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Characterization of the effect of foaming water content on the performance of foamed crumb rubber modified asphalt

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Abstract: Crumb rubber modified asphalt (CRMA) is a "green" paving material which provides an effective way to recycle waste tires. However, it also faces the criticism of increased energy consumption and air emissions during construction. Foaming technology allows CRMA to be constructed at lower temperatures, but very limited research has been conducted on the influence of foaming water content on the properties of foamed CRMA binder. In this study, foamed CRMA binders were produced at various foaming water contents (0%, 1%, 2%, 3%, and 4%) in laboratory, and their high-temperature performance, low-temperature performance, temperature sensitivity, and fatigue resistance were characterized and compared through laboratory testing. The test results indicated that foamed CRMA binders provide slightly worse high-temperature performance but better low-temperature performance, temperature stability, and fatigue resistance, compared to regular CRMA binder. With the increase of foaming water content, the high-temperature performance of foamed CRMA binder drops off, the low-temperature performance of foamed CRMA binder first decreases and then increases, and the temperature stability and fatigue resistance of foamed CRMA binder keep increasing. And we recommend that 4% is the optimum water content for CRM binder.

Keywords: Crumb rubber modified asphalt; Foamed asphalt; Foaming water content; Rheological properties

Highlights:

- The rheological properties of foamed CRMA binders with different foaming water contents were characterized and compared.
- Foamed CRMA binders were found to provide slightly worse high-temperature performance but better low-temperature performance, temperature stability, and fatigue resistance.
- The temperature stability and fatigue resistance of foamed CRMA binder increase with the increase of foaming water content.
- The high-temperature performance of foamed CRMA binder drops off with the

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increase of foaming water content.

- The low-temperature performance of foamed CRMA binder first decreases and then increases with the increase of foaming water content.
- 4% is the optimum water content for CRM binder.

1. Introduction

With the increasing awareness of the environmental challenges, such as global warming, environmental pollution, and energy depletion, pavement industry has shown greater interests in using sustainable paving materials, such as warm mix asphalt (WMA), crumb rubber modified asphalt (CRMA), and recycled asphalt pavement (RAP).

Currently, three types of WMA technologies have been commonly used to reduce the production temperature of hot mix asphalt (HMA): organic additives which decrease the viscosity of binder [1-3], foaming process or additives [4-7], and chemical additives which decrease the interfacial friction between asphalt and aggregate [8]. Among these technologies, foaming process is the only one which does not require any costly additives [9], and it allows asphalt mixture to be compacted at a temperature as low as 76 °C [10]. The mechanism of foaming process is based on the injection of water into hot liquid asphalt during the mixture mixing process, which causes the liquid asphalt to foam and expand in volume, therefore lowering the mixing temperature.

Casteclo-Franco et al. investigated the conditions for foaming asphalt and found that any asphalt can be foamed under appropriate conditions [11]. Shu et al. evaluated the moisture susceptibility of plant-produced foamed WMA containing high percentages of RAP [12]. They found that foamed WMA with incorporation of RAP provides comparable performance with respect to HMA in terms of moisture susceptibility, but some other researchers claimed that the amount of RAP cannot be too high [13]. Punith et al. [14] studied the effect of long-term aging on the moisture susceptibility of foamed WMA containing moist aggregate. The results showed that aggregate source significantly affects the moisture resistance of foamed WMA regardless of the foaming technology and aggregate moisture content. Xiao et al. found that the foaming process might reduce the stored elastic energy of the mixture due to additional water or released water from water-bearing additive, and aggregate source affects the fracture resistance of foamed WMA [15]. Kavussi et al. claimed that lower mixing and compaction temperatures result in higher moisture susceptibility and rutting potential of foamed WMA, and the addition of hydrated lime powder is effective in decreasing rutting and moisture susceptibility of foamed WMA [16]. Cong et al. investigated the effects of asphalt binder, crumb rubber type and crumb rubber content on the properties of CRMA binders [17]. Their experimental results revealed that crumb rubber decreases the penetration, ductility and phase angle of asphalt binder, but increases the softening point, elastic recovery, viscosity, complex modulus and rutting parameter of asphalt. Wang et al. found that crumb rubber can significantly improve the viscosity of binder at high temperature and lower the creep stiffness at low temperature, which is beneficial to both high temperature stability and low temperature cracking resistance of asphalt pavements, and a rubber-asphalt ratio of 15% to 20% was proposed for the production of CRMA binder [18].

