morphology, and pore structure.

152 3.2.1. Chemical Composition and Mineral Phases

153 The XRD patterns (Fig. 3) were dominated by broad diffuse humps superimposed with a small number of sharp diffraction
154 peaks, indicating that all six CGS powders contained both amorphous matter and crystalline minerals. Quartz was the principal
155 identifiable crystalline mineral. Peak positions were generally similar among the samples, whereas peak shapes and relative inten-
156 sities differed. The slag source and gasification process therefore mainly affected the relative contents and structural development of
157 the phases without altering the basic coexistence of an aluminosilicate-rich amorphous phase and a small amount of crystalline
158 minerals.

159 The XRF results are listed in Table 4. It can be seen that SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO were the principal inorganic constituents
160 of all six CGS powders, but their contents varied considerably. Unlike LF, the CGS powders were multicomponent aluminosilicate
161 materials. Among the six powders, LCPGS had the highest CaO content and the highest MgO content, while containing the least
162 residual carbon. LCWGS had the highest SiO_2 and Al_2O_3 contents.

163 3.2.2. Particle Morphology

164 SEM observations (Fig. 4) showed irregular, rough, and heterogeneous particles in all six CGS powders, with clear differ-
165 ences in particle shape and surface compactness among sources. LCPGS powder shown in Fig. 4 (a), consisted mainly of relatively
166 regular lamellar particles. LCWGS powder was mostly blocky with irregular protrusions, shown in Fig. 4 (b). WCGCS powder (Fig.
167 4 (c)) had a comparatively smooth surface and contained a small number of spherical particles. PCGCS and PCGFS powders (Fig. 4
168 (d) and (e)) mainly consisted of flaky or fractured particles, whereas WCGFS powder formed agglomerates with pronounced surface
169 folds and interconnected pores, shown in Fig. 4 (f). Overall, the morphology changed from the relatively compact layered structure of
170 LCPGS to the rough, porous structures of PCGCS, PCGFS, and WCGFS, providing direct evidence for differences in specific sur-
171 face area and adsorption capacity.

172 3.2.3. Pore Structure and Its Relationship with Residual Carbon

173 The BET parameters are listed in Table 5, and pore-size distributions are shown in Fig. 5. The average pore diameters of the
174 six CGS powders were lower than that of LF, indicating that their pores were concentrated in the smaller mesopore range. The total
175 pore volume of LCPGS was close to that of LF, whereas its specific surface area was higher. PCGCS, PCGFS, and WCGFS exhibited
176 substantially higher specific surface areas and total pore volumes. In conjunction with the residual carbon data in Table 2, the specific
177 surface area and total pore volume generally increased as residual carbon content rose from 1.8% for LCPGS to 20.5% for WCGFS.
178 This correspondence indicates that the residual-carbon skeleton and rough particle surface jointly contribute to pore formation and
179 are major sources of the differences in surface adsorption capacity among the CGS powders.

180 3.2.4. Integrated Analysis of Physicochemical Characteristics

181 The chemical composition, mineral phases, particle morphology, and pore structure demonstrate that CGS powder is not a
182 uniform material. Inorganic composition and phase assemblage determine its basic mineral attributes, whereas particle roughness,
183 residual carbon, and pore structure jointly control the effective contact area and adsorption capacity with asphalt binder. PCGCS,
184 PCGFS, and WCGFS, which contained more residual carbon, had greater specific surface areas and pore volumes and were expected
185 to produce stronger adsorption and structuring. LCPGS had the lowest residual carbon content, a total pore volume close to that of
186 LF, and the highest CaO content among the six slags. It was therefore more likely to retain sufficient interfacial interaction without
187 excessive adsorption. The significant differences in these physicochemical properties were mainly attributed to differences in the
188 feed coal and gasification processes employed by the respective technologies.

189 3.3. Rheological Performance of Asphalt Mastics and Selection of CGS

190 3.3.1. High-Temperature Rheological Response and Temperature Sensitivity

191 The results of DSR temperature sweep tests are shown in Fig. 6. It can be seen that the values of rutting parameter ($G^*/\sin\delta$)
192 for the seven mastics decreased monotonically with increasing temperature, and the order from smallest to largest was LF-AM,
193 LCPGS-AM, LCWGS-AM, WCGCS-AM, PCGCS-AM, PCGFS-AM, and WCGFS-AM throughout 46–76 °C. At 64 °C, the
194 $G^*/\sin\delta$ of LCPGS-AM was approximately 19.4% higher than that of LF-AM, whereas that of WCGFS-AM was approximately three
195 times that of LF-AM. Therefore, WCGFS-AM exhibited the highest high-temperature rutting resistance, while LCPGS-AM provided
196 the most moderate enhancement among the six CGS mastics.

197 Given that the particle-size distributions were standardized, the differences among the CGS mastics were mainly related to
198 their physicochemical characteristics. The increase in $G^*/\sin\delta$ generally corresponded to increasing residual-carbon content and
199 specific surface area, which enhanced the adsorption of asphalt components and filler–binder interactions [2, 3]. However, a higher
200 rutting parameter does not necessarily indicate superior overall performance; therefore, the low-temperature responses must also be
201 considered when selecting the preferred CGS powder.

