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ORIGINAL ARTICLE

Influences of temperature on mechanical properties of cement asphalt mortars

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Abstract The compressive mechanical properties of cement asphalt mortars (CAMs) with varied bitumen-cement ratio (B/C) were studied under different temperatures, in order to reveal the susceptibility of mechanical properties to temperature. Results indicate that the compressive strength and the elastic modulus generally increase with a decrease in temperature for all tested CAMs. The quantitative evaluation of the temperature dependence of the strength and the elastic modulus using defined temperature-sensitivity factors is proposed and validated by the test results, which show that the mechanical properties of those CAMs with higher B/C have greater temperature sensitivity. For a given CAM, the temperature-sensitivity factor of the strength is larger than that of the elastic modulus. The temperature-sensitivity factors enable estimating the compressive strength and the elastic modulus of CAMs at selected temperatures from the tested values at a reference temperature, such as room temperature, by using the proposed equations. The relative elastic modulus is found to be in direct proportion to the square root of the relative compressive strength at a selected temperature, i.e. $E_{\mathrm{r}} \propto \sqrt{\sigma_{\mathrm{pr}}}$.

Keywords Cement asphalt mortar (CAM) · Temperature · Compressive strength · Elastic modulus · Temperature-sensitivity factor

1 Introduction

Cement asphalt mortar (CAM), consisting primarily of Portland cement, bitumen emulsion, fine aggregates, water and chemical additives, has been vastly utilised in the slab track railroad systems, which is one of the key technologies in high-speed railways (HSR). It functions as a cushion layer between the track slab and the concrete bed, and its properties have direct influences on the structural performance of the track system. Mechanical properties of the hardened CAM including elastic modulus and strength are key properties to ensure its proper function in the slab track structure. Experiments conducted by Li et al. [6] on the mechanical properties of a cement-asphalt composite indicated that it combined many characteristics of cement and asphalt, such as low temperature sensitivity of cement concretes and higher toughness of asphalt concretes. The incorporation of bitumen emulsion into Portland cement-based materials generally reduces the strength and the modulus [14, 15] but improves the deforming ability [14]. When Portland cement is added

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into bituminous emulsion mixtures, on the other hand, the beneficial effects including the improvements in mechanical properties and the temperature susceptibility were reported [1, 3, 11–13].

Obviously, the mechanical properties of such CAM composites depend mainly on the binder which basically consists of two phases, namely hardened Portland cement paste (hcp) and a solidified bitumen phase. However, the two binding phases show totally different mechanical behaviour and different sensitivity to external temperature. In the temperature range of −20 to 60 °C, which is usually the environmental temperature variation range during service of HSR, the mechanical properties of hcp remains little changed while the solidified bitumen phase is rather temperature sensitive due to its typical visco-elastic features. So the relative content of bitumen to Portland cement in the binder of CAMs must be the key factor determining the mechanical properties of CAMs and also their susceptibilities to temperature.

In practically applied CAMs in slab track structure, the relative content of bitumen to cement is in a wide range of 0.2–1.2 by mass ratio, which consequently produces widely varied mechanical properties [16, 17]. At present, most of the research work on CAMs involves formulation optimization, studying various practical properties like flowability and mechanical properties at ambient temperature [4, 7, 8, 16–20]. However, the environmental temperature to which CAMs are exposed during service could vary in large amplitude, such as from −40 °C to even beyond 70 °C, due to local climate changes and the geographical location of the HSR. Therefore, a full understanding of the impacts of temperature on the mechanical properties of hardened CAMs is urgently needed.

In this paper, therefore, CAMs with varied bitumen content were prepared in order to investigate their mechanical properties under different temperatures, where bitumen content in CAMs is represented by mass ratio of bitumen to cement (B/C). CAMs with a B/C ranging from 0.2 to 1.0 were prepared for mechanical testing. Uni-axial compressive stress–strain curves of CAMs at a temperature of −40, −20, 0, 20, 40, 60 and 80 °C were obtained by loading specimens with a Material Testing System, MTS 810. The aim of the study is to establish a correlation between the mechanical properties of CAMs and the environmental temperatures.

