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Research Article

Temperature Sensitivity of Mechanical Properties of Cement Asphalt Mortar with Nanoparticles

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Cement asphalt mortar (CAM) in high-speed lines is subjected to varying environmental conditions, which lead to the deterioration of CAM. The nanoparticles of nano-SiO_2 and nano-TiO_2 are added to improve the performance of CAM, and the temperature sensitivity of CAM with nanoparticles is primarily studied in this paper. The flexural strength and compressive strength of CAM with and without nano-SiO_2 and nano-TiO_2 were measured and compared to study the effect of nanoparticles on the performance of CAM subjected to different temperatures. Temperature sensitivity factors of flexural and compressive strength based on Arrhenius model were proposed to evaluate the temperature dependence of CAM by nanoparticles. Furthermore, the microstructure of hardened CAM was studied using scan electronic microscope (SEM) to investigate the mechanism of temperature sensitivity of CAM with and without nanoparticles. The results indicated that the flexural and compressive strength of CAM with and without nanoparticles decreased with the increasing temperature; however, the decreasing rate of strength with temperature was different in CAM with and without nanoparticles. The reduction in the decreasing rate of strength was obtained by using nano-SiO_2 rather than nano-TiO_2 in CAM. Based on the SEM results, the free asphalt was seen to be greatly reduced in the CAM with nano-SiO_2, suggesting a positive effect of nano-SiO_2 on the mitigation of temperature sensitivity of CAM.

1. Introduction

Cement asphalt mortar (CAM) is an organic-inorganic material composed of cement, asphalt emulsion mortar, fine aggregate, and other chemical admixtures [1, 2]. The fresh CAM is grouted between the concrete bed and track slab in high-speed lines [3, 4]. CAM cushion is mainly served as an energy absorption layer to maintain the comfort during the service of high-speed lines [4].

As an important part of the nonballast track system, the workability, mechanical properties, and durability of CAM were widely studied with the development of high-speed lines worldwide [5–9]. Based on the existing research, it should be noted that the performance of asphalt mixtures including hardened CAM is significantly influenced by the temperature [2, 8–10]. The compressive strength, tensile strength, dynamical modulus, and stress-strain response of CAM with different asphalt to cement ratio were experimentally studied when the temperature was varied. The experimental results indicated that (1) the mechanical properties of CAM decreased with the increasing temperature [2, 9], (2) the temperature sensitivity of CAM was closely related to the asphalt to cement ratio [11, 12], and (3) the temperature-sensitive behavior of CAM was also found to be correlated with the loading rate and water pressure [13–15]. According to the research, the behavior of CAM under low and high temperature can be well interpreted and reasonably predicted by the proposed model. However, the method to mitigate the temperature sensitivity of CAM has been scarcely mentioned by now.

The temperature-related behavior of CAM was suggested to be largely attributed to the forms of asphalt [2]. The asphalt in CAM is categorized into structural asphalt and free asphalt. Through physical and chemical interactions, the

structural asphalt with the thickness of several microns can be strongly conglutinated to inorganic phases of CAM. The free asphalt exists in the hardened paste without attachment to the inorganic phases of CAM, while the structural asphalt is preferentially absorbed into the fine aggregate and has higher viscosity than the free asphalt. Therefore, the free asphalt is susceptible to the temperature and accounts for the temperature sensitivity of CAM. In this sense, the way to improve the temperature resistance of CAM is to convert as much as free asphalt into structural asphalt [2]. Given this background, silica fume (SF) and crumb rubber (CR) were added in the CAM to investigate the effect on the strength of CAM under varying temperatures [2]. It was found that silica fume rather than crumb rubber was favorable to the compressive strength of CAM. On the one hand, due to the high reactive pozzolanic characteristics, the incorporation of SF increased the amount of C-S-H gel, which contributes to the strength of CAM. On the other hand, silica fume increased the surface area of inorganic phases of CAM, which can convert free asphalt into structural asphalt [2]. The experimental observation provides a reliable way in decreasing temperature dependence of CAM. However, more information has not been found since then.

Nowadays, supplementary materials are found to help improve the performance of cementitious materials, bitumen and asphalt binders [16–20]. Among the useful admixtures, nanoparticles such as nano-SiO_2 and nano-TiO_2 are now widely used to improve the strength and durability of cementitious material considerably. Nanoparticles are also used in both asphalt pavement and concrete pavement widely and have received good response in terms of mechanical performance and environmental performance. Sadeghnejad and Shafabakhsh [21] studied the effect of nano-SiO_2 and nano-TiO_2 in stone mastic asphalt (SMA) mixtures. The results suggested that the use of nanoparticles can increase the fatigue life and reduce the rutting of SMA. Similar conclusions were drawn on asphalt mixtures by Arabani et al. [22] and Tanzadeh et al. [23]. Meanwhile, it was found by Li et al. [24] and Salami and Behfarnia [25] that nanoparticles can improve the strength, the abrasion resistance, and the frost resistance for concrete pavement. As an environment friendly additive, TiO_2 in asphalt pavement was proved to be effective in photodegrading mixed NO_2 and NO gases from the atmosphere [26, 27]. The nanoparticles with ultrafine particle size have a high galactic surface area. The findings among the nanoparticle related research indicated that the nanoparticles can react with $Ca(OH)_2$ crystal and produce more C-S-H gel, which fills the void and improve the density of interfacial transition zone [17, 28, 29]. In view of the functions of nanoparticles, it is expected that more hydration products that can absorb the free asphalt in CAM may exist by the incorporation of nanoparticles. Adding nanoparticles is potentially beneficial for mitigating the temperature sensitivity of CAM.

The objective of this paper is to evaluate the capacity of nanoparticles to mitigate the temperature sensitivity of mechanical properties of CAM, and to study the mechanism of the nanoparticles on the thermal-related performance of CAM. The flexural and the compressive tests of CAM with nano-SiO_2 and nano-TiO_2 under five different temperatures ranging from −20°C to 60°C were firstly conducted, and the flexural strength and compressive strength of CAM were measured. The type, amount of nanoparticles on the temperature sensitivity of flexural strength and compressive strength were investigated based on the experimental results. In addition, the changes in composition and microstructure of CAM were studied by scan electronic microscope (SEM), and the temperature-related behavior of CAM is explained based on the experimental observations.