202 3.3.2. Low-Temperature Creep and Relaxation Performance

203 Fig. 7 presents the results of BBR tests of seven asphalt mastics. As shown in the Fig. 7, the rankings of low-temperature
204 rheological properties based on m or S alone were inconsistent; therefore, the combined indicator m/S was adopted as the evaluation
205 criterion. LCPGS-AM exhibited a lower S than LF-AM, while its m/S was only approximately 2.2% lower, indicating that its
206 low-temperature creep response was close to that of the conventional LF-AM. In terms of m/S values, LCPGS-AM showed the best
207 low-temperature flexibility, followed by LCWGS-AM, WCGCS-AM, PCGCS-AM, PCGFS-AM, and WCGFS-AM. The

high-residual-carbon PCGFS-AM and WCGFS-AM exhibited lower m/S , indicating that strong filler-induced structuring restricted low-temperature relaxation.

3.3.3. Relationship between Rheological Response and Physicochemical Characteristics

Differences in rheological response can be attributed to the combined effects of volume fraction, surface properties, pore structure, and mineral composition, rather than solely to residual carbon. Nevertheless, residual carbon content and specific surface area generally increased in the order LCPGS, LCWGS, WCGCS, PCGCS, PCGFS, and WCGFS, consistent with the ranking of $G^*/\sin\delta$. Thus, porous surfaces and residual carbon at least exhibited a consistent correlation with asphalt mastic stiffening. The combined influence of filler particle size, effective volume fraction, and asphalt structuring on asphalt mastic modulus is also in agreement with previous multiscale mechanistic studies [1, 32, 39].

The high specific surface area and porous structure strengthened the interaction between CGS powder and asphalt, thereby increasing asphalt mastic stiffness. This structuring effect was two-sided. Moderate adsorption and particle constraint improved resistance to high-temperature shear deformation, whereas an excessive effect reduced the free asphalt available for relaxation, increased low-temperature S , and decreased m/S . The PCGCS, PCGFS, and WCGFS results clearly demonstrated this trade-off.

Similar rough porous-surface-stiffening-fatigue-or-low-temperature penalties have been reported for steel-slag, glass fiber reinforced plastic (GFRP), phosphogypsum, and furnace-slag fillers [2, 3, 6, 13, 15]. However, the individual rankings of S and m did not completely follow the change in residual carbon. The residual-carbon-pore-structure relationship was therefore treated as a mechanistically consistent association rather than proof of a single causal factor.

3.3.4. Integrated Selection of CGS

With respect to individual performance indices, WCGFS-AM and PCGFS-AM exhibited the highest rutting parameter values, whereas LCWGS-AM showed the lowest S ; however, these extreme values do not necessarily indicate optimal overall suitability, as

the advantages in individual indices were accompanied by either excessive stiffening or a low m -value. In contrast, LCPGS-AM provided a moderate high-temperature enhancement and had the highest m/S among the six CGS asphalt mastics, while remaining close to LF-AM in low-temperature response. The physicochemical characteristics further support this selection. Among the six slags, LCPGS had the lowest residual carbon content and specific surface area, and its total pore volume was comparable to that of LF, thereby reducing the risk of performance imbalance caused by excessive adsorption. In addition, LCPGS possessed the highest CaO, which is conducive to favorable mineral filler–asphalt interfacial interactions. Considering resistance to high-temperature deformation, low-temperature relaxation behavior, and physicochemical characteristics together, LCPGS was selected not because it maximized one index, but because it provided the best balance between moderate enhancement and performance retention. Accordingly, LCPGS was identified as the preferred CGS powder for the subsequent complete replacement assessment of limestone filler.

3.4. High-Temperature Rheological Performance of LCPGS-AM

3.4.1. DSR High-Temperature Response

Fig. 8 presents the DSR results for LF-AM and LCPGS-AM at various F/B_v ratios. As F/B_v ratio increased from 10% to 50%, $G^*/\sin\delta$ at 64 °C generally increased for both LCPGS-AM and LF-AM, indicating that a higher filler volume fraction enhanced particle filling, interparticle constraint, and asphalt–filler interaction. The curves crossed between 20% and 30%: the $G^*/\sin\delta$ of LCPGS-AM was slightly lower than that of LF-AM at $F/B_v = 10\text{--}20\%$, but exceeded that of LF-AM at $F/B_v \geq 30\%$. Thus, the high-temperature advantage of LCPGS-AM exhibited a threshold effect and was not evident at all low filler contents. This content dependence is consistent with previous findings for comparable solid-waste fillers [2, 3]. At $F/B_v = 30\%$, $G^*/\sin\delta$ was 14.5% higher for LCPGS-AM than for LF-AM. When F/B_v increased to 40% and 50%, the relative improvements were approximately 6.7% and 6.8%, respectively, and did not continue to increase, indicating that the high-temperature advantage of LCPGS-AM stabilized rather than

expanded further above 30%. Therefore, $G^*/\sin\delta$ supports 30% as the lower boundary at which the high-temperature benefit became stable, but it does not by itself justify a higher filler content.

3.4.2. MSCR Response under Repeated High-Temperature Loading

Fig. 9 shows the MSCR strain–time curves, which exhibited stepwise creep-recovery responses. As F/B_v increased, both the cyclic strain increment and the accumulated nonrecoverable strain generally decreased for both mastics. The responses at 3.2 kPa were larger than those at 0.1 kPa, reflecting stronger nonlinear viscoelastic deformation under the higher stress. Unlike the small-strain high-temperature stiffness represented by $G^*/\sin\delta$, MSCR directly captures recovery and residual deformation under repeated loading. Therefore, the agreement between the two types of indices is more informative than the rutting parameter alone [2, 3].