2 Experimental

2.1 Raw materials

Ordinary Portland cement, P.O. 42.5 conforming to Chinese Standard GB 175-2007 and manufactured by Beijing Jinyu Cement Corporation, was used as the inorganic binder. Its chemical and mineral compositions and its properties are listed in Tables 1 and 2, respectively. Anionic emulsified bitumen was supplied by Sinopec and its properties are shown in Table 3. Dried fine sands with particle size of 0.21–0.42 mm were used for preparation of CAMs. An organic siloxane-type defoaming agent, DF642 provided by Rhodia Co. Ltd., was added to prevent from foaming in the mixture and a polycarboxylate-type super-plasticizer with a solid content of 37 % was used to control the fluidity. Tap water was used in the preparation of all CAMs.

2.2 Sample preparation

CAMs with different B/Cs were prepared according to the formulations in Table 4. Both bitumen and cement serve as binders in the hardened CAMs, where the mass ratios of bitumen to cement vary from 0.2 to 1.0. The mass ratio of fine aggregates to binders is fixed at 1.5 in the formulations of all CBMs. Slump flow tests [20], in which the initial diameter of slump flow should exceed 280 mm, were performed to ensure their self-compacting ability during casting. In the case CAM3, 0.3 % superplasticizer (mass ratio to cement) was added to ensure sufficient flowability of the fresh CAM. The liquid components such as bitumen emulsion, water and chemical additives were added into the previously well mixed sand and cement mixture. The whole mixture was blended in a 2.5-l stirring mixer for about 5 min. Then the fresh paste was poured into cylindrical PVC moulds with an outside diameter of 63 mm and a height of 180 mm without vibration. After being cured in a standard curing room (20 ± 2 °C and relative humidity of 95 ± 5 %) for 24 h, samples were removed from the moulds, transferred into another room with a constant temperature (23 ± 2) °C and a constant relative humidity (65 ± 5) % and cured for 120 days. Cylinder test pieces with dimensions of Φ (56.50 ± 0.50) × (51.50 ± 0.50) mm^2 were produced with a cutting machine before the loading tests were carried out.

Table 1 Compositions of Portland cement (wt%)

Chemical composition									Mineral composition			
SiO_2	Fe_2O_3	Al_2O_3	SO_3	MgO	CaO	Na_2O	K_2O	L.O.I	C_3S	C_2S	C_4AF	C_3A
23.47	2.97	7.41	2.39	1.97	60.28	0.14	0.62	2.80	49.58	28.04	8.57	7.28

Tested according to Chinese Standards, GB/T17671-1999 and GB/T1346-2001

Table 2 Properties of Portland cement

Water content for standard consistence (%)	Initial setting time	Final setting time	Soundness	Flexural strength (MPa)			Compressive strength (MPa)		
				3 d	7 d	28 d	3 d	7 d	28 d
27.5	172 min	262 min	Satisfied	5.5	7.0	8.7	27.9	40.9	51.7

Table 3 Properties of anionic bitumen emulsion [10]

Tests on emulsion	Value	Tests on residue from distillation	Value
Engler viscosity (25 °C, Pa.s)	20.7	Solid content (%)	58.5
Mean particle diameter (μm)	1.9	Penetration (25 °C, 100 g, 5 s, 0.1 mm)	78.0
Sieve test (1.18 mm, %0)	0.02	Softening point (R&B, °C)	57.2
Storage stability (1 d, 25 °C, %)	0.2	Ductility (15 °C, cm)	43.1
Storage stability (7 d, 25 °C, %)	0.6	Solubility in trichloroethylene (%)	99.5

Table 4 Mix proportions of CAMs with different B/Cs

Type	B/C	Bitumen emulsion (g)		Cement (g)	Bitumen + Cement (g)	Sands (g)	Tap water(g)	W/C
		Bitumen	Water					
CAM1	0.2	420	298	2,100	2,520	3,780	752	0.50
CAM2	0.4	720	510	1,800	2,520	3,780	390	0.50
CAM3	0.6	945	670	1,575	2,520	3,780	118	0.50
CAM4	0.8	1,120	794	1,400	2,520	3,780	0	0.55
CAM5	1.0	1,260	893	1,260	2,520	3,780	0	0.69