2. Materials and Methods

2.1. Materials. An ordinary type I Portland cement produced in China was used in this study. The nanoparticles of nano-SiO_2 and nano-TiO_2 were selected for construction use. The specific information of nanoparticles is listed in Table 1. XRD graphs of nanoparticles are given in Figure 1. An anionic emulsified emulsion was used, and the physical properties of asphalt can be found in Table 2. The fine aggregate is the sand with the maximum size of 0.6 mm, and the grading curve can be found in Figure 2. A polycarboxylate superplasticizer with a relative density of 1.06 was added to adjust the flowability of the CA mortar with nanoparticles.

2.2. Mix Design. Nano-SiO_2 and nano-TiO_2 with dosages of 0, 1, 2, and 3 wt.% of binder were added in the CAM, respectively. According to the experimental results by Oltulu and Sahin [30, 31], a better performance of cementitious material was obtained by the nanoparticles in single use. Therefore, the combined effect of nano-SiO_2 and nano-TiO_2 on the performance of CAM is not considered in this paper. The mix proportion of CAM with and without nanoparticles is given in Table 3. It should be noted that a higher amount of nanoparticles is accompanied by the adjustment of superplasticizer in order to ensure that the specimens do not suffer from excessive self-desiccation and cracking [25, 32]. The workability of CAM with and without nanoparticles is shown in Table 4, which demonstrates the good flowability of fresh CAM.

2.3. Specimens. In order to avoid negative effect on the performance of CAM by the agglomeration of nanoparticles, the mixing procedures of fresh CAM were used as follows:

(1) The water, nanoparticles, and the superplasticizer were added and mixed for 30 seconds at a speed of 60 rad/min.

(2) The asphalt emulsion was added in the mixture and mixed for 30 seconds at a speed of 60 rad/min.

(3) The sand and cement were added in the mixture within one minute. The mixture was stirred for another two minutes at a high speed of 180 rad/min and 30 seconds at a low speed of 30 seconds before stopping.

The fresh CAM was poured in the mould with the size of 40 mm × 40 mm×160 mm. After demoulding, the CAM

Table 1: Physical properties of nanoparticles.

Nanoparticles	Average particles size (nm)	Specific surface (m^2/g)	Density (g/cm^3)
Nano-SiO_2	10.576	161.800	2.425
Nano-TiO_2	0.969	24.300	4.026

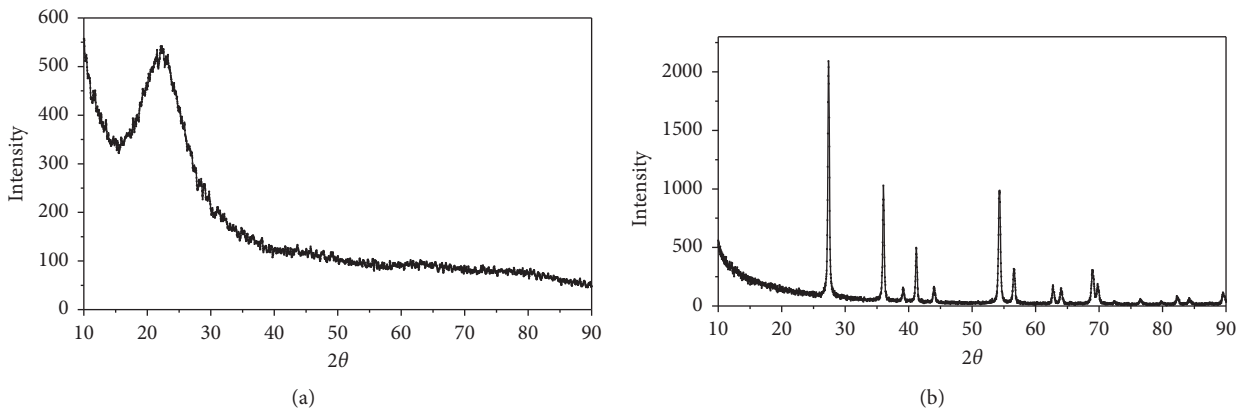

Figure 1: Diffractograms of (a) nano-SiO_2 and (b) nano-TiO_2.

Table 2: Physical properties of asphalt emulsion.

Density (g/cm^3)	Solid content (%)	Penetration depth at 25°C (0.1 mm)	Residual on 1.18 mm sieve (%)	Storage stability 5 d (%)
1.02	61.2	72	0.02	2.3

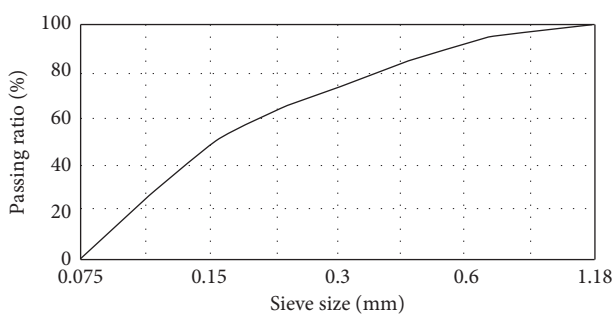

Figure 2: Grading of fine aggregates.

Table 3: Mix design of CAM with and without nanoparticles (kg/m^3).

Specimens	Cement	Sand	Asphalt emulsion	Nano-SiO_2	Nano-TiO_2	Water	Superplasticizer
CAM	640	1040	265	0	0	150	13
CAMS1	633.6	1040	265	6.4	0	150	13
CAMS2	627.2	1040	265	12.8	0	150	13.88
CAMS3	620.8	1040	265	19.2	0	150	16.4
CAMT1	633.6	1040	265	0	6.4	150	14.38
CAMT2	627.2	1040	265	0	12.8	150	15.63
CAMT3	620.8	1040	265	0	19.2	150	16.43

Table 4: Workability of fresh CAM.