Although large amount of studies have been conducted on foamed asphalt and CRMA binder, few of them have focused on combining these two sustainable techniques. Specifically, the influence of foaming water content on the properties of foamed CRMA binder has not been well studied yet. Thus, this study aims to investigate the effects of foaming water content on the rheological properties of foamed CRMA binder. To achieve this objective, foamed CRMA binders were first produced at various foaming water contents (0%, 1%, 2%, 3%, and 4%) using a laboratory foaming machine, and then their high-temperature performance, low-temperature performance, temperature sensitivity, and fatigue resistance were characterized and compared through laboratory testing.

2. Material preparation and experimental program

2.1 Material preparation

2.1.1 Materials

The raw asphalt used in this study had a penetration grade of 70# and an equivalent Superpave performance grade of PG64-22. Its basic properties are summarized in Table 1. The crumb rubber modifier (CRM) was manufactured by mechanically shredding waste tires at ambient temperature. To ensure the uniformity, all the CRM used in this study were from the same production batch and within the same size range of minus 20mesh. Ordinary tap water was used as the foaming water.

Table 1 Properties of the Raw Asphalt

Property	Test Standards	Test Results
Penetration (25^{o}C,100g,5s) (0.1mm)	ASTM D 5	68.7
Ductility (15^{o}C,5cm/min) (cm)	ASTM D 113	>100
Softening point ($T_{R\&B}$) (^{o}C)	ASTM D 36	49.3
Density (15^{o}C) (g/cm^3)	ASTM D 70	1.032
Solubility (trichloroethylene) (%)	ASTM D 2042	99.8
PG grade	ASTM D 946	PG64-22

2.1.2 Preparation of CRMA binder

CRMA binder was produced by adding 18% of CRM by weight of asphalt into the raw asphalt. The mixing of CRM and asphalt was accomplished by using a paddle stirrer at a rotation speed of 1500 rpm at 175°C for 45 minutes [19].

2.1.3 Preparation of foamed CRMA binder

Foamed CRMA binder was produced using the foaming machine manufactured by Wirtgen Group (Fig. 1). With this machine, the foaming temperature in the asphalt heating barrel can be effectively controlled, and the accuracy of water meter can reach 0.5% of the normal foaming asphalt dosage.