The percent recovery R increased with F/B_v , but the advantage of LCPGS-AM over LF-AM occurred in stages (Fig. 10(a)). At 0.1 kPa, R was lower for LCPGS-AM at $F/B_v = 10\text{--}20\%$ and became higher at $F/B_v \geq 30\%$. At 3.2 kPa, the transition occurred at approximately 20%. For example, at $F/B_v = 30\%$, R was slightly higher for LCPGS-AM at both 0.1 and 3.2 kPa. The overall decrease in R at the higher stress indicates that part of the recoverable structure was weakened under the larger load.

As shown in Fig. 10(b), J_{nr} decreased continuously with increasing F/B_v , consistent with the accumulated strain trend. The two mastics were similar at $F/B_v = 10\%$; from 20% onward, LCPGS-AM exhibited lower J_{nr} than LF-AM at both stress levels. Combined with R , these results indicate that at $F/B_v \geq 30\%$, LCPGS-AM simultaneously increased recovery and reduced permanent deformation, shifting its high-temperature advantage from simple stiffening to a coordinated improvement in repeated-load creep response.

$J_{nr,diff}$ was used to evaluate the sensitivity of nonrecoverable deformation to the change in stress. Across the five F/B_v levels, the mean $J_{nr,diff}$ values were approximately 6.8% for LCPGS-AM and 9.6% for LF-AM, indicating low overall stress sensitivity for

both mastics, with LCPGS-AM showing a lower mean. Considering $G^*/\sin\delta$, R , J_{nr} , and $J_{nr,diff}$ together, $F/B_v \approx 30\%$ was the point at which LCPGS-AM began to provide a stable advantage in resistance to high-temperature permanent deformation.

3.5. Low-Temperature Rheological Performance of LCPGS-AM

The BBR results presented in Fig. 11 show that, for both mastics, S generally increased and m/S generally decreased with increasing F/B_v , indicating that filler-induced structuring increased stiffness while progressively restricting low-temperature relaxation. This trend was opposite to those observed for $G^*/\sin\delta$ and MSCR at high temperatures, demonstrating the temperature-dependent nature of the same particle-constraint effect: it reduced permanent deformation at high temperatures but hindered stress relaxation at low temperatures. A comparable high-temperature benefit–low-temperature penalty has been reported in previous filler-mastic studies [3].

The differences between LCPGS-AM and LF-AM exhibited three distinct stages. At $F/B_v = 10\text{--}20\%$, LCPGS-AM had a lower S and higher m/S . At $F/B_v = 30\%$, the m/S values of LCPGS-AM and LF-AM were generally comparable. At $F/B_v = 40\text{--}50\%$, S became higher and m/S lower for LCPGS-AM than for LF-AM, indicating that the low-temperature penalty was concentrated in the transition from 30% to 40%. At $F/B_v = 40\%$, m/S was approximately 15.6% lower for LCPGS-AM than for LF-AM, and the low-temperature loss was no longer negligible. Increasing F/B_v from 20% to 30% stabilized the high-temperature advantage, whereas a further increase toward 40% noticeably diminished the low-temperature performance. Therefore, the BBR results support identifying 40% as a critical upper boundary.

284 3.6. Fatigue Performance of LCPGS-AM

285 3.6.1. LAS Stress–Strain Response

286 All LAS stress–strain curves (Fig. 12) exhibited three characteristic stages: stress increase, peak transition, and post-peak
287 decay. To improve the readability of the overlaid curves, only isolated post-peak fluctuations were smoothed for graphical presen-
288 tation; the measured peak values were retained, and all LAS parameters and fatigue lives were calculated from the original unpro-
289 cessed data. Increasing F/B_v generally shifted the peak toward a lower strain and accelerated the post-peak decay, indicating that a
290 stronger particle skeleton increased small-strain load capacity but reduced the large-strain damage tolerance. At the same F/B_v , the
291 peak stress and corresponding strain were generally higher for LF-AM than for LCPGS-AM, suggesting that the interfacial constraint
292 developed by LCPGS-AM did not translate into a higher fatigue tolerance. Peak stress can only identify the damage transition
293 qualitatively and must be interpreted together with VECD fatigue life [2].

294 Fig. 13 presents the results of LAS fatigue lives (N_f) of LF-AM and LCPGS-AM at the strain levels of 3% and 5%. N_f gen-
295 erally decreased with increasing F/B_v for both asphalt mastics, but LCPGS-AM did not consistently exhibit a lower N_f than LF-AM at
296 all ratios. At each F/B_v , N_f at 5% was approximately one order of magnitude lower than that at 3%. At $F/B_v = 20\%$, N_f was higher for
297 LCPGS-AM than for LF-AM; at $F/B_v = 10\%$, 30%, 40%, and 50%, it was lower. This nonmonotonic difference indicates that a
298 moderate particle content may improve local damage tolerance through filling and crack-path extension, whereas continued struc-
299 turing progressively makes mastic hardening and interfacial strain concentration dominant [2, 6].

300 The most pronounced transition occurred as F/B_v increased from 30% to 40%: at the strain levels of 3% and 5%, N_f decreased
301 by approximately 90.0% and 90.5%, respectively, for LCPGS-AM, and by 67.5% and 69.2%, respectively, for LF-AM. This abrupt
302 fatigue loss directly competed with the high-temperature improvement shown by MSCR. A stable high-temperature benefit had
303 already been achieved at $F/B_v \approx 30\%$, whereas the low-temperature and fatigue penalties increased rapidly near 40%. A design rang
304 for F/BV of 30–40% is proposed, with 40% as the upper boundary; the filler content should ideally be selected near the lower end of
305 this range (i.e., 30%).