Workability indexes	CAM	CAMS1	CAMS2	CAMS3	CAMT1	CAMT2	CAMT3
Spread flow (cm)	32 × 33	33 × 34	32 × 32	28 × 29	28 × 31	28 × 29	28 × 29.5
t_{280} (s)	10	9	10	10	8	10	10
Time to pass J-type funnel (s)	82	87	95	102	107	110	106

specimens were cured in a standard curing room (20 ± 1°C, 95% relative humidity). After 28 days, the CAM specimens were taken out of the curing room and dried at room temperature. Before testing, the specimens were put into the environmental box for 8 hours at the target temperature until the stable thermal properties of specimens were achieved. Based on the climate in China, the maximum temperature can be found approximately 60°C in surveys related to the service environment of high-speed lines [1, 33]. Therefore, five temperatures of −20°C, 0°C, 20°C, 40°C, and 60°C were selected in this paper.

2.4. Flexural Test and Compressive Test. The flexural test and the compressive test of CAM specimens were performed according to the technical specification of CAM [34]. A four-point bending test was conducted on CAM specimens with the size of 40 mm × 40 mm × 160 mm. The span of flexural specimen is 120 mm. The CAM specimens with the size of 40 mm × 40 mm × 80 mm were performed for compressive testing. For each test, the results of flexural strength at a minimum number of three specimens and compressive strength at a minimum number of six specimens were obtained.

2.5. Scanning Electronic Microscope (SEM) Tests. The specimens for SEM test were prepared and cured with the compressive specimens. The specimens were soaked in pure alcohol to stop hydration before testing. The coin-size-like specimens were cut and sharpened for scanning. In this study, a QUANTA FEG 650 type SEM machine was used with the resolution ratio as high as 0.8 nm. The hydration products and the distribution of asphalt were investigated then.

3. Results and Discussion

3.1. Temperature Sensitivity Model. It is generally believed that a viscoelastic material like CAM possesses both the elastic property of a solid and the viscous behavior of a liquid. It is thus natural to use the theory of elasticity or viscoelasticity to describe the thermal behavior of CAM. In the remainder of this section, some typical models to analyze the effect of temperature on strength of CAM are presented.

3.1.1. Linear Model. Based on the results by Wang et al. [2] and Qiu et al. [9], the strength of CAM was considered to decrease linearly with the temperature. In this respect, a linear model of strength was developed as follows:

$$\frac{f_T}{f_{Tr}} = I_{TS} \cdot \frac{T}{T_r} + M, \tag{1}$$

where f_T is the strength at any temperature T and f_{Tr} is the strength at the reference temperature T_r. I_{TS} is the temperature sensitivity of the strength and the value of I_{TS} is the slope of the linear curve of the strength. M is a constant and can be determined by numerical regression.

The linear model is relatively simple to capture the characteristics of strength, yet insufficiently accurate to predict the effect of temperature since I_{TS} is varied once T_r is changed.

3.1.2. Arrhenius Equation Model. Arrhenius equation was often used to evaluate the temperature effect on setting time or strength development in cementitious materials [11]. According to the previous research, the general equation of strength can be given as follows:

$$\frac{f_T}{f_{Tr}} = M \cdot \exp\left[I_{TS} \cdot \left(\frac{1}{T} - \frac{1}{T_r}\right)\right], \tag{2}$$

The model has been used in CAM with low and high elastic models [11]. Compared with the linear model, I_{TS} in this model is not affected by the reference strength T_r.

3.1.3. Burgers Model. The burgers model is a combination of two basic mechanical models for viscoelastic materials [35]. The model is formed of a series of elements of a spring, a dashpot, and a spring and a dashpot in parallel. Its constitutive relationship can be expressed by

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\varepsilon} + q_2\ddot{\varepsilon}, \tag{3}$$

where $p_1 = \eta_2/E_1 + (\eta_2 + \eta_3)/E_3$, $p_2 = \eta_2\eta_3/E_1E_3$, $q_1 = \eta_2$, $q_2 = \eta_2\eta_3/E_3$. E_1, E_2, E_3 are the elastic moduli of the elastic springs, respectively, and η_1, η_2, and η_3 are the viscosity of each dashpot, respectively.

The elastic modulus and the viscosity can be determined by least-square method. The characteristics of elasticity and viscosity of a material are thus quantitatively analyzed, which in turn help identify the material characteristics and explain the mechanism of temperature sensitivity. However, the model is slightly sophisticated in engineering use.

In this study, Arrhenius equation was adopted to determine the temperature sensitivity factor of CAM with and without nanoparticles. This model is comparatively simple for engineering purpose yet with sufficient accuracy. The application of the Arrhenius model will be shown with test data in the following sections.

3.2. Flexural Strength. The experimental results of flexural strength of CAM subjected to the five temperatures are listed in Table 5. It can be firstly noticed that the strength of CAM with nanoparticles seems not to monotonically increase with increasing nanoparticles ratio, in contrary to some findings which showed that the higher ratio of nanoparticles contributes to the higher strength [24, 25]. The flexural strength of CAM with nano-SiO_2 decreased with increasing nano-SiO_2 content and reached a minimum strength at 3% content of nano-SiO_2, while the flexural strength of nano-TiO_2 is basically lowest when the content of nano-TiO_2 is 1%. In fact, such phenomenon was noticed and explained in some research. Nazari and Riahi [36] investigated the effect of 0–5% nano-SiO_2 replacement on the strength of self-compacting concrete and found that the highest amount of nanoparticles has led to a reduction in the compressive

Table 5: Flexural strength of CAM with nanoparticles.