2.3 Testing methods

Uni-axial compressive stress–strain curves of CAMs with varied B/Cs under different temperatures ranging from −40 to 80 °C were obtained by means of loading cylindrical samples in a Material Test System (MTS 810) at a deformation rate of 1.0 mm/min. An environmental chamber, in which the temperature could be controlled from −70 °C to +150 °C, was attached to the MTS 810 machine in order to achieve the target test temperatures. Before the test, the samples were stored at the same temperature as the test temperature in another environmental chamber for at least 24 h to ensure the body temperature of the test samples were exactly at the target temperature. High temperatures of 40, 60 or 80 °C and low temperatures of −40, −20 or 0 °C were chosen. The two loading surfaces were coated with French chalk before loading, to reduce the surface restraint effect. On stress–strain curves from mechanical testing, the peak stress value σ_p is defined as the compressive strength and the chord modulus between $0.3\sigma_p$ and $0.5\sigma_p$ is used as the elastic modulus of the CAMs. The average compressive strength and the average elastic modulus are calculated based on three repetitions for each test.

3 Results and discussion

3.1 Mechanical properties of CAMs at room temperature

As can be seen in Fig. 1, both compressive strength and elastic modulus decrease significantly with an increase of B/C for CAMs. In the hardened CAMs, both the hcp and the demulsified bitumen play a role as the binder, bonding the fine aggregates together. As these two phases have distinct mechanical and visco-elastic properties, the overall mechanical properties of the CAMs matrix certainly depend on the contents of the two phases. When B/C is low, the hcp dominates the structure of the matrix in CAMs [16, 19] and hence determines the mechanical properties whilst the bitumen is functioning as a secondary binder. On the other hand, usually at B/C higher than 0.6, the bitumen phase becomes the dominating phase, which leads to sharp decreases of the mechanical strength and the elastic modulus [8, 9]. The unhydrated cement grains and the hcp play a role as fillers in a continuous bitumen matrix.

3.2 Mechanical properties of CAMs under different temperatures

As well known, the mechanical properties of bitumen are very sensitive to temperature while those of hardened cement paste are less affected by temperature. In this study, temperatures ranging from −40 to 80 °C were selected for tests of CAMs with varied B/Cs in order to disclose the temperature dependence of mechanical properties of CAMs.

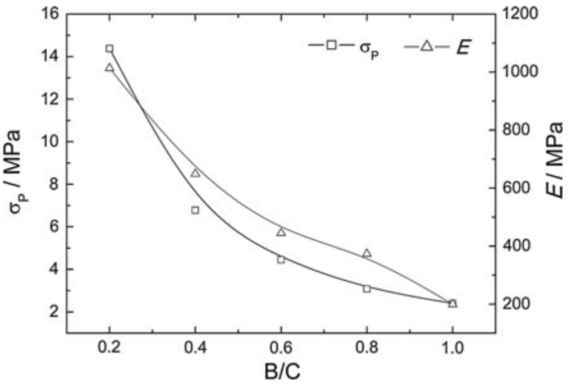

Fig. 1 Mechanical properties of CAMs at room temperature

Strain–stress curves of two typical CAMs with B/Cs of 0.2 and 0.8 under different temperatures are presented in Fig. 2. It can be seen that for both CAMs, lower temperature leads to increases in both strength and modulus without exception. It is well established that the bitumen itself is a complex mixture with a typical colloid structure [5], and transitions of its mechanical characteristics from the Newtonian fluid, the visco-elastic state, to the elastic glassy solid can be generated with reducing temperature. It is easily understood that the mechanical behaviour of the binder in CAMs, a composite of cement and bitumen, will be likewise temperature dependent. For the CAM with B/C of 0.8, due to its higher bitumen content, the temperature dependence of its mechanical properties is much stronger than that for the CAM with B/C of 0.2.

The compressive strength σ_p and the elastic modulus E of different CAMs are plotted as functions of temperature as shown in Fig. 3. Generally, it can be clearly seen that both σ_p and E decrease with increasing temperature. At low B/C ratio, the mechanical properties are less affected by the temperature because the hcp is the major binding phase in the matrix of the CAMs. As more bitumen is incorporated, the role played by bitumen in the CAMs is transformed from the secondary to the dominant one, leading to more significant temperature sensitivity.