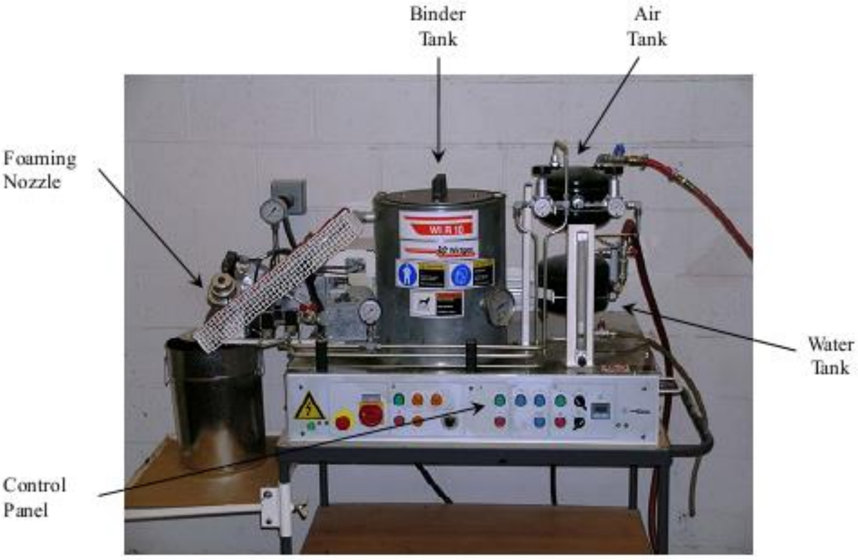

Fig. 1 Foaming Machine

Foamed CRMA binders (Fig. 2) with 1%, 2%, 3%, and 4% foaming water by weight of CRMA were prepared, and the foaming temperatures of the asphalt and water were controlled at 185^{o}C and 30^{o}C, respectively.

Fig. 2 Foamed CRMA Binder

2.2 Experimental program

To evaluate the rheological properties of the foamed CRMA binders with different foaming water contents at different temperatures as well as their long-term aging behaviors, various laboratory tests were conducted in this study.

Dynamic shear rheometer (DSR) tests were conducted to obtain the failure temperature, logarithms of storage and loss modulus at different temperatures, and ultimate fatigue temperature, which were used to evaluate the high-temperature performance, temperature sensitivity, and fatigue resistance of foamed CRMA binder, respectively. Bending beam rheometer (BBR) tests were conducted to obtain the creep stiffness and m-value, which were used to assess the low-temperature performance of foamed CRMA binder. Fig. 3 summarizes the experimental program of this study.