306 Taken together, the DSR temperature-sweep, MSCR, BBR, and LAS results describe different but complementary perfor-
307 mance dimensions. A stable high-temperature advantage for LCPGS-AM emerged at a filler-to-binder volume ratio of approximately
308 30%, whereas low-temperature relaxation and fatigue life deteriorated markedly as the ratio approached 40%. Accordingly, the
309 results suggest that an F/Bv range of 30–40% is suitable for LCPGS-AM, providing a practical reference for asphalt mastic and
310 mixture design.

311 3.7. Cost Comparison

312 In general, raw coal gasification slag is supplied free of charge, while the processed price of LCPGS powder, including drying
313 and grinding, was estimated at 50 CNY/t. The processed price of LF, including extraction and processing, was 150 CNY/t. Assuming
314 that the project site is 50 km from the LCPGS processing plant and 70 km from the LF processing plant, with a freight rate of 0.8
315 CNY/ (t·km), the unit material costs of LF and LCPGS powder calculated by Eq. (2) are 206 CNY/t and 90 CNY/t, respectively.
316 Therefore, the unit material cost of LCPGS powder is 56.3% lower than that of conventional mineral filler. For this case, the total cost
317 of mineral filler required for 1 km of pavement is 109,015 CNY; if LCPGS powder completely replaces mineral filler, the total cost is
318 47,628 CNY, reducing the project cost by 61,387 CNY, which represents a considerable economic benefit.

319 In addition, if the unit material cost of LF remains unchanged (i.e., 206 CNY/t), Eq. (2) indicates that the haul distance at which the
320 unit cost of coal gasification slag powder equals that of mineral filler is approximately 195 km. This implies that as long as the
321 distance between the project site and the coal gasification slag powder processing plant is within this range, the cost of coal gasifi-
322 cation slag powder is lower than that of LF.

323 4. Conclusions and Future Work

324 This study focuses on the fundamental physicochemical properties of CGS powders and the rheological properties of their
325 asphalt mastics. The main conclusions drawn from laboratory tests and economic analysis are as follows:

326 (1) Under the premise that the six typical CGSs were ground to essentially the same particle-size distribution, their physico-
327 chemical properties, including specific surface area, pore structure, pore volume, and mineralogical and chemical compositions,
328 differed significantly owing to differences in the feed coal and gasification process employed by each gasification technology.

329 (2) In general, with increasing residual carbon content, specific surface area, and pore volume of the coal gasification slag
330 powder, the high-temperature rheological property of the asphalt mastic was enhanced (higher $G^*/\sin\delta$), whereas the
331 low-temperature rheological property deteriorated (lower m/S). This is attributed to the high specific surface area and porous struc-
332 ture strengthening the interaction between the CGS powder and asphalt, thereby increasing the stiffness of the asphalt mastic.

333 (3) Compared with LF-AM, LCPGS-AM exhibited a 19.4% higher $G^*/\sin\delta$ at 64 °C and only a 2.2% lower m/S at -12 °C, in-
334 dicating more balanced high- and low-temperature rheological properties. LCPGS can therefore be preferentially selected as a CGS
335 powder to replace LF.

336 (4) Based on the comprehensive analysis of the rheological and fatigue-resistance properties of LCPGS-AM at different F/B_v
337 values, a suitable F/B_v range of 30%–40% was determined. Complete replacement of LF in asphalt mixtures with LCPGS can reduce
338 the unit price of filler by approximately 56.3%, corresponding to a filler material cost reduction of 61,387 CNY per kilometer of
339 asphalt layers for a two-way four-lane expressway, thereby yielding considerable economic benefits.

340 (5) This study preliminarily demonstrated the feasibility of using CGS powder, especially LCPGS, to replace conventional LF in
341 asphalt mastic. However, partial replacement of LF by one or more CGS powders was not investigated. The long-term pavement
342 performance, field validation, and environmental impacts of asphalt mastics and mixtures containing CGS powder remain to be
343 addressed and are key topics for future research.

344

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446

447 Table 1. Basic properties of the 70# paving asphalt binder.

Property	Measured value	Test method
Penetration at 25 °C (0.1 mm)	62.3	JTG 3410–2025, T 0604
Ductility at 15 °C (cm)	>100	JTG 3410–2025, T 0605
Softening point (°C)	49.3	JTG 3410–2025, T 0606
Brookfield viscosity at 135 °C (Pa·s)	0.52	JTG 3410–2025, T 0625
Density (g·cm ⁻³)	1.021	JTG 3410–2025, T 0603

448 Table 2. Basic physical properties of the fillers.

Fillers	Apparent density (g·cm ⁻³)	Hydrophilic coefficient	pH	Residual carbon (%)
LF	2.701	0.770	10–11	—
LCPGS	2.872	0.879	9–10	1.82
LCWGS	2.554	0.636	9–10	5.03
WCGCS	2.589	0.710	6–7	10.42
PCGCS	2.863	0.670	9–10	16.58
PCGFS	2.992	0.530	7–8	18.01
WCGFS	2.603	0.570	8–9	20.53

449 Note: The moisture content of each CGS powder was no greater than 1%, and no visible agglomeration or caking was observed.

