

# Fatigue Characteristics Of Inorganic Micro-Powder Modified Asphalt

Xiaodong Jia<sup>1</sup>, Naixing Liang<sup>2</sup>, and Kaifeng Zheng<sup>3\*</sup>

<sup>1</sup>School of Urban Construction Engineering, Chongqing Open University, Chongqing 400052, China

<sup>2</sup>School of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China

<sup>3</sup>Shenzhen Cheng Chung Design Co., Ltd., Shenzhen 518017, China

\* Corresponding author. E-mail: ZhengKaifeng\_zfk@outlook.com

Received: June 19, 2025; Accepted: November 11, 2025

To explore the influence of inorganic-micro-powder materials on the fatigue performance of asphalt, hydrated lime (HL), silica fume (SF), and Portland cement (PC) were selected as representatives of inorganic-micro-powder materials. Based on the type, content, and particle size of inorganic-micro-powder materials, the influence of the micro-powder modifier on the fatigue performance of asphalt was analyzed by a dynamic shear rheometer (DSR) time sweep test using dissipation energy index  $N_{DER}$  and damage mechanics index  $C \times N$  peak. The core characteristic parameters of the micro-powder that affect the fatigue life of asphalt were determined. The results show that, among the three different types of micro-powder, the influence of SF on the fatigue performance of asphalt was the most significant, followed by HL, and PC was the least influential. An increase of stress resulted in a gradual decrease of the influence of various micro-powder modifiers on the fatigue performance of asphalt. The surface area content (It refers to the surface area value of micro-powder per gram of asphalt material) of micro-powder is purported to be the core characteristic parameter affecting the fatigue life of asphalt, and the surface content stress fatigue equation between the fatigue life of the modified asphalt and the surface content and stress of micro-powder was established. The fatigue life prediction of micro-powder modified asphalt under the influence of different surface area content was realized.

**Keywords:** Portland cement; Silica fume; Hydrated lime; Particle size; Surface volume; Fatigue performance

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[http://dx.doi.org/10.6180/jase.202607\\_30.017](http://dx.doi.org/10.6180/jase.202607_30.017)

## 1. Introduction

Fatigue cracking in asphalt pavements has become one of the main forms of pavement failure [1, 2] and the most difficult problem encountered in the design and maintenance of asphalt pavement. The main internal cause of fatigue cracking is fatigue damage to the asphalt materials that play an adhesive role in the asphalt mixture. Therefore, the analysis and study of the fatigue performance of asphalt materials forms the basis for solving fatigue failures in asphalt pavement.

At present, adding inorganic micro powder modifiers to asphalt to improve its fatigue performance has become one of the research hotspots for many scholars. Dong et al. studied the effect of different fineness and dosage of hy-

drated lime on the adhesion performance of asphalt based on surface energy theory, and found that increasing the fineness and dosage of lime can effectively improve the adhesion of asphalt [3, 4]. Gan et al. employed four activation strategies (HCl, KOH, steam, and CO<sub>2</sub>) to enhance the performance of PCB-modified asphalt. Additionally, they characterized the physical and chemical properties of PCB through ash content measurement, scanning electron microscopy (SEM), and nitrogen adsorption [5]. Fan et al. studied the fatigue performance of modified asphalt with different dosages of calcium sulfate whiskers and found that the addition of 5% CSW can improve the fatigue resistance of asphalt under UV conditions and increase the fatigue life of its modified asphalt [6]. Guo et al. studied

the fatigue performance of modified asphalt prepared from red mud, fly ash, and diatomaceous earth in two stages: non aging and long-term aging. It was found that all four materials could improve the fatigue performance of asphalt after aging, with diatomaceous earth showing the most significant improvement effect [7]. Xu et al. explored the evaluation of the composite modification effect of cement and rubber in asphalt binder through thermo-oxidative aging tests. During rheological experiments, it was found that thermo-oxidative aging and an appropriate cement content could enhance the high-temperature resistance to deformation [8]. Mohammed et al. investigated the impact of silica fume (SF) on the moisture susceptibility of asphalt and found that incorporating 6% silica fume reduced the asphalt's sensitivity to moisture, with the tensile strength ratio (TSR) and index of retained strength (IRS) increasing by 12.49% and 13%, respectively [9]. Hou et al. studied the modification of bio-asphalt with silica fume (SF) and found that the dosage of SF could enhance the high-temperature rutting resistance, anti-aging capability, and temperature stability of bio-asphalt. The higher the SF content, the more significant the enhancing effect [10]. Wang et al. clarified the common types, physicochemical properties, and application methods of inorganic powders. The road performance of modified asphalt and its mixtures was evaluated. Additionally, the modification mechanism of inorganic powders in asphalt was analyzed. On this basis, the cooling effect and cooling mechanism of inorganic powders were revealed [11, 12]. Al-Mohammedawi et al. performed fatigue tests using DSR and found that the uniform distribution of inorganic-micro-powder filler particles in the original asphalt also affects the overall fatigue life of the asphalt mortar and mixture. This phenomenon is mainly manifest through the blocking of microcracks, generated in the fatigue damage process, by small filler obstacles, to prevent crack development [13]. Song et al. studied the impact and mechanism of silicon carbide (SiC) ceramic micro-powder on the performance of modified asphalt. It was found that, owing to its high specific surface area and abundant porous structure, SiC ceramic micro-powder effectively adsorbed the lighter components in asphalt, significantly enhancing its viscosity and high-temperature stability. Furthermore, it was discovered that the modification of asphalt by SiC is a physical process, during which no new functional groups are formed [14, 15]. Xing et al. confirmed that under the same volume dosages, the smaller the particle size of inorganic-micro-powder filler, the better the fatigue properties of the mortar, that is, the elastic properties [16].