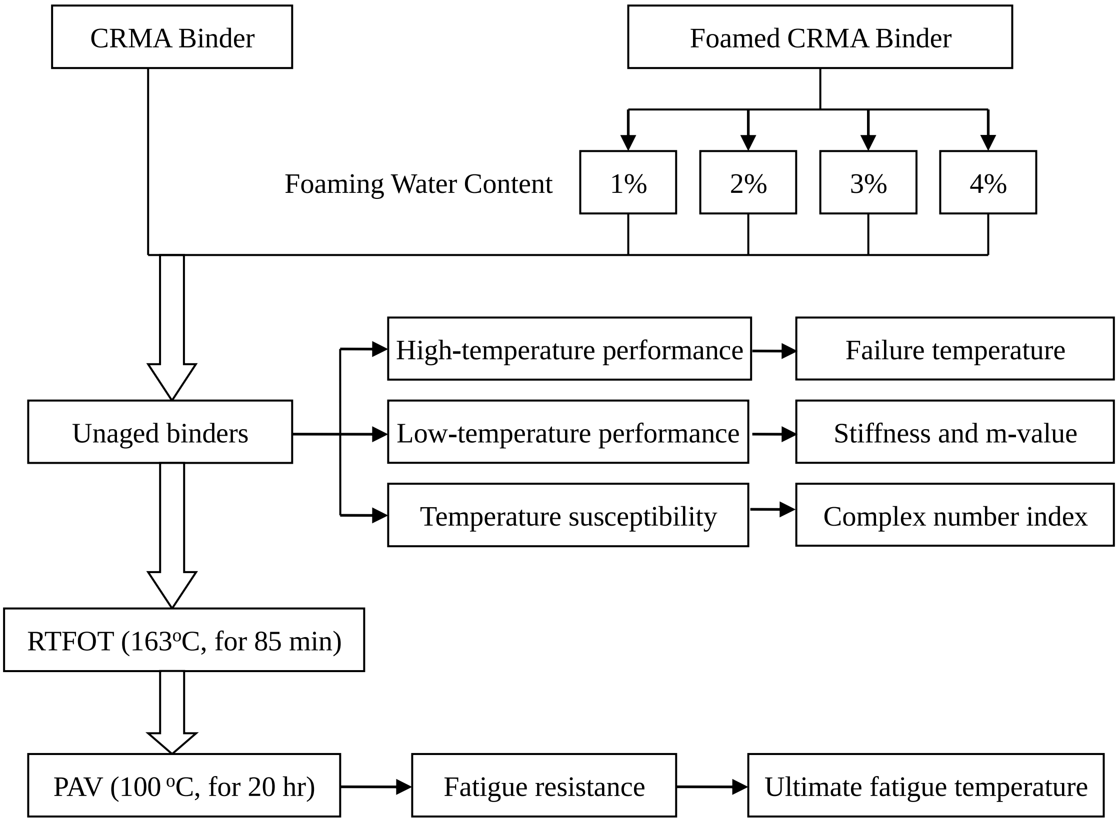

Fig. 3 Flow Chart of the Experiment Program

2.2.1 High-temperature performance

To evaluate the high-temperature performance of foamed CRMA binder, temperature sweep tests were conducted using a ATAAR1500^{EX} DSR machine according to AASHTO T315 [20]. Based on the test results, the rutting factor, $G^*/\sin\delta$, where G^* is the complex shear modulus and δ is the phase angle, was calculated. Liner regression models were then developed between the logarithm of $G^*/\sin\delta$ and the logarithm of temperature. The failure temperatures, which correspond to the temperatures when $G^*/\sin\delta$ are equal to 1.0KPa, were obtained from the linear regression models [21-22], and a higher failure temperature indicates better high-temperature performance of an asphalt binder. The specific testing parameters are as follows:

- Temperature: 40-80°C (10°C intervals)
- Frequency: 10 rad/s
- Sample dimension: 25 mm diameter with 3.5 mm gap

- Strain level: 12%

2.2.2 Low-temperature performance

The low-temperature performance of foamed CRMA binder was evaluated by the creep stiffness (S) and m-value from the BBR tests at different temperatures (-12°C, -18°C, and -24°C) [23]. The BBR machine was manufactured by Cannon Instrument Company. According to the Superpave binder specifications, the m-value is defined as the slope of the stiffness (MPa) in logarithmic scale at 60 seconds [24].

2.2.3 Temperature sensitivity

Several methods are available for evaluating the temperature sensitivity of asphalt binders, such as Penetration Index (PI) [25], Penetration-Viscosity Numbers (PVN) [26], Viscosity-Temperature Susceptibility (VTS) [27], complex shear modulus (G*) [28], and storage and loss moduli (G’ and G’’) [29]. In this study, the storage modulus and loss modulus of the asphalt binders at different temperatures were selected. Linear regression equations were developed between the logarithms of the storage and loss moduli and the temperatures, respectively. Then, the slopes of the linear regression equations were calculated to evaluate the temperature sensitivity of the tested binders [30]: a larger slope indicates a higher sensitivity.

2.2.4 Fatigue resistance

To evaluate the fatigue resistance, foamed CRMA binders were first short-term and long-term aged through rolling thin film oven (RTFO) test and pressure aging vessel (PAV) test, respectively. Then, DSR tests were conducted on the aged binders to obtain G*·sinδ, which is an indicator of the fatigue performance of the binders [31]. Statistical regressions were conducted between the logarithms of G*·sinδ and the logarithms of temperatures. From the regression equations, the temperatures corresponding to 5.0MPa, which are defined as the ultimate fatigue temperatures, were obtained. The specific testing parameters are as follows:

- Temperature: 10-40°C (10°C intervals)
- Frequency: 10 rad/s
- Sample dimension: 8 mm diameter with 4 mm gap
- Strain level: 1%

3. Results and discussion

3.1 High-temperature performance

Table 2 shows the measured G*/sinδ of the foamed CRMA binders with different foaming water contents at different temperatures. Fig. 4 illustrates the relationships between the logarithms of the G*/sinδ and the logarithm of temperatures for different foaming water contents. From Fig. 4, it can be seen that there is a linear relationship between the logarithm of G*/sinδ and the logarithm of temperature, which is consistent with the findings in previous studies [32]. It can also be observed that the values of G*/sinδ of the foamed CRMA binders are smaller than that of the regular CRMA binder at the same temperature. In other words, after foaming, the high-temperature performance of CRMA binder is decreased.