450

451 Table 3. Basic pavement parameters.

Parameter	Length/m	Pavement width/m	Asphalt layer thickness/m	Average density/t·m ⁻³	Asphalt mix- esmass/t	Fillermass/t
Value	1000	20	0.18	2.45	8820	529.2

452

453 Table 4. Major chemical composition of the fillers (wt.%).

Filler	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	C
LF	9.63	2.90	1.96	78.05	5.47	0.38	—
PCGCS	24.23	12.18	22.92	16.88	0.635	1.024	16.58
PCGFS	29.52	15.89	14.06	14.54	0.500	0.691	18.01
WCGCS	28.88	14.82	21.18	18.24	0.818	0.810	10.42
WCGFS	29.05	13.89	18.74	9.351	1.053	3.576	20.53
LCPGS	39.35	16.72	13.84	20.10	2.000	1.650	1.82
LCWGS	45.67	20.95	10.62	8.74	1.280	3.050	5.03

454

455 Table 5. Pore-structure parameters of the fillers.

Fillers	Average pore diameter (nm)	Specific surface area (m ² ·g ⁻¹)	Total pore volume (cm ³ ·g ⁻¹)
LF	12.4889	2.4401	0.008462
LCPGS	6.5740	5.6129	0.008220
LCWGS	5.2036	16.3156	0.021225
WCGCS	4.9573	20.6298	0.025567
PCGCS	5.0500	69.8916	0.089963
PCGFS	5.4362	75.2051	0.108898
WCGFS	4.3274	89.1315	0.092922

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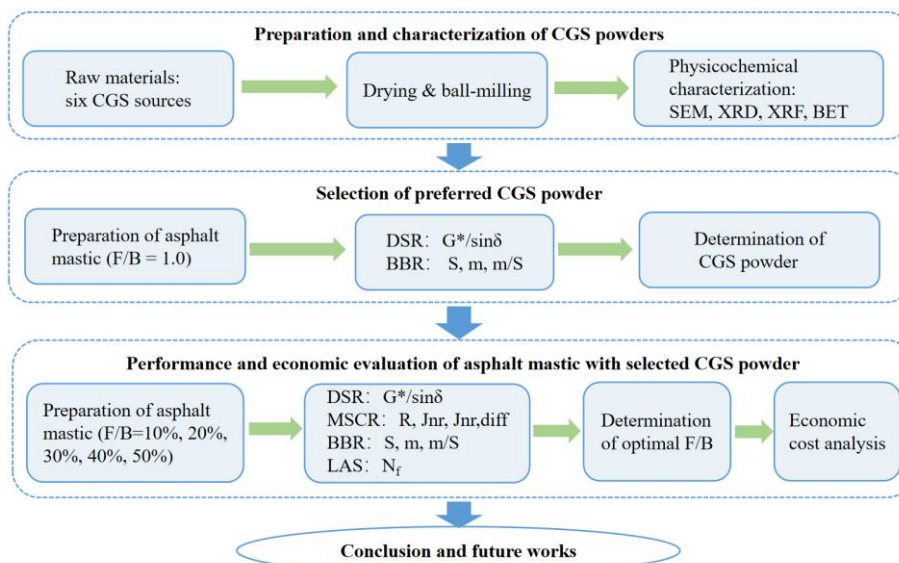
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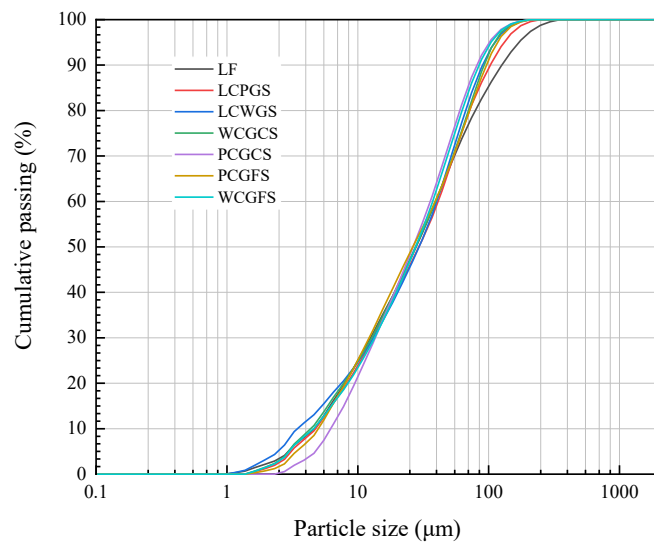
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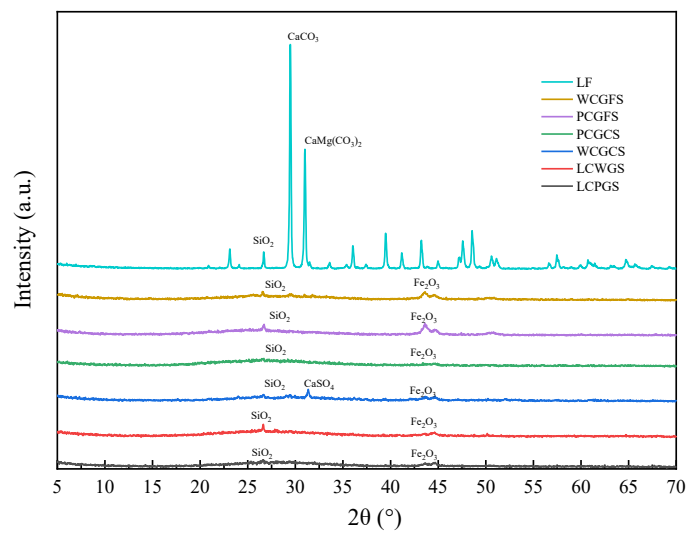
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475 Figure 1. Research framework.



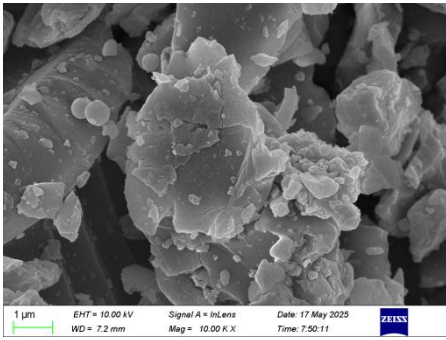
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477 Figure 2. Particle-size distributions of the fillers after standardized grinding.