Temperature (°C)	Flexural strength (MPa)						
	CAM	CAMS1	CAMS2	CAMS3	CAMT1	CAMT2	CAMT3
−20	10.45	9.48	7.80	5.03	7.97	7.92	10.33
	8.73	9.34	8.84	5.25	9.38	10.03	10.31
	9.27	7.77	8.31	5.72	8.50	10.27	9.56
0	9.01	8.36	4.55	4.51	6.70	7.32	6.35
	8.06	8.43	5.57	4.21	6.16	7.50	9.12
	8.81	8.21	5.65	4.65	6.86	7.03	8.02
20	4.16	3.8	3.32	3.14	4.91	5.27	4.68
	3.95	4.11	3.50	3.06	4.27	5.42	4.90
	4.27	5.10	3.61	2.31	3.94	5.39	5.77
40	3.22	3.07	2.31	2.14	3.19	2.98	2.32
	2.17	3.04	2.85	1.69	2.41	1.96	3.14
	2.85	2.59	2.31	1.50	3.19	3.19	3.15
60	2.40	1.59	1.92	1.58	2.27	2.14	1.70
	2.51	2.12	1.86	1.80	1.95	2.21	2.07
	2.00	2.24	2.16	1.92	2.03	2.18	2.10

strength. Similar results were also reported by Stefanidou and Papayianni [37], Salemi and Behfarnia [25], and Aydın et al. [38]. It is likely that nanoparticles are hard to disperse uniformly when the amount of nanoparticles exceeds the optimum range. The agglomeration of nanoparticles causes a poor workability of fresh nanoincorporated mixtures and in turn leads to the voids in the hardened mixtures and a reduction of strength. In this paper, the flowability of nanoincorporated CAM was generally decreased despite the inclusion of superplasticizer, as shown in Table 4. Therefore, it can be speculated that the weak rheology of CAM with nanoparticles resulted in the reduction of strength.

It is seen in Table 5 that the flexural strengths of CAM with and without nanoparticles follow the same pattern related to the variation of temperature. The flexural strengths of CAM with and without nanoparticles were found to decrease with the increasing temperature, which agrees with the results in the previous research [2, 9, 11, 14]. However, the strength decreasing rate of each CAM is different with respect to the type and amount of nanoparticles.

In order to describe the temperature sensitivity of flexural strength of CAM, Arrhenius model was used and expected to characterize the temperature dependence of flexural strength within the studied temperature range. Based on equation (2), the relative flexural strength of CAM is plotted in Figure 3 with respect to $((1/T) - (1/T_r))$, where T_r is determined as 253.15 Kelvins (−20°C). Linear fittings of $(f_T/f_{Tr})_{\mathrm{FL}}$ in flexural strength with respect to $((1/T) - (1/T_r))$ were conducted for specimens in each group. Then the results of I_{TS} of flexural strength were determined by numerical regression.

The value of I_{TS} of flexural strength is shown in Table 6. A high value of I_{TS} indicates more significant dependence of flexural strength on the temperature. In general, the results of I_{TS} indicate that both nano-SiO_2 and nano-TiO_2 can mitigate the temperature sensitivity of flexural strength to some extent. CAMs with nano-SiO_2 and nano-TiO_2 with amount of 1 and 2 wt.% of binder have basically lower values of I_{TS} than those of CAM without nanoparticles, which suggests that the temperature sensitivity of flexural strength of CAM has been mitigated by incorporation of nanoparticles. However, as the amount of nanoparticles increases, CAM with nano-TiO_2 shows a different behavior compared with CAM with nano-SiO_2. It is found in Table 6 that I_{TS} of flexural strengths of CAM with nano-SiO_2 decreases with the increasing amount of nano-SiO_2, while I_{TS} of flexural strengths of CAM with nano-TiO_2 keeps increasing with the nanoparticles' amount. The experimental observations implied that CAM with nano-SiO_2 rather than nano-TiO_2 has better performance in the resistance of temperature influence.

3.3. Compressive Strength. The compressive strengths of CAM with and without nanoparticles are listed in Table 7. Similar to the flexural strength of CAM, the compressive strength of each CAM was found to decrease monotonically as the temperature increases. In order to analyze the decreasing trend of the compressive strengths of CAM, the relationship between $(f_T/f_{Tr})_{\mathrm{FL}}$ in compressive strength and $((1/T) - (1/T_r))$ based on equation (2) is investigated through Figure 4. The temperature sensitivity factors I_{TS} of compressive strength were determined by numerical regression of equation (2).

The results of I_{TS} of compressive strength are listed in Table 8. Compared with the results in Table 6, it was found that I_{TS} of flexural strength is higher than that of compressive strength. It is therefore suggested that the flexural strength of CAM is more sensitive to the temperature. According to Tables 5 and 7, the compressive strength of CAM at the temperature of 60°C has decreased down to approximately 60% of the compressive strength of CAM at the temperature of −20°C, while the corresponding figure has reached 80% for the flexural strength of CAM. From the previous findings [7, 39], when the asphalt to cement ratio is low, the primary skeleton of CAM is the network formed by the hydration products of cement, which the compressive