In summary, although some research has been con-

ducted on the fatigue performance of inorganic-micro-powder materials in asphalt and its mixture, most of these involved the mechanical properties of asphalt or mortar after adding modifiers. The relationship between the modifier properties and asphalt performance were not analyzed, nor were the core characteristic factors of inorganic-micro-powder affecting asphalt performance determined. Therefore, in this study, the rheological properties were assessed using DSR time sweep testing. Three types of commonly used inorganic micro-powder, namely SF, PC, and HL, among which three dosages and three particle sizes of hydrated lime were used to prepare a total of seven types of inorganic micro-powder modified asphalt. Furthermore, the influence of the type of micro-powder, dosages, and particle size characteristics on the fatigue performance of asphalt was analyzed. Based on the results, a prediction model of fatigue performance of modified asphalt based on the core characteristic parameters of the inorganic material modifier was established. The outcomes of this study provide a new direction for the research and development of new materials for asphalt pavements.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Inorganic-micro-powder

Seven types of solid waste micro-powders were selected across three experimental categories, varying in material type, dosage levels, and particle size distributions. Specific parameters are detailed in Table 1. Given that surface morphology and particle size significantly influence asphalt modification performance, scanning electron microscopy (SEM) analysis revealed distinct microstructural characteristics among the samples: Fig. 1a shows a loose granular structure with abundant surface pores and corrugations, indicating strong adsorption capacity during asphalt interaction. Fig. 1b displays particles with diverse shapes (spherical, blocky, acicular) and sharp edges, featuring relatively smooth surfaces that exhibit weaker interfacial bonding with asphalt. Fig. 1c presents predominantly spherical ultra-fine particles ( $\sim 1 \mu\text{m}$  diameter) with rough surfaces, demonstrating the highest specific surface energy and strongest adsorption performance due to their minimal size. Complementary X-ray diffraction (XRD) analysis of all micro-powder samples was conducted to examine crystalline structures. Results are summarized alongside SEM observations in Table 1, providing comprehensive material characterization for subsequent asphalt modification studies.

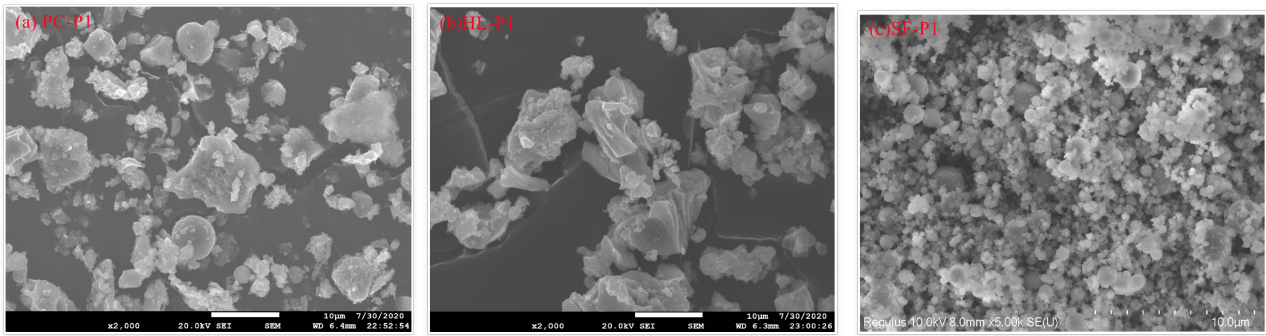


Fig. 1. SEM images of three types of inorganic-micro-powders.

### 2.1.2. Inorganic-micro-powder modifier

This study prepared seven types of modified asphalt by blending three categories of micro-powders with 70# original asphalt. The dispersion of micro-powders in asphalt was achieved using a self-developed ultrasonic pressure-pulse disperser. The optimal preparation process ensuring homogeneous dispersion of micro-powders in asphalt was determined through fluorescence microscopy analysis, with detailed parameters pre-sented in Table 1.

### 2.2. Methods

A TA DSR (United States) was used for time scanning to study the fatigue characteristics of the micro-powder modified asphalt. Stress levels of 0.1, 0.15, and 0.2 MPa were selected. The frequency was 10 Hz, temperature was 25°C, and the mold had a flat plate geometry (8 mm diameter and 2 mm gap). The loading frequency of 10 Hz was selected because it is the most commonly used loading frequency in fatigue research. The experiment was conducted at 25°C [17]. All laboratory tests were conducted with triple replicate measurements to ensure data reliability.

## 3. Results and discussion

The key problem when analyzing the fatigue life of asphalt pavements and their mixtures is the identification of the fatigue failure of the materials. The fatigue life of materials can be clearly determined by determining the fatigue failure identification index of materials. Globally, there are two main methods to determine fatigue failure of asphalt materials, namely the dissipation energy method, based on energy change, and the damage mechanics method, based on continuous medium.

### 3.1. Fatigue performance analysis based on dissipated energy

In the dissipative energy method, two indexes, namely dissipative energy change rate ( $DR$ ) and cumulative dis-

sipative energy ratio ( $DER$ ), were selected to analyze the fatigue life of the micro-powder modified asphalt. For the fatigue loading process of modified asphalt, the equations used to calculate dissipation energy per unit load cycle, cumulative dissipation energy ratio, and dissipation energy change rate during loading are as follows [18]:

$$\omega_i = \pi\sigma_i\varepsilon_i \sin \delta_i = \pi G_i^* \varepsilon_i^2 \sin \delta_i, \quad (1)$$

$$DER = \frac{\sum_{i=1}^n \omega_i}{\omega_n}, \quad (2)$$

$$DR_j = \frac{\omega_j - \omega_i}{\omega_j(i-j)}, \quad (3)$$

where  $\omega_n$ ,  $\omega_i$ , and  $\omega_j$  are the energy dissipated in the  $n$ ,  $i$ , and  $j$  load cycles, respectively;  $\varepsilon$  is the strain;  $\sigma$  is the internal stress;  $\delta$  is the phase angle;  $G^*$  is the complex shear modulus;  $DER$  is the cumulative dissipation energy ratio; and  $DR$  is the rate of change of dissipated energy.