In the real application of CAMs in slab track systems, the environmental temperatures vary in a wide range and hence so do the mechanical properties of CAMs as seen in Fig. 3. However, the mechanical properties of CAMs are specified to be tested at room temperature in laboratory, which actually does not fully reflect the properties of CAMs during service. Comprehensive knowledge about the temperature dependence of the mechanical properties of CAMs is in demand. In this study, we define the relative strength σ_{pr} and the relative modulus E_r as $\sigma_{pr} = \sigma_{pT}/\sigma_{pRT}$ and $E_r = E_T/E_{RT}$, respectively, to quantify the change of the mechanical properties with temperature by choosing the strength σ_{pRT} and the modulus E_{RT} at room temperature as the references, where σ_{pT} and E_T are strength and modulus at various temperatures,

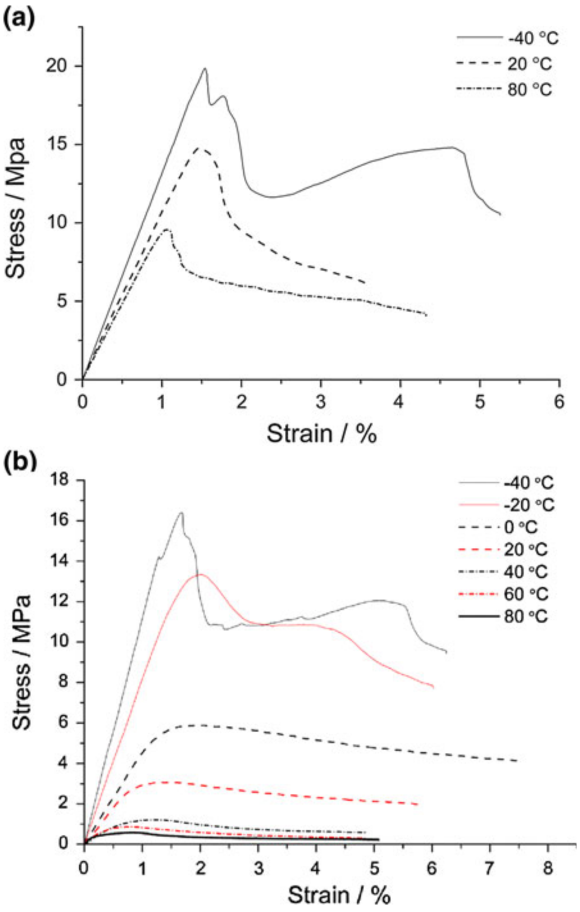

Fig. 2 Strain-stress curves of CAMs with varied B/Cs under different temperatures **a** B/C = 0.2 and **b** B/C = 0.8

respectively. The σ_{pr} and E_r versus temperature are plotted in Fig. 4. It can be seen that there are sharp changes of both compressive strength and elastic modulus in the temperature range of −20 to +60 °C, which is approximately the service temperature range for most of the slab tracks. Moreover, the effect of low temperature is more marked than that of high temperature.

3.3 Temperature susceptibility

From the above presented results, it can be seen that to use the CAMs properly, the effect of temperature on their mechanical properties must be well-understood and ideally, be predictable. In cementitious materials, Arrhenius equation is often adopted to evaluate the temperature influences on setting time, strength development etc. [2]. In this paper, a hypothesized empirical expression as Eq. (1) is chosen to reveal the temperature effect on mechanical properties of CAMs,