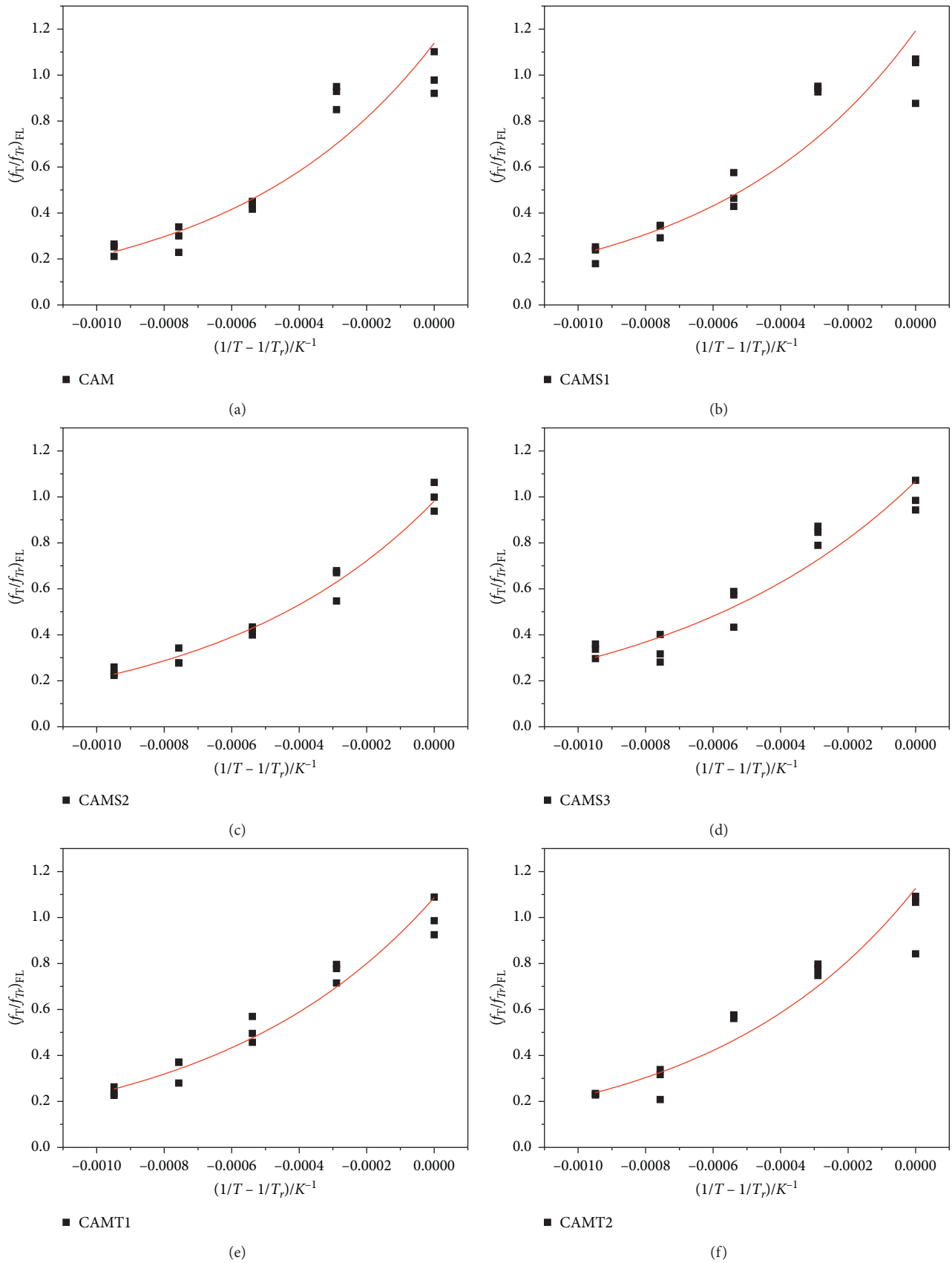

Figure 3: Continued.

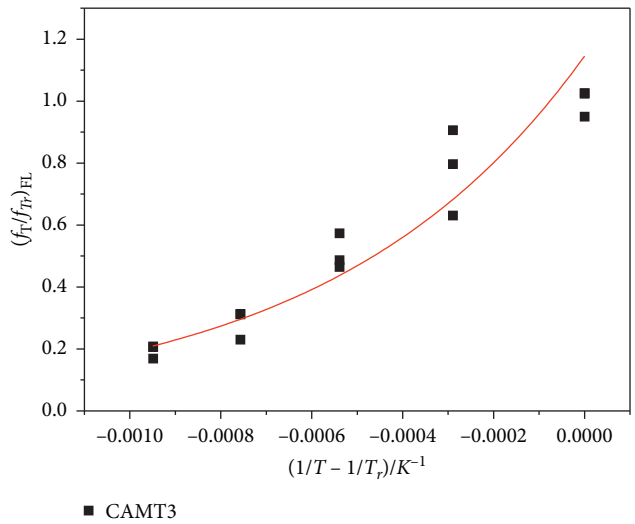

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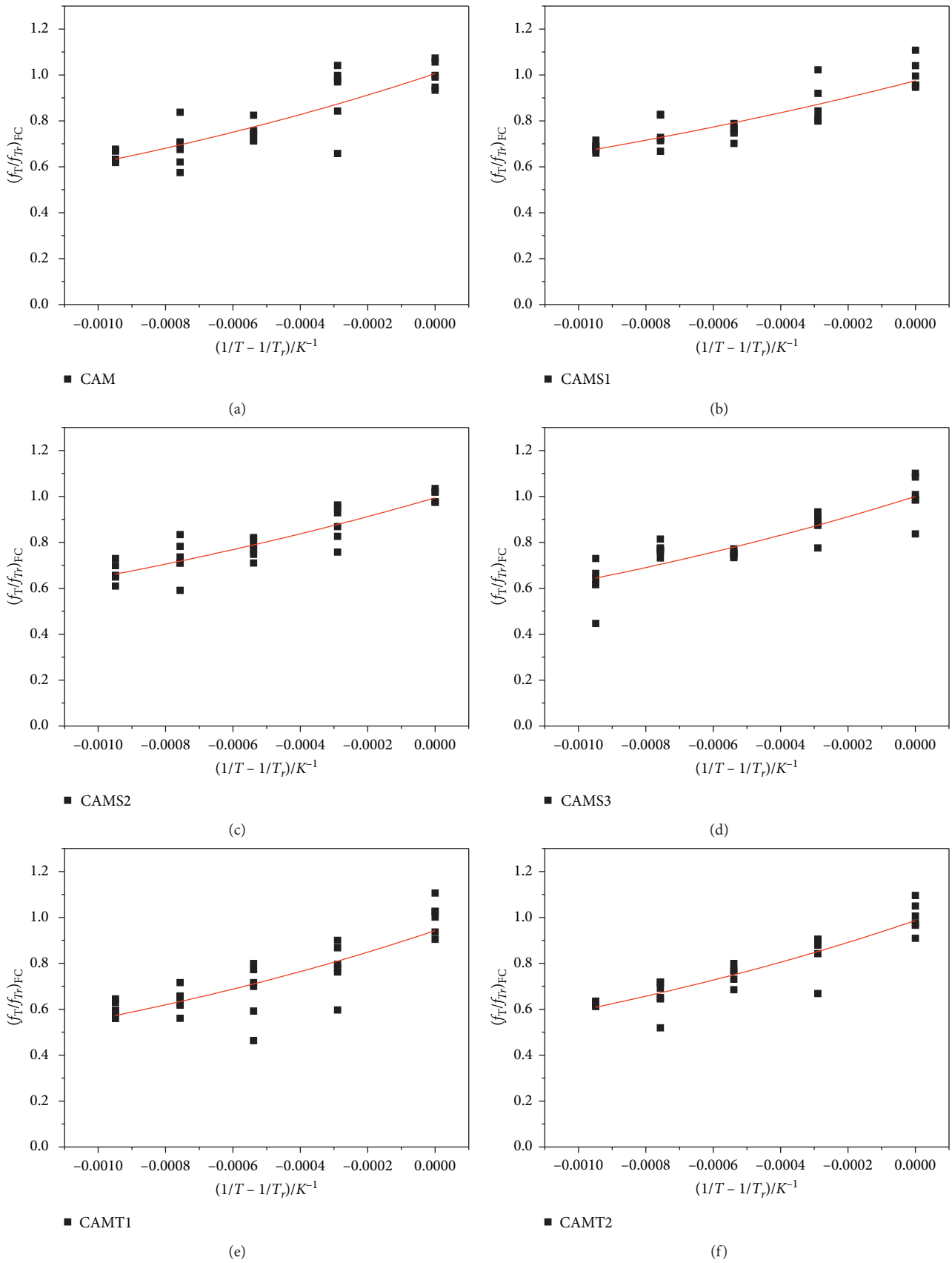
Figure 3: Relationship between $(f_T/f_{Tr})_{FL}$ and $((1/T) - (1/T_r))$ of (a) CAM, (b) CAMS1, (c) CAMS2, (d) CAMS3, (e) CAMT1, (f) CAMT2, and (g) CAMT3.