#### 3.1.1. Change rate of dissipated energy ( $DR$ )

$DR$  is used to assess the stage of damage of the material according to the change rate of dissipated energy of the material under two adjacent loads. When the rate changes suddenly, the corresponding loading time is defined as the fatigue life  $N_{DR}$ . The fatigue failure of asphalt materials is considered to be caused by abnormal changes in the internal dissipation energy of materials, thus the internal dissipation energy of the materials will change significantly when damaged [19, 20]. Therefore,  $N_{DR}$  was chosen to analyze the fatigue characteristics of the micro-powder modified asphalt.

Fig. 2(a) illustrates the  $DR$ - $N$  evolution curves of PC-P1 modified asphalt under varying stress levels, with other modified asphalt variants exhibiting similar trends. The dissipated energy change rate ( $DR$ ) curves of asphalt typically demonstrate three sequential stages: during initial loading, the  $DR$  value initially rises sharply then gradually decreases before stabilizing in what is termed the adaptation phase; this is followed by the cumulative damage

phase where the curve shows minimal fluctuation with  $DR$  values approaching zero; finally, an inflection point appears in the failure phase, after which the  $DR$  value increases rapidly, indicating internal material damage. This critical point is defined as the fatigue failure threshold, with the corresponding loading cycle count designated as fatigue life ( $N_{DR}$ ), which serves as the criterion for determining material fatigue performance under cyclic loading conditions.

Fig. 2(b) presents the fatigue life data derived from  $DR$  curves of modified asphalt, revealing that the incorporation of micro-powder particles significantly influences the fatigue performance of asphalt, with fatigue life increasing as particle size decreases ( $HL-P1 < HL-P2 < HL-P3$ ), indicating that modified asphalt prepared with the smallest particles ( $HL-P3$ ) exhibits the highest number of cyclic loading cycles. This phenomenon primarily stems from the reduced interparticle spacing in asphalt as micro-powder size decreases, creating more obstacles that hinder microcrack propagation-effectively "pinning" microcracks with fine particles and thereby extending fatigue life. Additionally, compared to coarse particles, finer particles offer greater mass-specific quantity and higher specific surface area, leading to enhanced adsorption of free asphalt and stronger interfacial interactions between micro-powder and asphalt matrix, which further improves fatigue resistance. Notably,  $HL-P1$  exhibits enhanced fatigue life with increasing dosage levels, a phenomenon attributed to the cumulative surface area augmentation resulting from higher particle incorporation. This mechanism shares a fundamental similarity with the effects of particle size reduction, as both processes amplify interfacial interactions between the filler and asphalt binder. Furthermore, comparative analysis of materials with similar particle size distributions ( $HL-P1$  vs.  $PC-P1$ ) reveals significant differences in fatigue performance (Fig. 2). Specifically,  $HL-P1$ 's porous surface structure facilitates superior adsorption of asphalt light fractions, thereby improving its fatigue resistance through enhanced interfacial bonding. These findings align with the physical adsorption mechanism of micropowder modification reported in Literature 14, which identifies specific surface area as the critical parameter governing asphalt performance enhancement. Consequently, under identical mesh size and specific surface area conditions, different micropowder types are expected to yield equivalent modification effects when incorporated into asphalt.

Under varying stress conditions, the influence of particle size, dosage, and material type on fatigue performance diminishes with increasing stress levels, indicating accelerated cumulative damage development in materials under

**Table 1.** Basic parameters and test scheme of micro powder:

Type	Code	Mesh	Dosage in asphalt (%)	Specific surface area ( $m^2/g$ )	Stress (MPa)	Chemical composition	Preparation Conditions for Modified Asphalt		
							Temperature (°C)	Time (min)	Speed (r/min)
Hydrated lime	HL-P1	200-300	2.5	0.7836			150	40	5000
	HL-P2	400-500	7.5	2.0956	0.10	Ca(OH) <sub>2</sub>	150	40	5000
	HL-P3	800-1000		4.9374	0.15		170	20	5000
Portland cement	PC-P1	200-300	5.0	0.3852		C <sub>3</sub> S C <sub>2</sub> S C <sub>3</sub> A	150	40	5000
	SF-P1	2000-3000		9.7901		SiO <sub>2</sub> Al <sub>2</sub> O <sub>3</sub>	170	20	5000
Original asphalt	OR	/	/	/		/	/	/	/

high-stress conditions.

### 3.1.2. Cumulative dissipation energy ratio (DER)

DER is another important index to characterize the fatigue life of asphalt and mortar. It is the ratio of the cumulative dissipation energy generated by the first  $n$  loads and the dissipation energy of the  $n$ th load.

Fig. 3(a) displays the  $DER - N$  evolution curves of PC-P1 modified asphalt under varying stress levels, with similar patterns observed for other modified asphalt variants. During initial loading, fatigue damage accumulation within micro-powder modified asphalt remains negligible, resulting in minimal dissipated energy variation—the curves initially align with the  $45^\circ$  reference line ( $DER \approx N$ ). As sustained constant stress is applied, cumulative damage progressively develops within the modified asphalt, causing per-cycle dissipated energy to increase and the cumulative dissipated energy ratio (DER) curves to gradually deviate from the  $45^\circ$  line. When fatigue damage exceeds the material's critical threshold, accelerated failure occurs, marked by an inflection point on the  $DER - N$  curves. This inflection point is defined as the fatigue life criterion based on cumulative dissipated energy ratio ( $N_{DER}$ ).