Table 2 G*/sin δ of Formed CRMA Binders (kPa)

Temperature	0%	1%	2%	3%	4%
80°C	7.822	3.179	2.889	2.534	2.368
70°C	18.97	6.429	5.621	6.012	5.501
60°C	47.42	14.45	11.61	13.74	12.37
50°C	124.3	34.34	26.21	31.41	27.82
40°C	375.3	100.7	70.63	71.83	58.87

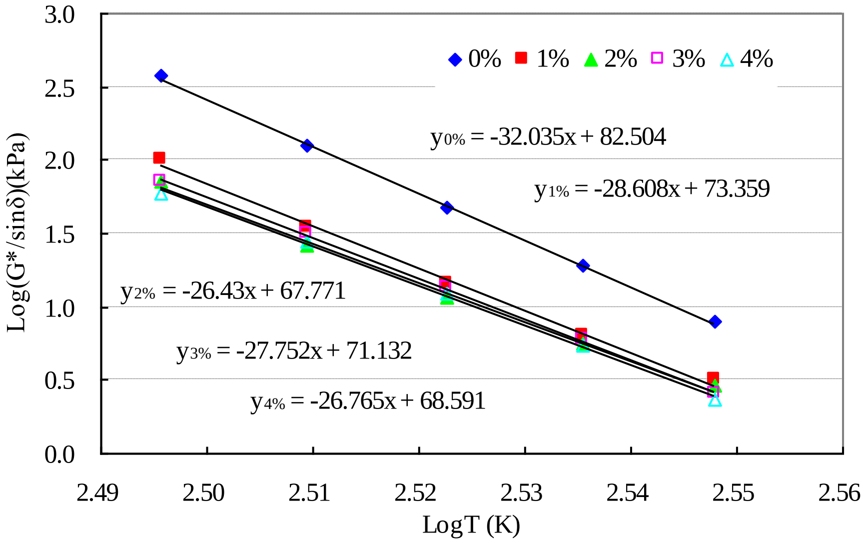

Fig. 4 Logarithm of the G*/sin δ of Formed CRMA Binders

Table 3 lists the failure temperatures corresponding to a G*/sinδ of 1.0kPa obtained from the linear regression models shown in Fig. 4. From Table 3, it can be seen that the failure temperatures of the foamed CRMA binders are much smaller than that of the regular CRMA binder. With the increase of foaming water content, the failure temperature of foamed CRMA binder decreases gradually, indicating gradually compromised high-temperature performance. When 4% foaming water is applied, the failure temperature of the CRMA binder drops 10.6%.

Table 3 Failure Temperatures of Formed CRMA Binders

Foaming Water Content	0%	1%	2%	3%	4%
Failure Temperature (°C)	103.1	93.5	93.4	92.6	92.2

3.2 Low-temperature performance

The low-temperature performance of foamed CRMA binder was evaluated through the BBR tests conducted at different temperatures (-12°C, -18°C, and -24°C). From the BBR test results, the creep stiffness (S) and creep rate (m-value) of each binder were obtained and the test results are shown in Table 4. Fig. 5 illustrates the stiffness of the foamed CRMA binders with different foaming water contents at different temperatures.

Table 4 Creep Stiffness and m-value of Formed CRMA Binders

		-12°C		-18°C		-24°C	
		S (MPa)	m-value	S (MPa)	m-value	S (MPa)	m-value
Foaming Water Contents	0%	66.1	0.355	225	0.298	433	0.216
	1%	51.5	0.432	128	0.383	338	0.270
	2%	58.7	0.431	149	0.410	334	0.312
	3%	53.4	0.429	136	0.396	342	0.307
	4%	48.3	0.456	117	0.428	321	0.298