Table 6: Temperature sensitivity factor of flexural strength.

Specimens	CAM	CAMS1	CAMS2	CAMS3	CAMT1	CAMT2	CAMT3
I_{TS}	1679.2	1695.4	1536.0	1328.9	1531.2	1638.9	1788.4
R^2	0.9144	0.9127	0.9773	0.8993	0.9579	0.9109	0.9350

Table 7: Compressive strength of CAM with and without nanoparticles.

Temperature (°C)	Compressive strength (MPa)						
	CAM	CAMS1	CAMS2	CAMS3	CAMT1	CAMT2	CAMT3
−20	22.13	23.02	16.35	13.99	17.89	23.10	24.36
	24.69	20.68	16.38	14.29	20.28	25.96	22.04
	25.1	19.88	17.12	15.38	19.81	22.88	21.27
	23.33	21.63	16.39	15.61	21.88	23.83	22.31
	23.16	19.82	17.10	13.95	18.52	21.55	23.25
	21.81	19.67	17.36	11.87	20.31	24.88	20.94
0	15.37	21.24	14.57	12.54	11.81	20.76	21.58
	22.97	17.53	15.59	12.89	15.41	21.46	18.54
	22.66	16.72	12.71	12.39	15.08	21.27	18.74
	23.32	16.6	16.16	13.23	17.81	21.38	20.02
	24.33	16.95	15.98	12.70	15.74	15.85	20.67
	19.7	19.11	13.86	11.00	17.16	19.95	16.67
20	16.65	15.98	12.55	10.62	15.28	18.94	15.3
	17.47	14.59	13.78	10.46	11.72	—	15.93
	16.77	15.52	13.21	10.64	13.83	18.24	16.49
	19.27	15.54	11.92	10.4	15.8	18.16	16.12
	17.71	16.39	13.64	10.77	9.17	17.32	16.66
	17.36	15.85	12.88	10.95	14.17	16.23	14.98
40	16.38	14.93	13.13	10.88	13.01	12.31	14.16
	16.56	15.13	9.91	10.78	14.16	15.43	10.04
	19.58	14.84	13.99	10.92	12.22	15.29	15.74
	14.52	13.88	12.36	11.55	11.09	16.4	14.89
	13.43	17.15	11.9	11.00	12.96	16.95	15.65
	15.78	17.21	11.93	10.38	12.36	17.03	15.51
60	15.81	14.39	11.02	8.74	11.49	15.00	12.46
	14.45	13.71	10.96	10.35	12.76	14.51	12.92
	14.59	14.88	10.89	8.74	11.77	14.91	11.51
	15.66	13.99	11.73	9.43	11.08	14.64	12.88
	14.80	14.31	10.23	9.13	11.77	14.71	13.39
	15.67	14.24	12.25	6.33	12.45	15.05	13.13



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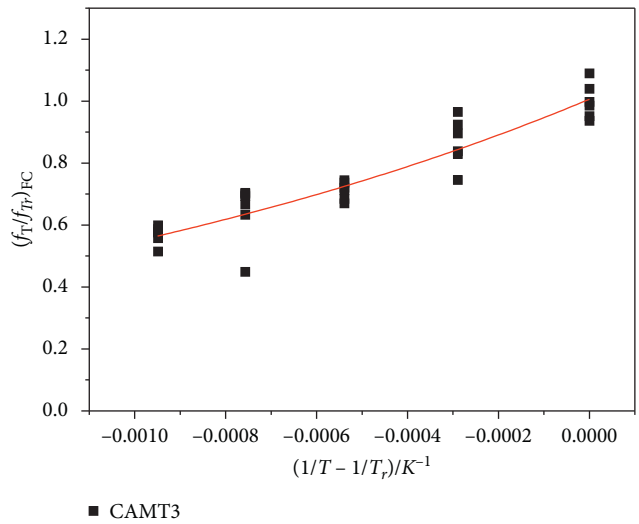

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Figure 4: Relationship between $(f_T/f_{Tr})_{FC}$ and $((1/T) - (1/T_r))$ of (a) CAM, (b) CAMS1, (c) CAMS2, (d) CAMS3, (e) CAMT1, (f) CAMT2, and (g) CAMT3.

Table 8: Temperature sensitive factor of compressive strength.

Specimens	CAM	CAMS1	CAMS2	CAMS3	CAMT1	CAMT2	CAMT3
I_{TS}	487.43	385.60	429.02	463.05	525.35	508.19	608.35
R^2	0.7364	0.7829	0.8017	0.7159	0.6717	0.8223	0.8403

strength of CAM is mainly attributed to. On the other hand, the dispersed asphalt, which fills in the pores of hydration products, contributes to the flexibility of CAM rather than the compressive strength of CAM. The asphalt is prone to be influenced by temperature while the hydration products of cement are not. Therefore, the temperature sensitivity of asphalt leads to a significant dependence of flexural strength on the temperature [40].