Fig. 3(b) illustrates the fatigue life data derived from DER curves of modified asphalt, revealing that smaller particle sizes reduce the sensitivity of cumulative dissipated energy ratio (DER) to stress levels. For the same material type, micro-powder modified asphalt with smaller particles (higher specific surface area) demonstrates greater load-bearing capacity and longer fatigue life. Comparative analysis of three material variants shows that silica fume exhibits the highest loading cycle count, followed by hydrated lime, with cement showing the lowest. Additionally, when compared to original asphalt, all three micro-powder modified asphalts demonstrate significantly higher fatigue life under identical stress conditions, confirming that micro-powder incorporation substantially enhances asphalt fatigue performance under stress-controlled loading.

Comparative analysis of Fig. 2(b) and Fig. 3(b) reveals minimal discrepancies in fatigue life determinations between the two methods, though  $N_{DR}$  values consistently exceed  $N_{DER}$  values. From the perspectives of pavement design and material selection, adopting  $N_{DER}$  as a performance evaluation metric offers higher safety reliability. Furthermore, Fig. 2(a) demonstrates that fatigue life inflection points defined by  $N_{DR}$  exhibit indistinct curve transitions, complicating loading cycle determination. In contrast, Fig. 3(a) shows that  $N_{DER}$  curves present clear maximum values with pronounced inflection points indicating accelerated internal fatigue damage, facilitating straightforward fatigue life assessment. Research confirms

these inflection points correspond to abrupt changes in cumulative internal damage energy.

Therefore, this study recommends employing the cumulative dissipated energy ratio ( $N_{DER}$ ) as the primary fatigue life evaluation criterion for micro-powder modified asphalt when conducting dissipated energy-based fatigue analysis.

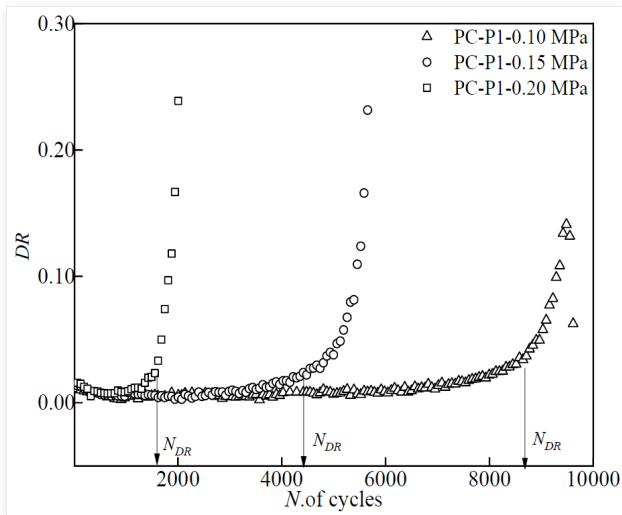
## 3.2. Fatigue performance analysis based on the continuous damage mechanics (VECD) model

According to the research, the accelerated loading (LAS) and time scanning (TS) tests using DSR are applicable to the VECD model of continuous damage mechanics [21]. Therefore, in this study, the peak value of  $C \times N$  based on the VECD model was used as the fatigue failure discrimination index, and the curve of the product between the virtual modulus and number of load actions  $N$  was established. For the unloaded material, the virtual modulus of the material is 1. When the load accumulation time increases, the value of the virtual modulus  $C$  gradually decreases, and damage gradually accumulates in the material, causing the  $C \times N - N$  curve to show an obvious turning point. According to the research by Wang et al, the turning point of this curve is taken as the failure point of the fatigue life in asphalt materials [22, 23].

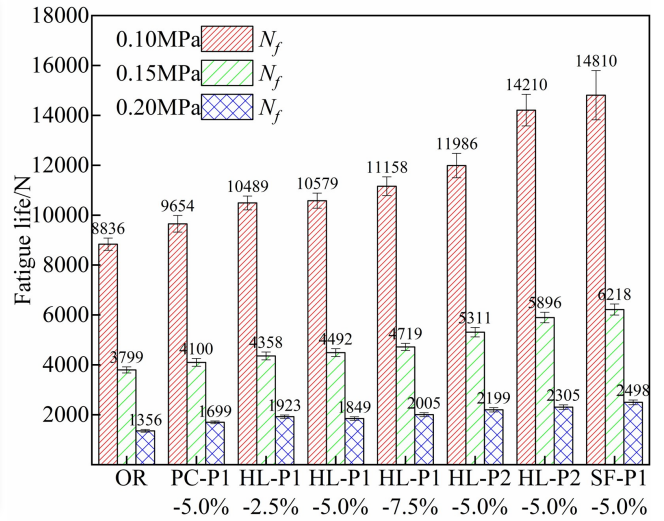
### 3.2.1. Fatigue life results

Fig. 4 shows  $C \times N - N$  loading curves of three micro-powder materials under 0.1 MPa stress. The corresponding inflection point loading times were recorded as the fatigue life. Under the stress loading mode, the  $C \times N - N$  curve inflection point was at the transition point between the second stage of slow decline to the third stage of rapid decline. At this point, the interior of the material started experiencing accelerated failure, and microcracks started developing into macrocracks.