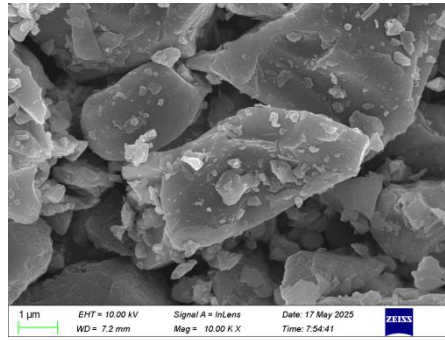


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 479 Figure 3. XRD patterns of the coal gasification slag powders.

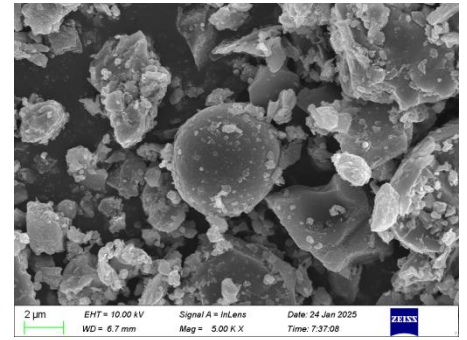
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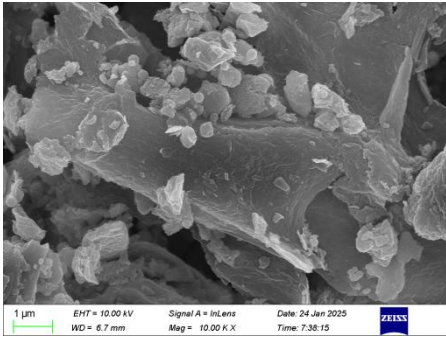
(a) LCPGS