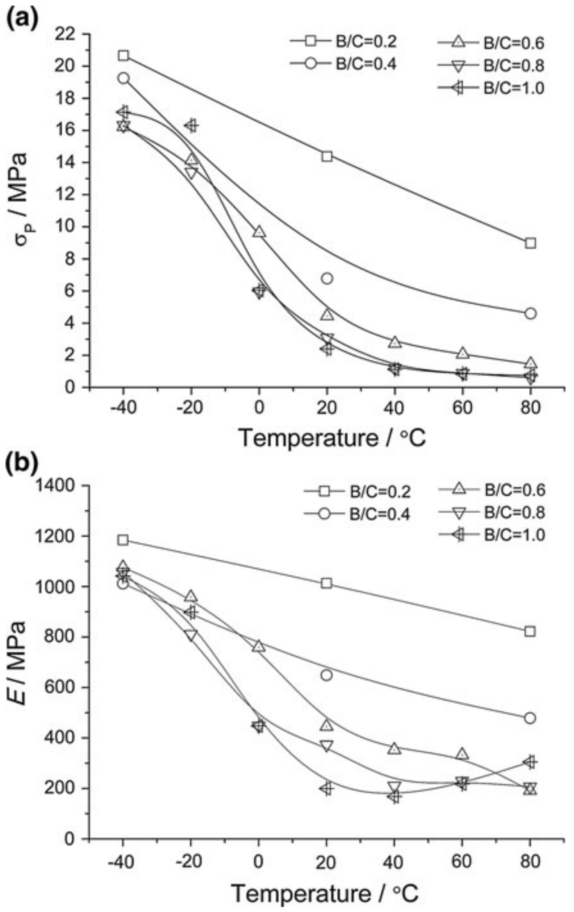

Fig. 3 **a** σ_p and **b** E of CAMs with varied B/Cs under different temperatures

$$f = f_0 \exp\left(-\frac{E_a}{RT}\right) \tag{1}$$

where, f is the parameter value such as elastic modulus or strength and T is the absolute temperature. R is the universal gas constant. f_0 and E_a are constants. The magnitude of E_a can reflect the temperature susceptibility of the parameter.

When Eq. (1) is adopted for elastic modulus, E, of CAMs, we get Eq. (2)

$$E = E_0 \exp\left(\frac{A}{T}\right) \tag{2}$$

Based on the Eq. (2), the relative modulus E_r in function of T could be described as follows:

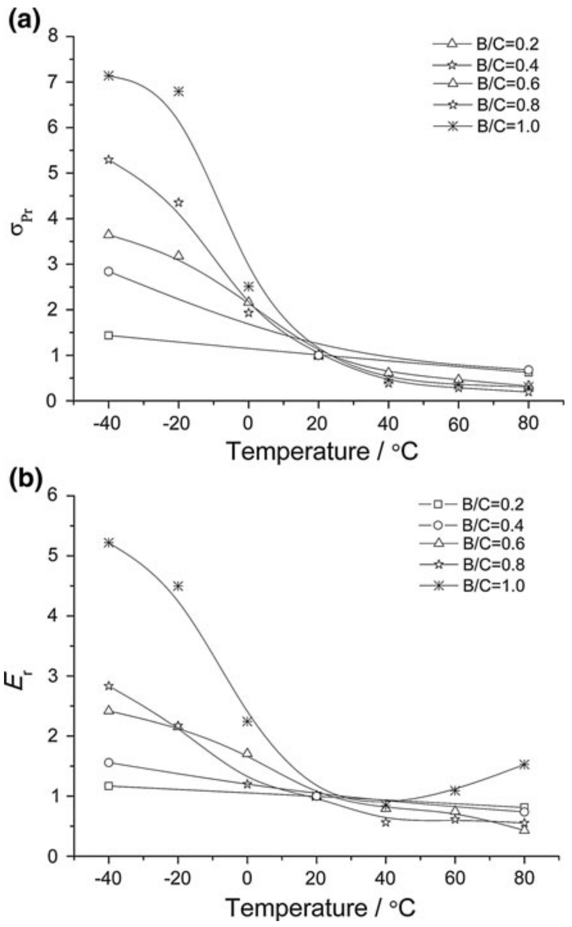

Fig. 4 **a** σ_{pr} and **b** E_r of CAMs with varied B/Cs under different temperatures

$$E_r = \frac{E_T}{E_{Tr}} = \exp\left[A_M\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad A_M > 0 \tag{3}$$

The similar equation is used to correlate the relative compressive strength σ_{pr} and the temperature T as shown in Eq. (4) below:

$$\sigma_{pr} = \frac{\sigma_{pT}}{\sigma_{pTr}} = \exp\left[A_S\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad A_S > 0 \tag{4}$$

A_M and A_S in the above equations are defined as temperature-sensitivity factors for the elastic modulus and the compressive strength of CAMs respectively. It is expected that these two factors can be used to characterise the temperature dependences of both the elastic modulus and the compressive strength.