Fig. 5 shows the fatigue life of various micro-powder modified asphalts obtained according to the  $C \times N - N$  curve. The fatigue life of the micro-powder modified asphalts, based on cumulative damage, was consistent with the fatigue life law, based on dissipation energy. After adding micro-powder into the original asphalt, the fatigue life increased, and the improvement effect was in order of magnitude: SF > HL > PC. The influence of different particle size of HL on the fatigue life of asphalt was also significant, HL-P3 > HL-P2 > HL-P1, indicating that the influence of the particle size of inorganic modified materials on the performance of asphalt gradually increased with a decrease in particle size. The effect of micro-powder on asphalt under different stresses is inconsistent. The effect of micro-powder on the improvement of asphalt fatigue life under

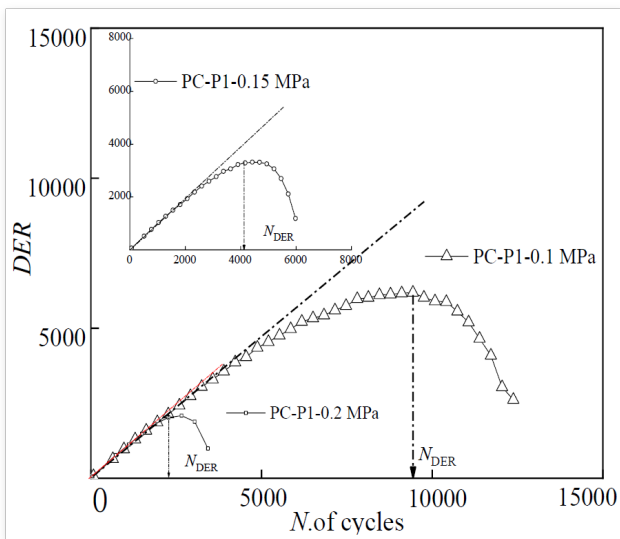


(a) Fatigue curve of PC-P1 modified asphalt.

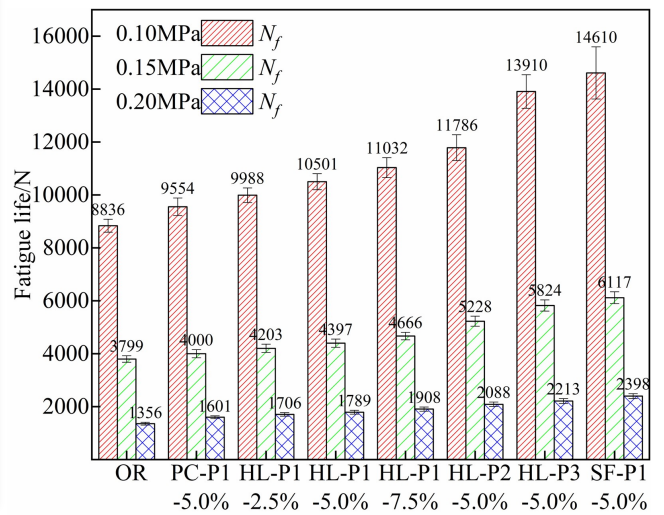


(b) Fatigue life of NDR modified asphalt.

Fig. 2. Modified Asphalt  $N_{DR}$  Fatigue Life Curve and Fatigue life.



(a) Fatigue curve of PC-P1 modified asphalt.



(b) Fatigue life of  $N_{DER}$  modified asphalt

Fig. 3. Modified Asphalt  $N_{DER}$  Fatigue Life Curve and Fatigue life.

small stresses is obvious. Among them, SF increases the fatigue life by more than 69.3% compared with the original asphalt. But at 0.2 MPa, the effect of SF on improving fatigue life of original asphalt decreases significantly. Under identical dosage conditions, HL-P1 and PC-P1 with similar particle sizes exhibit distinct performance characteristics, which is attributed to the larger surface structural pores in HL-P1 that facilitate adsorption of light asphalt components.

### 3.2.2. Damage characteristic curve

The cumulative damage characteristic curve ( $D - C$ ) was obtained according to the VECD model.  $D$  is the damage accumulation degree of the material during the loading process. With repeated loading, the damage inside the material gradually accumulates,  $D$  gradually increases, and the virtual modulus  $C$  gradually decreases. The value of  $D$  is the largest and the value of  $C$  is the smallest when the material begins to damage.

Fig. 6 shows the relationship between the virtual mod-

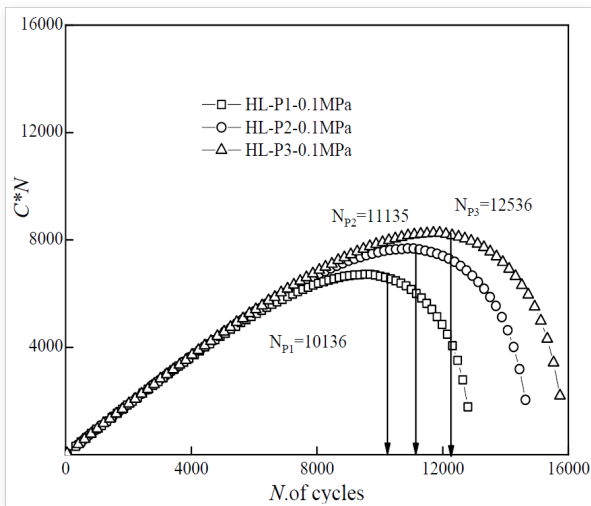


Fig. 4. CxN loading curve of powder different materials.