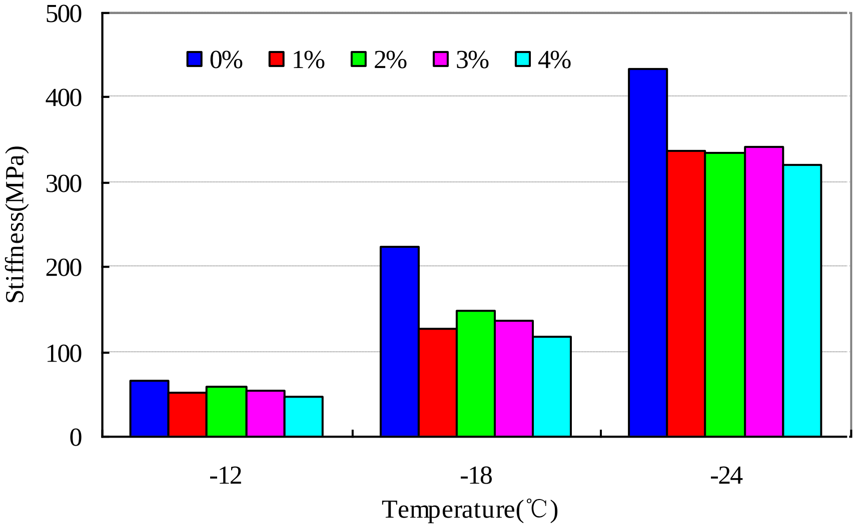

Fig. 5 Stiffness of Formed CRMA Binders at Different Temperatures

From Table 4 and Fig. 5, it can be seen that compared to regular CRMA binder, foamed CRMA binders provide smaller stiffness but higher m-value, indicating that the low-temperature performance of the binders are improved. With the increase of foaming water content, the stiffness of foamed CRMA binder first increases, and then decreases, while the change of m-value is insignificant. Li et al. [33] found that the creep stiffness is an appropriate evaluation index of low-temperature performance but the m-value is not. According to this finding, with the increase of foaming water content, the low-temperature performance of foamed CRMA binder first decreases and then increases. When 4% foaming water is added, the stiffness values of the foamed CRMA binders are 25.9% to 48.0% lower than that of the regular CRMA binder.

3.3 Temperature sensitivity

To evaluate the temperature sensitivity, the storage modulus (G') and loss modulus (G'') of each binder were measured within the temperature range from 40°C to 80°C with intervals of 10°C. Fig. 6 and Fig. 7 illustrate the relationship between log(G') and temperature, and the relationship between log(G'') and temperature, respectively. The statistical linear regression equations for these relationships are also shown in the figures. From Fig. 6 and Fig. 7, the slopes of each regression line were calculated and their absolute values are shown in Table 5.