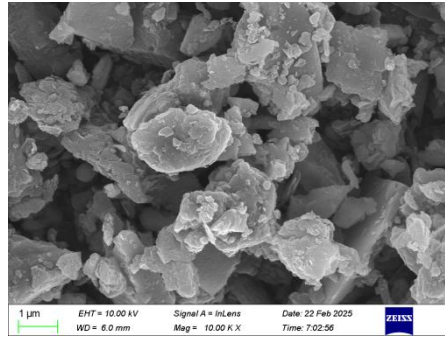
(b) LCWGS



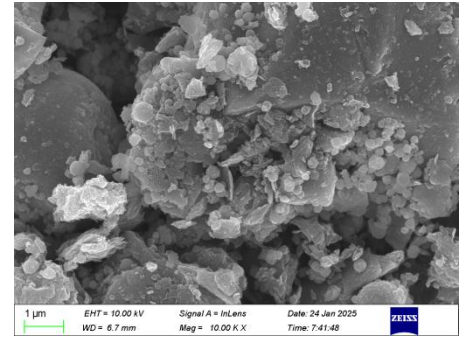
(c) WCGCS



(d) PCGCS

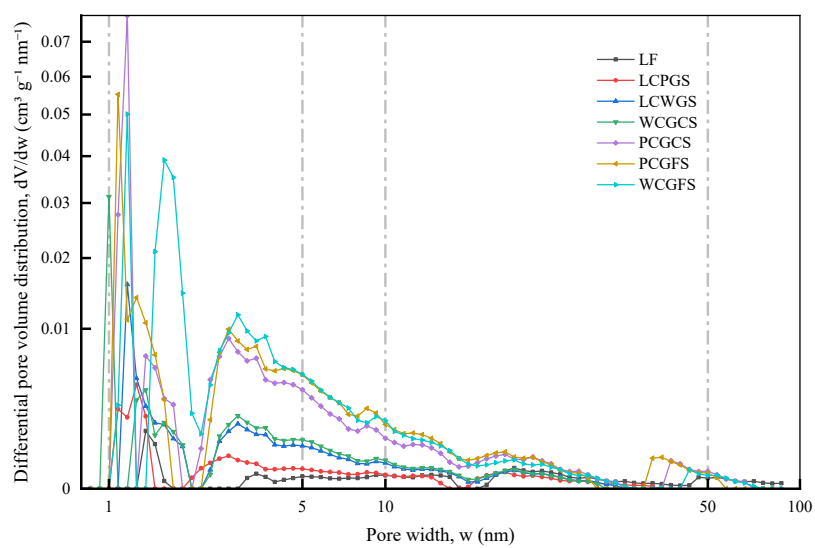


(e) PCGFS



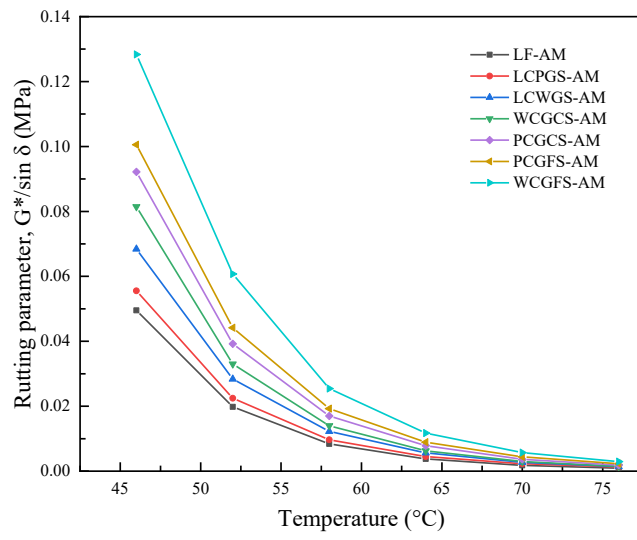
(f) WCGFS

481 Figure 4. SEM morphologies of six CGS powders.



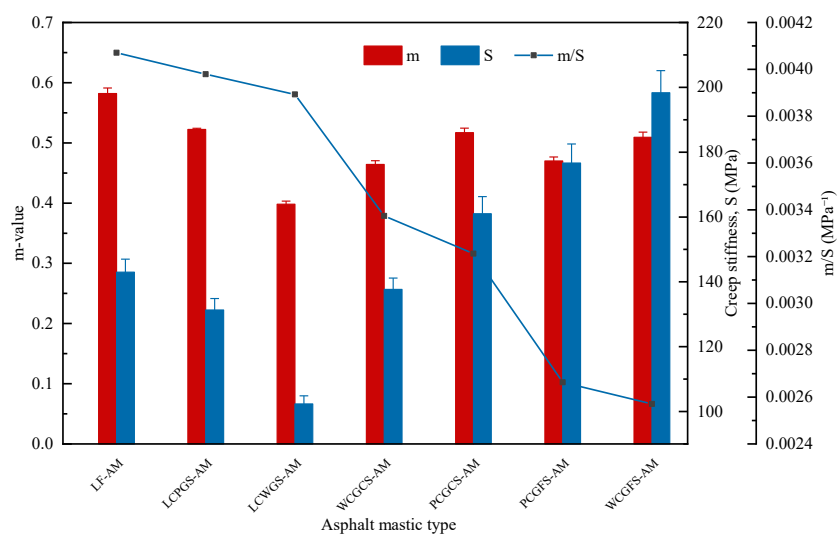
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483 Figure 5. Pore-size distributions of the fillers.



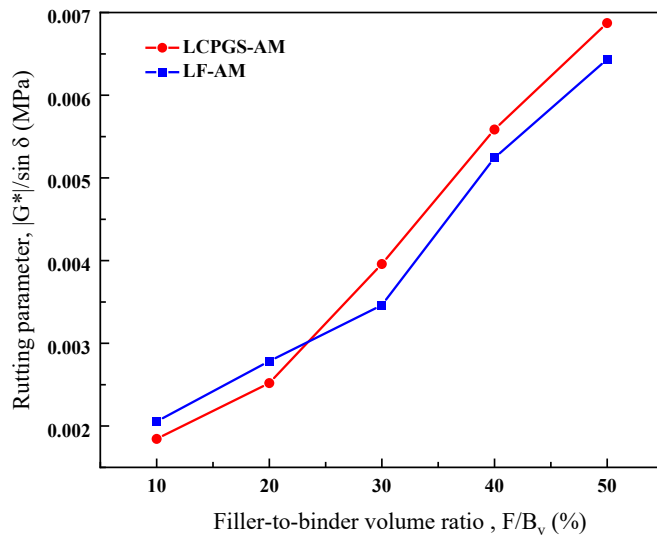
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485 Figure 6. Rutting parameter of the filler mastics at F/B = 1.0.



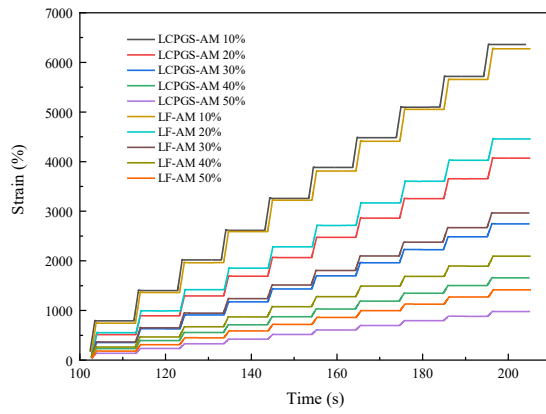
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487 Figure 7. BBR results for the filler mastics at F/B = 1.0.

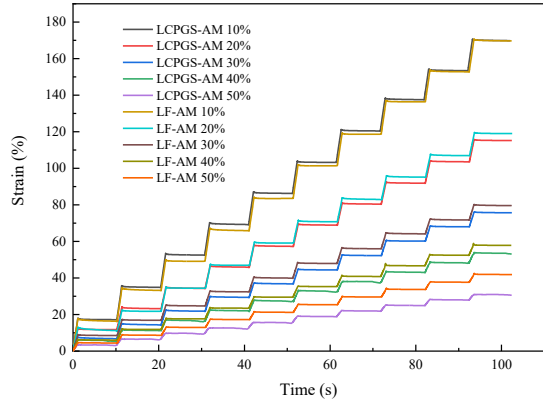


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489 Figure 8. Rutting parameters of LF-AM and LCPGS-AM at different F/B_v ratios.