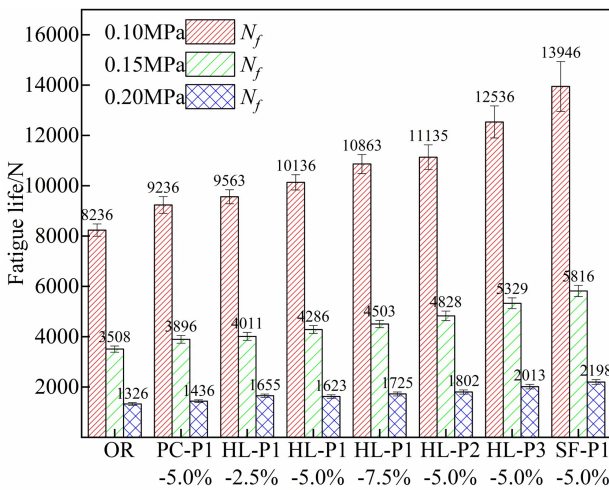


Fig. 5. Fatigue life of modified asphalt  $N_f$  of different stresses

ulus  $C$  and damage cumulative strength  $D$  of the micro-powder modified asphalt. Fig. 6(a) shows obviously separated damage curves after the cumulative damage strength of the three types of micro-powder modified asphalt exceed  $60(D)$ . The graph shows the curve of SF-P1 at the top and that of PC-P1 at the bottom. The virtual modulus  $C$  of SF is the largest, and the material damage is the smallest under repeated loading, indicating that the fatigue life is the longest. In Fig. 6(b), the damage curve of the modified asphalt mixed with HL is significantly higher than that of the original asphalt. The damage curve spacing of micro-powder modified asphalt for different dosages is notably smaller than that for different particle sizes, that is, the effect of increasing dosage is smaller than that of decreasing particle size.

### 3.3. Fatigue life analysis under different methods

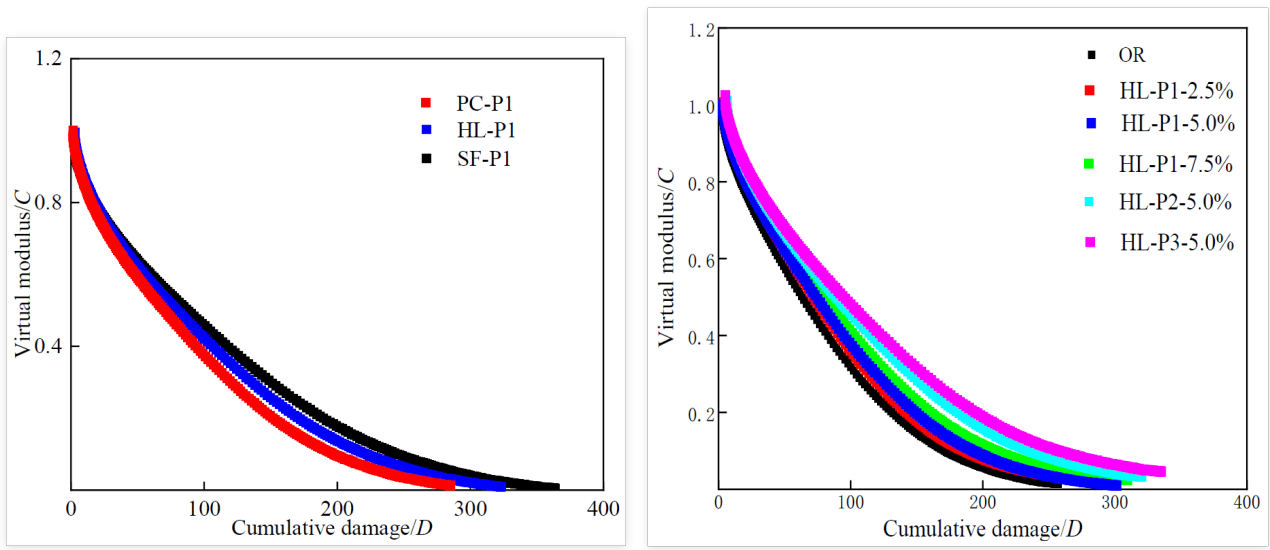
The  $N_{DER}$ , based on the dissipation energy, and fatigue life, based on the damage mechanics VECD model  $N_f$ , were compared and analyzed. The results are listed in Table 2.

From Table 2, it can be observed that the fatigue life patterns derived from both indices exhibit high consistency. Under the influence of particle size and dosage, fatigue life increases with decreasing particle size and increasing dosage. Regarding the effect of powder type, the fatigue life sequence follows: silica fume > hydrated lime > cement. However, experimental data reveal that the reduction ratio of material modulus at the inflection point  $N_f$  on the  $C \times N-N$  curve is consistently lower than that corresponding to the  $N_{DER}$  index. Consequently, the  $N_f$  index derived from continuum damage mechanics (CDM) is uniformly smaller than the  $N_{DER}$  index obtained through dissipated energy analysis. This discrepancy primarily arises because the VECD model within CDM framework excludes viscoelastic effects of asphalt materials, focusing solely on cumulative damage under external loading. Under this model, asphalt exhibits accelerated failure characterized by rapid propagation of internal microcracks and damage. Therefore, the  $N_f$  index based on CDM yields more conservative fatigue life estimates compared to the  $N_{DER}$  index derived from cumulative dissipated energy, recommending its adoption for material performance evaluation.