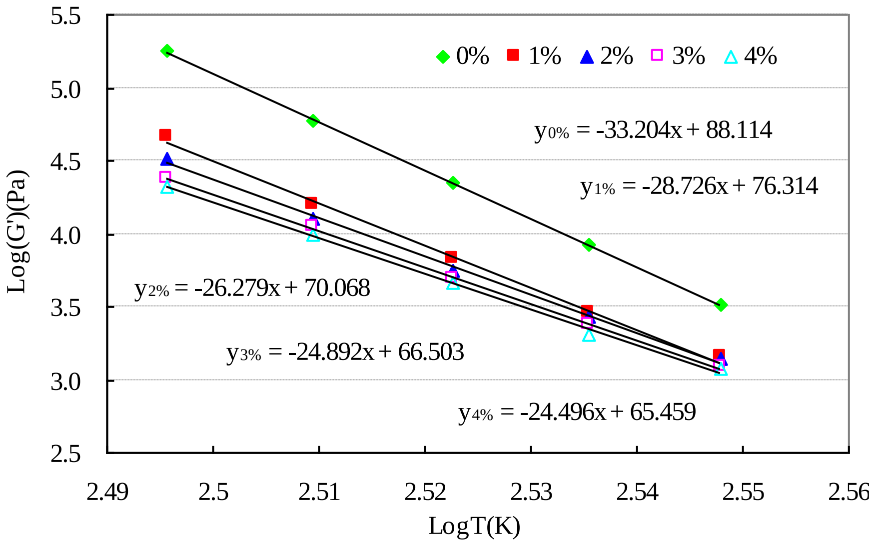

Fig. 6 Logarithm of Storage Modulus

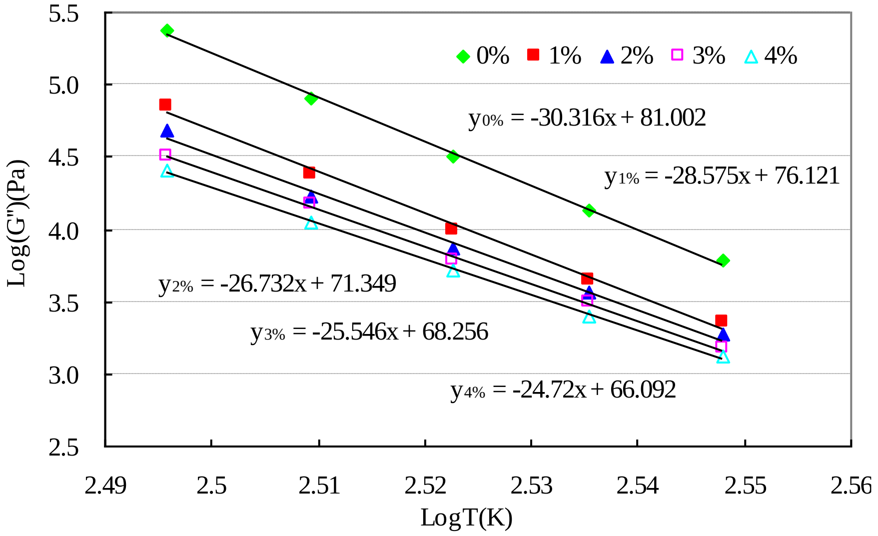

Fig. 7 Logarithm of Loss Modulus

Table 5 Absolute Slope Values for the Regression Lines in Fig. 6 and Fig. 7

		Absolute Value of Slope for Log(G') Regression Equation	Absolute Value of Slope for Log(G") Regression Equation
Foaming Water Contents	0%	33.204	30.316
	1%	28.726	28.575
	2%	26.279	26.732
	3%	24.892	25.546
	4%	24.496	24.720

Fig. 6 and Fig. 7 illustrate that, compared to the regular CRMA binder, the sensitivity of the storage modulus and the loss modulus of the foamed CRMA binders are substantially smaller, indicating that the foamed CRMA binders are less sensitive to temperature. From Table 5, it can be seen that with the increase of the foaming water content, the sensitivity of the storage modulus and the loss modulus of the foamed CRMA binders decrease gradually. In other words, the temperature stability of the foamed CRMA binders increases with the increase of foaming water content.

2.4 Fatigue resistance

To evaluate the fatigue resistance, each binder was first aged through RTFO and PAV tests, and then DSR tests were conducted on these aged binders. In the DSR tests, G*·sinδ was recorded every 10°C from 10°C to 40°C. The relationships between log(G*·sinδ) and logT are plotted in Fig. 8.