Based on Eqs. (3) and (4), linear fittings of $\ln E_r$ and $\ln \sigma_{pr}$ with respect to $(1/T - 1/T_r)$ are conducted respectively. The two factors, A_M or A_S as listed in Table 5, are obtained from the slope of the linear lines. It can be seen that for the CAMs investigated, the $\ln E_r$ and $\ln \sigma_{pr}$ express fairly good linear relationships with $(1/T - 1/T_r)$. These experimental results firmly validate Eqs. (3) and (4), which enable us to quantitatively describe the temperature dependence of strength and modulus of CAMs. From the fitted temperature-sensitivity factors, A_M and A_S, it is concluded that the higher B/C leads to the greater temperature dependence of the mechanical properties for CAMs as seen in Fig. 5. For a certain CAM, the compressive strength exhibits larger temperature-sensitivity factor than the elastic modulus, indicating that the compressive strength has stronger temperature dependence than the elastic modulus. For a composite material, the elastic modulus is mostly determined by the intrinsic properties of the involved component materials themselves, whereas the strength is influenced not only by the component materials, but also strongly by the micro-structure of the composite, including the original cracks, the interface nature between phases etc. During environmental temperature changing, along with the property changes of bitumen itself, the bitumen-hcp and bitumen-aggregates interfacial cohesions are changing due to the differences of bitumen, hcp and aggregates in thermal expansion coefficient and elastic modulus. The interfacial changes may be the reason why the temperature-sensitivity factor of compressive strength is larger than that of elastic modulus for a certain CAM.

Table 5 Fitted temperature-sensitivity factors of σ_{pr} and E_r

B/C	A_M	Degree of fitting (%)	A_S	Degree of fitting (%)
0.2	244.32	99.99	558.81	98.15
0.4	513.08	97.99	999.30	99.01
0.6	1171.58	96.84	1805.06	97.86
0.8	1231.08	97.45	2488.29	98.35
1.0	1177.65	84.21	2520.59	97.62

3.4 Discussion

For some materials, a direct relationship exists between the elastic modulus and the strength. According to the ACI Building Code 318, the elastic modulus of a concrete with unit weight between 1,500 and 2,500 kg/m^3 can be determined by Eq. (5) [10], where E_c and the square root of f_c' show linear relationship

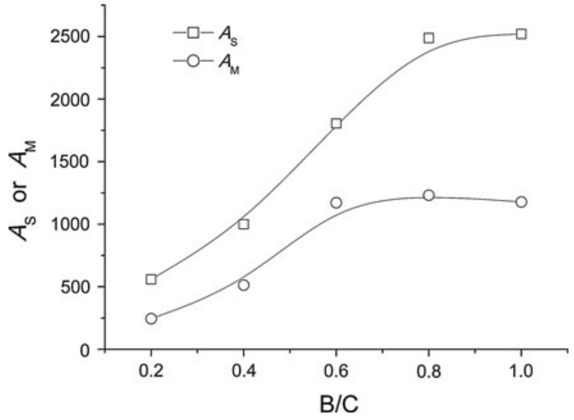

Fig. 5 Calculated values of temperature-sensitivity factors for different CAMs

$$E_c = w_c^{1.5} \times 0.043\sqrt{f_c'} \quad (5)$$

where, E_c, w_c and $f_c{}'$ are elastic modulus, unit weight and compressive strength of concretes, respectively.

When the $\ln\sigma_{pr}$ versus $\ln E_r$ for all CAMs at different testing temperatures are plotted in one diagram (Fig. 6), it is interestingly found that a straight line with a slope of 0.53 is exhibited. This result implies that there exists an intrinsic correlation between the strength and the elastic modulus for different CAMs under varied environmental temperatures.