## 4. Analysis of influence of micro-powder characteristics on fatigue performance of asphalt

### 4.1. Relationship between type, particle size, and micro-powder content, and fatigue performance of asphalt

1. The relationship between the type of micro-powder and fatigue life of asphalt Based on the fatigue failure criterion derived from the Viscoelastic Continuum Damage (VECD) model ( $N_f$  index), Fig. 7(a) presents the fatigue life of hydrated lime-, silica fume-, and cement-modified asphalts under three stress levels (0.1 MPa, 0.15 MPa, and 0.2 MPa). The fatigue life sequence SF-P1 > HL-P1 > PC-P1 primarily correlates with silica fume's particle size and surface morphology, which significantly influence its specific surface area and subsequent adsorption capacity in asphalt, thereby altering the modified binder's performance. For hydrated lime and cement with comparable particle sizes, the difference in fatigue life stems from their distinct surface morphological characteristics. The correlation between micropowder type and fatigue life deteriorates under high stress conditions: silica fume improves fatigue life by approximately 51%

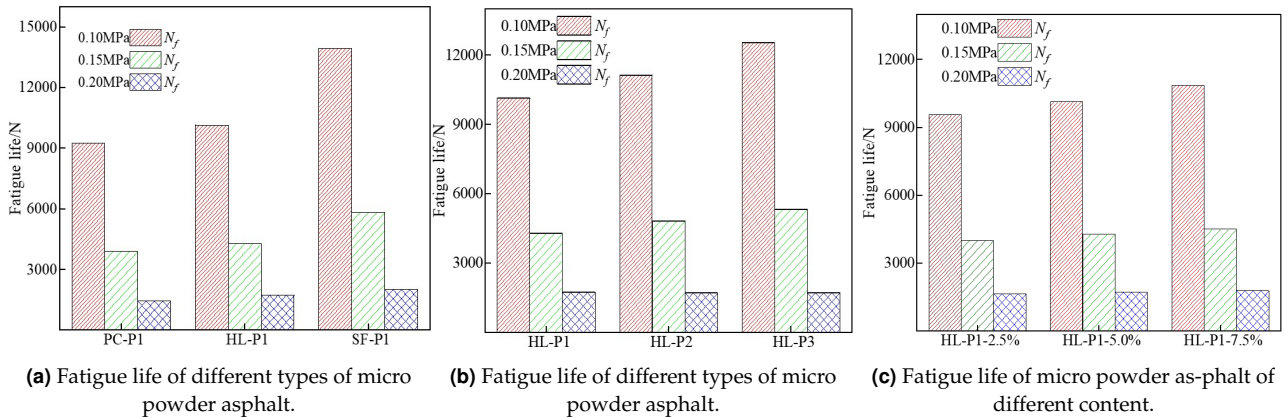


(a) Damage characteristic curve of 5% micro powder of different types

(b) Cumulative damage characteristic curve of HL.

**Fig. 6.** Relationship analysis between virtual modulus  $C$  and cumulative damage  $D(t)$ .**Table 2.** Fatigue life of  $N_f/N_{DER}$  modified asphalt of different stresses.

Type	Dosage in asphalt (%)	0.1 Mpa		0.15 Mpa		0.2 Mpa	
		$N_{DER}$	$N_f$	$N_{DER}$	$N_f$	$N_{DER}$	$N_f$
OR	/	8836	8236	3799	3516	1300	1326
HL-P1	2.5	9988	9563	4203	4011	1706	1655
	5.0	10501	10136	4397	4286	1789	1623
	7.5	11032	10863	4666	4503	1930	1789
HL-P2		11786	11135	5228	4828	2088	1802
HL-P3	5	13910	12536	5824	5329	2213	2013
SF-P1		14610	13946	6117	5816	2398	2198
PC-P1		9554	9236	4000	3896	1601	1436



(a) Fatigue life of different types of micro powder asphalt.

(b) Fatigue life of different types of micro powder asphalt.

(c) Fatigue life of micro powder asphalt of different content.

**Fig. 7.** Fatigue Life ( $N_f$ ) of Micropowder-Modified Asphalt.

compared to cement at 0.1 MPa under the  $N_f$  criterion, but this enhancement decreases to 30% at 0.2 MPa, indicating that micropowder type exerts a more pronounced influence on asphalt fatigue life under

low stress conditions.

2. Relationship between particle size of fine powder and fatigue life of asphalt Fig. 7(b) shows the fatigue life of modified asphalt under different particle sizes of

HL. The addition of HL micro powder can improve the fatigue life of asphalt. The improvement effect is more obvious with the reduction of the particle size to a micro powder. The specific order of magnitude is: HL-P3 > HL-P2 > HL-P1. However, there was a considerable difference in the lifting effect under the different stresses. For example, for the fatigue life under 0.1 MPa, P3 and P1 micro-powder increased by approximately 24% with the  $N_f$  index, whereas for the fatigue life under 0.2 MPa, P3 and P1 micro-powder increased by approximately 1%. This is mainly because under the same mass, the smaller the particle size and larger the specific surface area of the micro-powder particles under lower stress, the more free asphalt being adsorbed and the better the interfacial adhesion between the micro-powder and asphalt. However, under large stresses, the micro-powder is squeezed by the stress, which destroys the stable structure between the asphalt and micro-powder particles.

3. Relationship between the content of micro-powder and fatigue life of asphalt Fig. 7(c) shows the influence of HL micro-powder content on the asphalt fatigue life. The higher the content of HL micro-powder, the higher the fatigue life of the modified asphalt. This is owing to the increase in the amount of micro-powder and number of micro-powder particles. For the same particle size, the amount of micro-powder increases, resulting in an increase in the total surface area in the asphalt, amount of free asphalt in the adsorbed asphalt, and viscosity of the asphalt. In addition, the fatigue resistance improves.