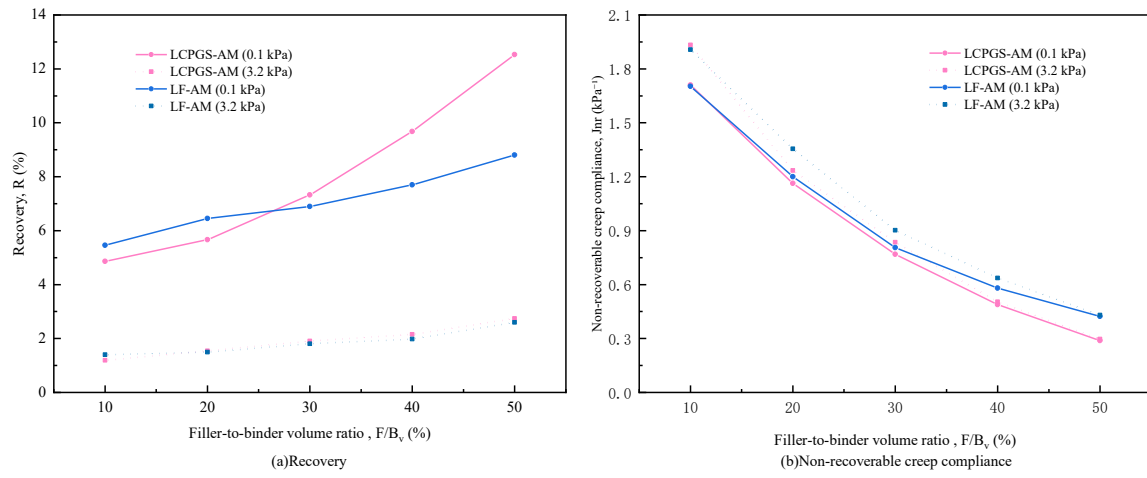
(a) 0.1 kPa



(b) 3.2 kPa

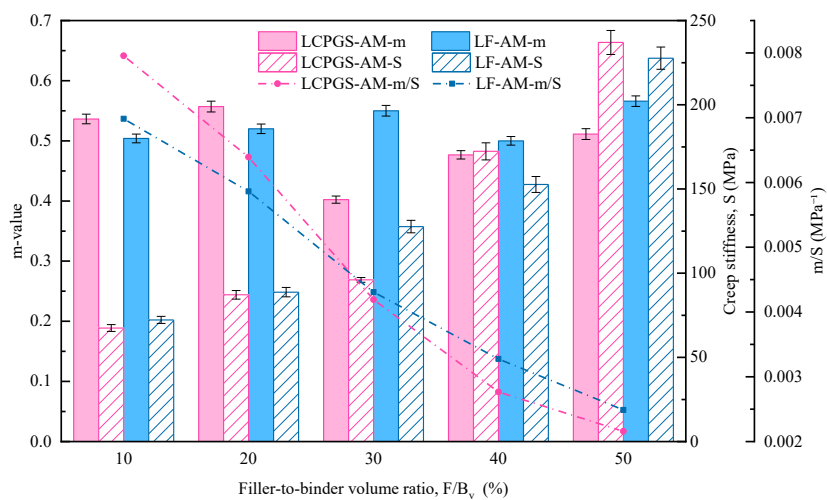
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491 Figure 9. MSCR creep-recovery curves of LF-AM and LCPGS-AM at different stress levels.



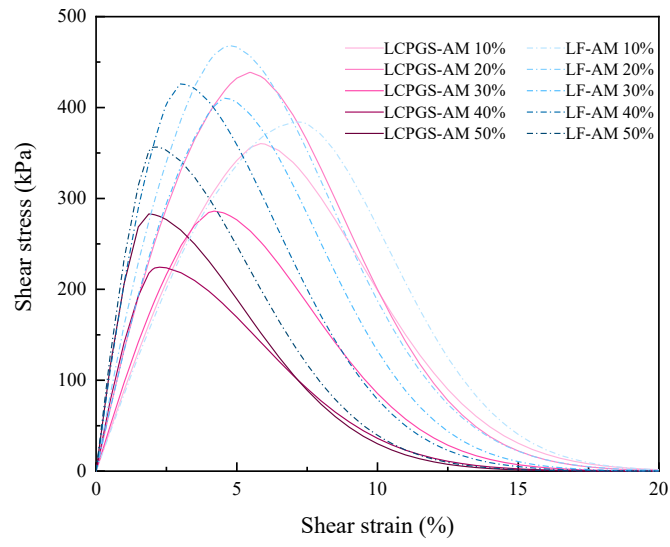
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493 Figure 10. MSCR parameters of LF-AM and LCPGS-AM at different volume/ B_v ratios.



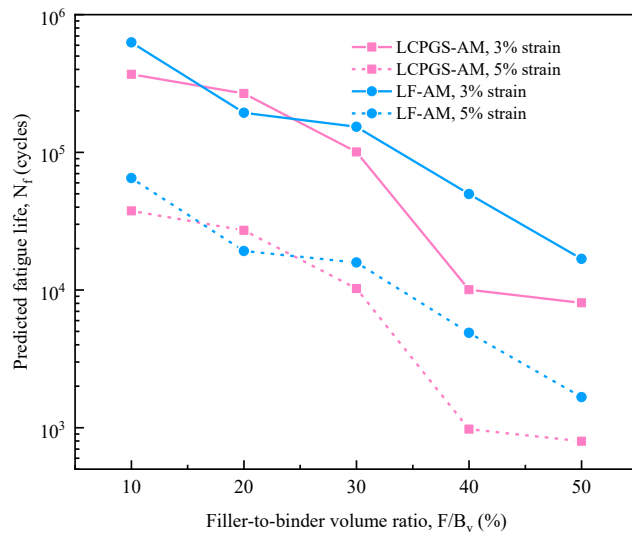
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495 Figure 11. BBR results for LF-AM and LCPGS-AM at different F/B_v ratios.



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497 Figure 12. LAS stress-strain curves of LF-AM and LCPGS-AM at different F/B_V ratios.



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499 Figure 13. LAS fatigue lives of LF-AM and LCPGS-AM at different volume/ B_v .