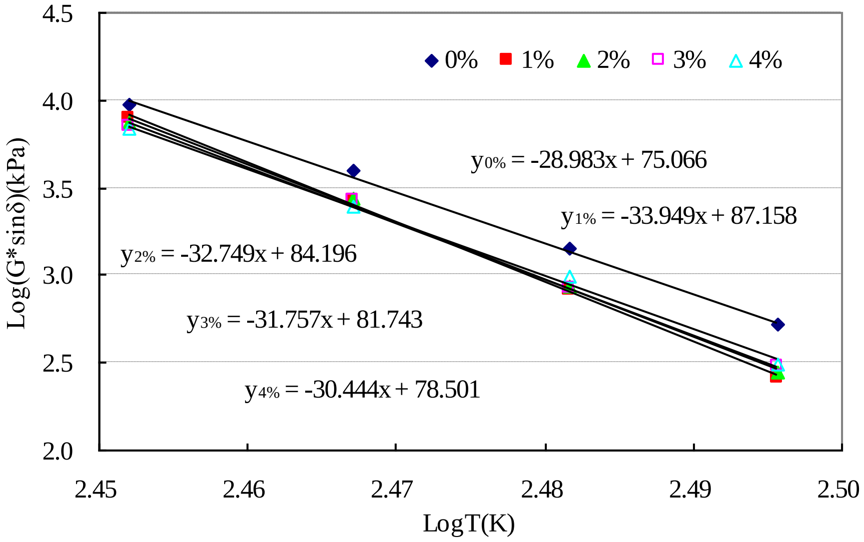

Fig. 8 Logarithm of the G*·sinδ of Aged Formed CRMA Binders

From Fig. 8, it can be observed that there is a negative linear relationship between log(G*·sinδ) and logT. At the same temperature, G*·sinδ of the foamed CRMA binders are smaller than that of the regular CRMA binder, indicating that foamed CRMA binders provide better fatigue resistance. However, with the increase of foaming water content, G*·sinδ of the foamed CRMA binder does not change significantly. According to the Superpave specification [34], G*·sinδ of an asphalt binder after PAV aging should be less than 5.0MPa. The threshold temperature corresponding to a G*·sinδ value of 5.0MPa is defined as the ultimate fatigue temperature, and a lower ultimate fatigue temperature indicates better fatigue performance of a binder. Table 6 lists the ultimate fatigue temperatures of the CRMA binders with different foaming water contents. It can be seen that the ultimate fatigue temperatures of the foamed CRMA binders are significantly lower than that of the regular CRMA binder. With the increase of the foaming water content, the ultimate fatigue temperature of foamed CRMA binder decreases gradually. 4% foaming water content provides the minimum ultimate fatigue temperature or the maximum improvement in fatigue resistance.

Table 6 Ultimate Failure Temperatures of the Aged Formed CRMA Binders

Formed Rubber Asphalt	0%	1%	2%	3%	4%
Ultimate Fatigue Temperature (^{o}C)	16.8	14.2	13.9	13.6	13.3

4. Summary

This study investigated the influence of foaming water content on the rheological properties of foamed CRMA binders. Laboratory tests were conducted to characterize and compare the high-temperature performance, low-temperature performance, temperature sensitivity, and fatigue resistance of the foamed CRMA binders produced with different foaming water contents. Based on the test results, the following conclusions have been achieved:

1. Foaming process compromises the high-temperature performance of CRMA binder. With the increase of foaming water content, the failure temperature of foamed CRMA binder decreases gradually, indicating slightly reduced high-temperature performance.
2. Compared to the regular CRMA binder, foamed CRMA binder provides better low-temperature performance. With the increase of foaming water content from 1% to 4%, the low-temperature performance of foamed CRMA binder first decreases, and then increases.
3. Foaming improves the temperature stability of CRMA binder. With the increase of foaming water content, the sensitivities of the storage modulus and loss modulus of the foamed CRMA binders decrease gradually, indicating that the temperature stability of foamed CRMA binder is improved.
4. Foaming improves the fatigue resistance of CRMA binder, as evidenced by the lower ultimate fatigue temperatures of the foamed CRMA binders compared to that of the regular CRMA binder. With the increase of foaming water content, the ultimate fatigue temperature of foamed CRMA binder decreases gradually.
5. Based on the rheological properties, we recommend that 4% is the optimum water content for CRM binder.

This study has shown that foaming water content plays an important role on the rheological properties of foamed CRMA binder. However, it is worth noting that only one type of raw asphalt and one type of crumb rubber were investigated in this study. To make the conclusions of this study more generally applicable, it is recommended that more types of raw material be evaluated in future research.

5. Acknowledgements

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