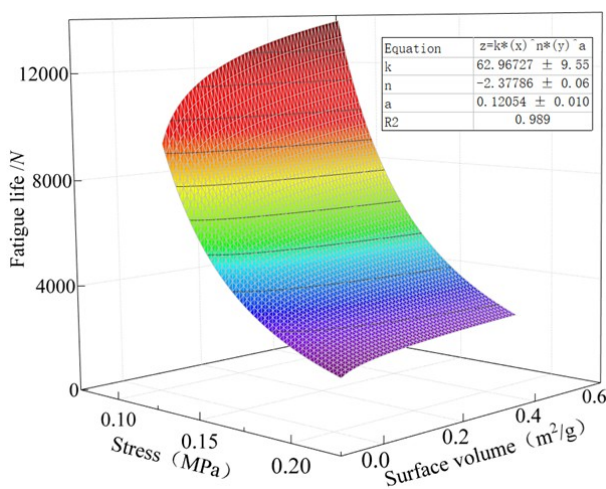


Fig. 8. Fitting surface and equation of fatigue life and surface product of micro powder modified asphalt.

#### 4.2. Correlation between the surface area of micro-powder in asphalt and fatigue performance

Based on the analysis of the relationship between the type, particle size, and content of micro-powder, the fatigue life of asphalt is found to be significantly affected not only by the type and content of micro-powder, but also by the particle size. The difference in fatigue life caused by the different types and contents of micro-powder is mainly owing to the change in surface area of the micro-powder in the asphalt. The change in particle size also affects the action surface area of the micro-powder in the asphalt. Therefore, in this study, the specific surface area parameters of the micro-powder mixed into the asphalt are converted into the internal surface area content per unit mass of asphalt, and expressed by the "surface area content" ( $m^2/g$ ), that is, the surface area content per gram of asphalt, as listed in Table 3.

Using the fatigue life data derived from the damage mechanics indicator  $N_f$ , a three-dimensional surface plot was constructed to establish the relationship between fatigue life, specific surface area ( $S$ ), and applied stress, as shown in Fig. 8. The conventional stress-based fatigue equation [24] was subsequently modified by incorporating the specific surface area parameter  $S$ , as presented in Eq. (4). Through nonlinear regression analysis of the 3D surface data, an inorganic micropowder-specific stress-fatigue life prediction model was developed (Eq. (5)). This model enables direct prediction of fatigue life under known stress conditions and micropowder surface area dosage ( $S$ ) in asphalt, effectively eliminating the confounding effects of material type, admixture content, and particle size distribution.

$$N_f = k(\sigma)^{-n}(s)^a \tag{4}$$

$$N_f = 62.97(\sigma)^{2.38}(s)^{0.12}, \tag{5}$$

where  $N_f$  is the fatigue life of the micro-powder based on damage mechanics;  $S$  is the surface area content of the micro-powder particles added to the asphalt ( $m^2/g$ ); and  $k$ ,  $n$ , and  $a$  are the fitting parameters.

#### 5. Conclusion

1. Based on the dissipative energy theory, the  $N_{DER}$  and  $N_{DR}$  were used to determine the fatigue life of different micro-powder modified asphalt. The comparison indicated that the fatigue life determined by the two methods did not differ significantly; however, the  $N_{DR}$  was slightly larger than that of  $N_{DER}$ . From the perspective of pavement design and material selection, the  $N_{DER}$  index is safe for the evaluation of asphalt performance.

**Table 3.** Fatigue Life of micro powder modified asphalt.

Type	Dosage in asphalt (%)	Fatigue life $N_f$			Specific surface area ( $m^2/g$ )	Surface area content S ( $m^2/g$ )
		0.1 MPa	0.15 MPa	0.2 MPa		
HL-P1	2.5	9563	4011	1655	0.7836	0.0196
	5	10136	4286	1723		0.0392
	7.5	10863	4503	1789		0.0588
HL-P2		11135	4828	1702	2.0956	0.1048
HL-P3	5	12536	5329	1713	4.9374	0.2469
SF-P1		13946	5816	1998	9.7901	0.4895
PC-P1		9236	3896	1436	0.3852	0.0193

- The continuous damage mechanics model VECD was used to analyze the fatigue damage characteristics of inorganic-micro-powder modified asphalt under loading. The  $C \times N$  peak value was used to determine the fatigue life to realize the mechanical response of the fatigue cumulative damage of the modified asphalt under the load only. Through comparison, the  $N_f$  determined by the  $C \times N$  peak of continuous damage mechanics was found to be more conservative than the fatigue life determined by the  $N_{DER}$ . This was because the VECD mechanical model excluded the influence of the viscoelastic mechanical response of asphalt materials on the fatigue life of materials.
- Comparative analysis of fatigue life predictions based on dissipated energy theory and continuum damage mechanics revealed consistent patterns: For the same micropowder type under identical stress conditions, modified asphalt exhibited enhanced fatigue resistance with decreasing particle size (increased specific surface area). The fatigue life ranking among three micropowder-modified asphalts followed: silica fume (SF-P1) > hydrated lime (HL-P1) > Portland cement (PC-P1). For hydrated lime-modified asphalt with varying dosages, the fatigue life sequence was: 7.5% > 5.0% > 2.5% (by mass of binder). Under different stress levels, the fatigue life decreased in the order: 0.10 MPa > 0.15 MPa > 0.20 MPa.
- Based on the fatigue life of the obtained damage mechanics index  $N_f$ , a three-dimensional curved surface between the fatigue life and micro-powder surface area content and stress was established. In addition, the surface area stress fatigue equation was determined by fitting the curved surface. The fatigue life prediction of the micro-powder modified asphalt under the influence of different surface area content was realized.

Funding: This study is supported by Key Science and Technology Projects of Chongqing Education Commis-

sion (Grant no. KJZD-K202304002), Postdoctoral Research Project of Chongqing Technology and Business Institute (BSH2024-02) and General Project of Chongqing Natural Science Foundation (2024NSCQ-MSX2005)

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