That is $E_r \propto \sqrt{\sigma_{pr}}$. (6)

The above equation reveals a generalised rule for all CAMs regardless of the composition of such composites as well as the test temperature in the investigated variation range. Based on Eqs. (3) and (4), the relationship can be further expressed through division as follows:

$$\frac{\ln E_r}{\ln \sigma_{pr}} = \frac{A_M}{A_S} \quad (7)$$

According to the fitted values of A_M and A_S (Fig. 6), it is seen that the ratio of A_M to A_S for CAMs with varied B/C value is mostly about 0.50 except the CAM with B/C of 0.6 (Fig. 7). This indicates that the strength of CAMs is stronger influenced by test temperatures than the modulus and its temperature-sensitivity factor is twice as large as that of the modulus. As an exception, for the CAM with B/C of 0.6, the ratio of A_M to A_S ratio is around 0.65, which is larger than those for other CAMs. It has been reported that for CAM with B/C of 0.6, a bi-continuous phase distribution in the binder system is observed [8, 9].

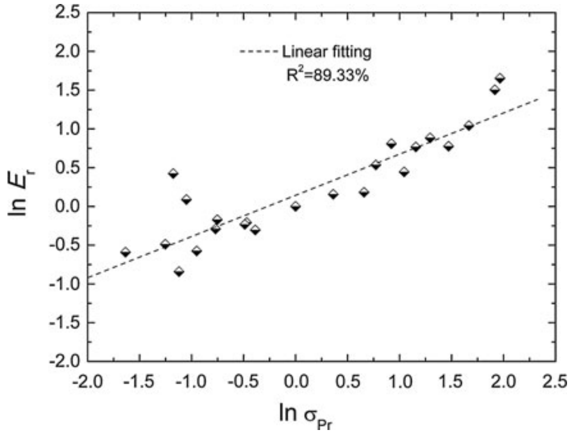

Fig. 6 Correlation between E_r and σ_{pr} of all CAMs

That is to say, at B/C lower than 0.6, the hcp is the dominating phase with bitumen as dispersed phase, while at B/C higher than 0.6, the bitumen becomes major phase and hcp acts as dispersed phase. In these two cases, the whole mechanical features of CAMs are mostly determined either by the hcp or by the bitumen. However, at B/C of around 0.6, interpenetrating network is formed involving bitumen and hcp phases. Thus, the overall mechanical features are not only decided by the two phases, but also by the properties of the interface between the two phases to a larger extent. This micro-structural distinctness may account for the deviation of A_M/A_s from 0.5.

4 Conclusions

In this paper, with the aim of revealing the temperature effects on mechanical properties of various CAMs, the following conclusions can be drawn from the presented results:

(1) Generally, both the compressive strength and the elastic modulus of CAMs decrease with an increase of B/C and the test temperature.

(2) The higher the B/C, the more significant temperature susceptibility of CAMs' mechanical properties is observed.

(3) By using the temperature-sensitivity factors, it is feasible to quantitatively characterise the mechanical behaviour of CAMs under various temperatures studied. For a certain CAM, the temperature-sensitivity factor of the compressive

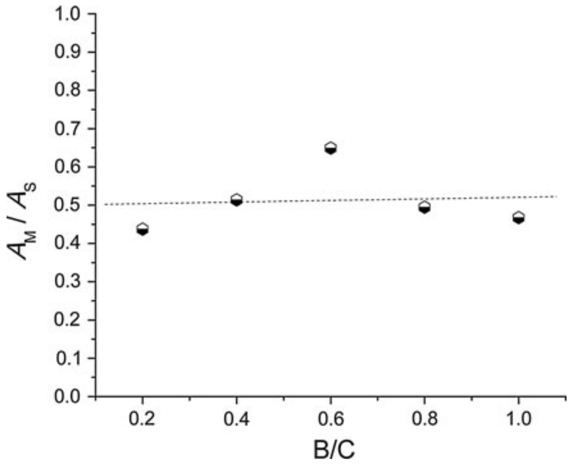

Fig. 7 The ratio of A_M to A_S for CAMs with varied B/Cs

strength is larger than that of the elastic modulus without exception.

(4) The relative elastic modulus is in direct proportion to the square root of the relative compressive strength for various CAMs at selected temperature within the studied variation range, i.e. $E_r \propto \sqrt{\sigma_{pr}}$.

The temperature-sensitivity factors enable estimating the compressive strength and the elastic modulus of CAMs at selected temperatures from the tested values at a reference temperature, such as room temperature, by using the proposed equations. The estimation of the mechanical properties of CAMs under different temperatures helps engineers to know the properties of CAMs under their practical service conditions.

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