It can be also found in Table 8 that the dependence of compressive strength on temperature is closely related to the type and amount of nanoparticles. I_{TS} of compressive strength of CAM with nano-SiO_2 was found to increase monotonically with the increasing amount of nano-SiO_2; however, I_{TS} of all CAM with nano-SiO_2 are lower than those of CAM without nanoparticles. The results showed that the temperature sensitivity of compressive strength of CAM has been reduced by adding nano-SiO_2. On the other hand, CAM with nano-TiO_2 have higher value of I_{TS} than CAM without nanoparticles regardless of the amount of nanoparticles, which indicates a strong dependence of CAM with nano-TiO_2 on the temperature.

Based on the experimental observations of both flexural strength and compressive strength, it can be generally concluded that adding nano-SiO_2 rather than nano-TiO_2 is favorable to improve the performance of CAM. For practical significance, CAM cushion in slab track is usually required to maintain the strength stability at high temperature and high crack resistance at low temperature. In this sense, the proper usage of nano-SiO_2 in CAM is a promising way to keep the strength stability in temperature-varied service environment. However, more researches are urgently needed to evaluate the effect of nano-SiO_2 on the cracking resistance, toughness, and deformation of CAM before the application of nanoparticles in real practice.

3.4. SEM Observations. The microstructure of CAM with and without nanoparticles was analyzed using a high resolution scanning electron microscope. The objective of the microstructural analysis is to observe the distribution of asphalt in hardened CAM and reveal the mechanism of nanoparticles in the temperature sensitivity of mechanical properties.

A typical fractured surface of CAM without nanoparticles and its enlarged view are presented in Figures 5 and 6. It is seen that a considerable amount of hydration products was formed in the hardened CAM structure. The main hydration products of CAM consist of clustered C-S-H gel, hexagonal plate-shaped $Ca(OH)_2$ crystal, and needle-shaped ettringite (AFt). A floccus of C-S-H gel can be found with needle-shaped hydration products AFt and hexagonal sheet of $Ca(OH)_2$ crystal penetrating inside the C-S-H gel. The edges of $Ca(OH)_2$ crystal were clear, and the crystal size was large up to approximately 40 μm in the SEM images. In agreement with the previous findings, none of the new hydration products was found in CAM with and without nanoparticles, which indicates that asphalt may not react with cement or nanoparticles [41].

The hydration products in CAM with nano-SiO_2 and nano-TiO_2 as shown in Figure 7 are similar to those in CAM without nanoparticles shown in Figure 5. However, the

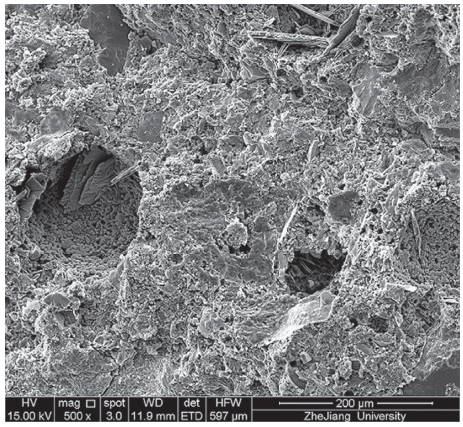
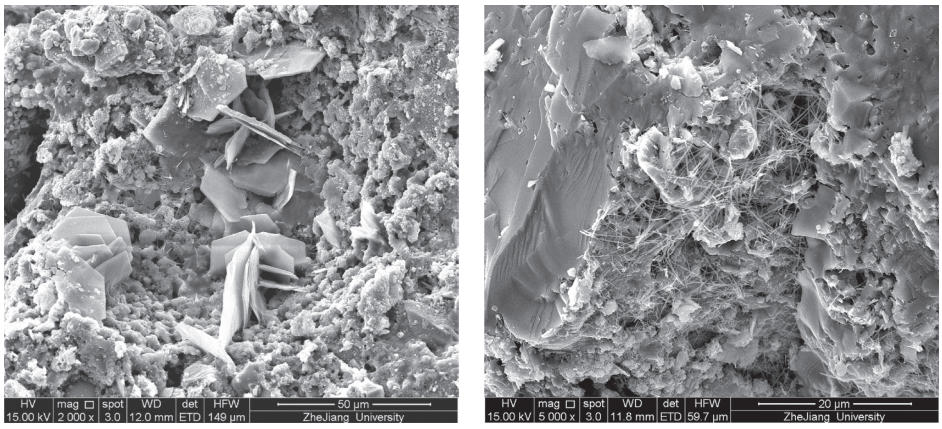
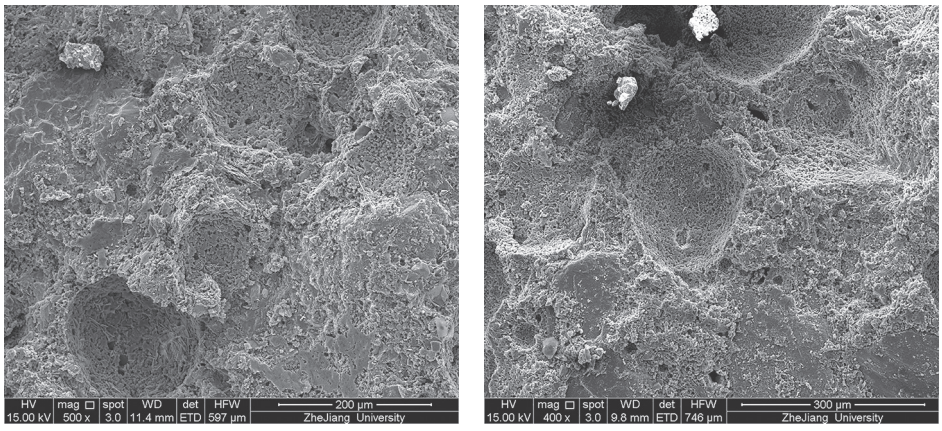


Figure 5: Microstructure of CAM without nanoparticles.



(a) (b)

Figure 6: Enlarged view of hydration products.



(a) (b)

Figure 7: Microstructure of CAM with nanoparticles.

texture quality of hydration products in CAM with nanoparticles is different from that in CAM without nanoparticles. The microstructure of CAM with nanoparticles reveals a dense and compacted formation of hydration products, and reduced number and size of $Ca(OH)_2$ crystals. In plain cement mortar, the increased amount of C-S-H gel and reduced content of $Ca(OH)_2$ crystal contribute to the improvement of strength [42]. As explained in strength formation mechanism of CAM with a low asphalt to cement ratio, the framework formed by the hydration products of

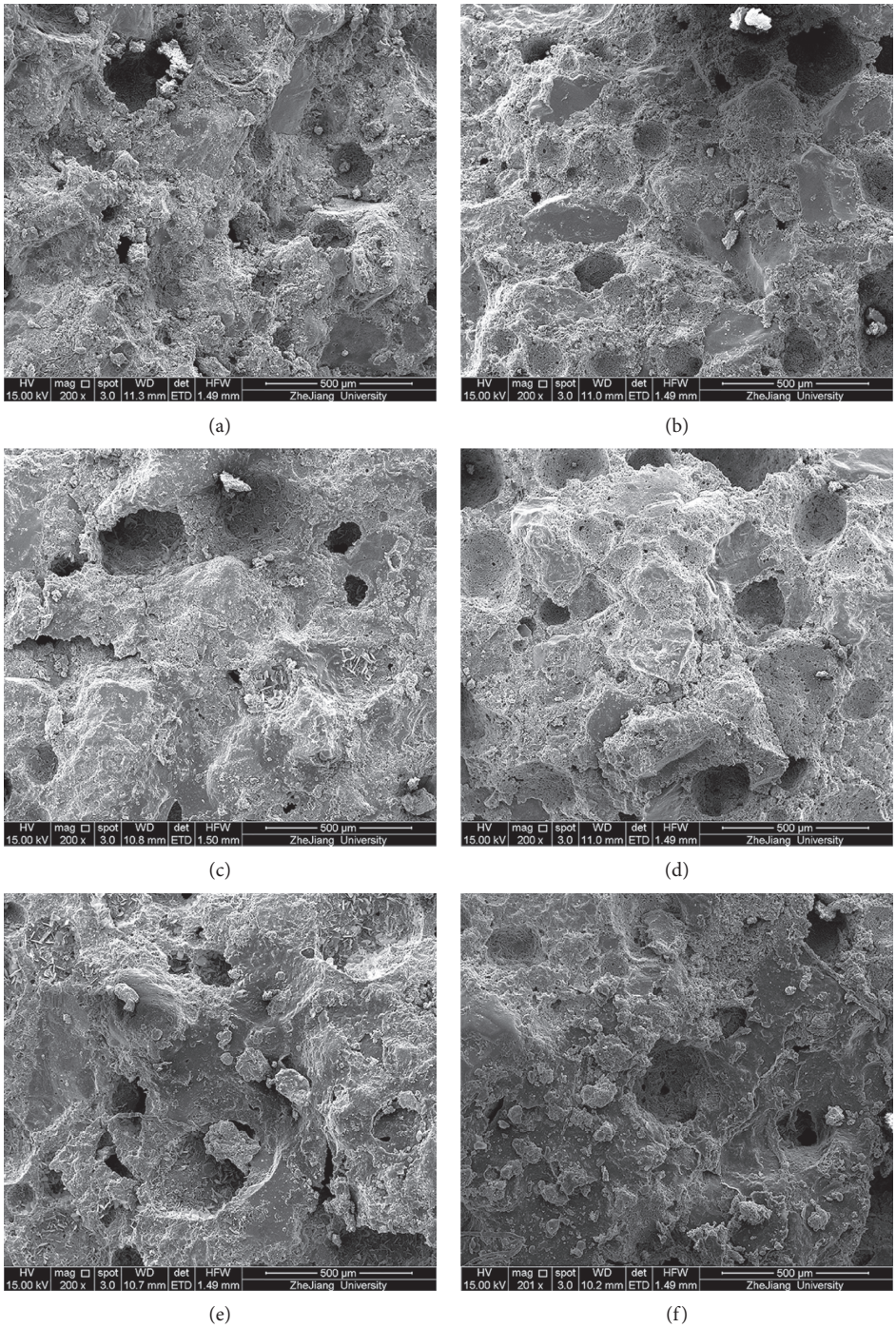
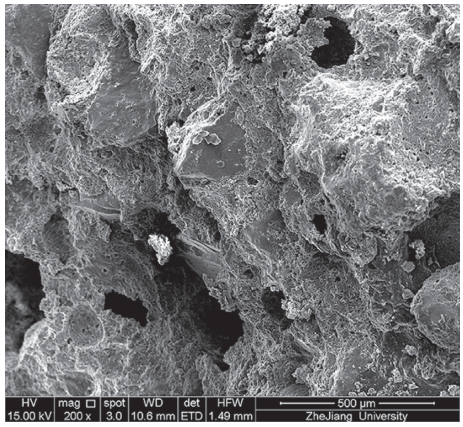


Figure 8: Continued.



(g)

Figure 8: Free asphalt in hardened specimens of (a) CAM, (b) CAMS1, (c) CAMS2, (d) CAMS3, (e) CAMT1, (f) CAMT2, and (g) CAMT3.

cement was the primary frame of the cementitious system [7]. Therefore, the dispersed asphalt contributes slightly to the compressive strength of CAM, but significantly, to some extent, for the viscoelastic behavior of CAM [43].

The asphalt is considered to play an important role in the thermal behavior of CAM [4, 8, 11]. The asphalt is sensitive to the temperature, which in turn results in the variation of strength of CAM under different temperatures. It is, therefore, to investigate the asphalt phase in the hardened CAM. As discussed, the amount of free asphalt is a critical factor to the temperature sensitivity of CAM. In the SEM observation results, the free asphalt membrane is found to disperse in the hardened CAM and stuck to the surface of hydration products, as shown in Figure 8. However, the amount of free asphalt is found to depend on the type and amount of nanoparticles. In the hardened CAM without nanoparticles, the free asphalt can be found to disperse randomly with the membrane area of width ranging from approximately 5 μm and 25 μm in the hardened paste. In the hardened CAM with nano-SiO_2, the dispersed asphalt is seen to be with less area. In the hardened CAM with nano-TiO_2, the area of asphalt membrane is expanded, and the majority of hydration products are wrapped by the asphalt membrane. The distribution and phase of asphalt indicate that the more free asphalt has been converted to the structural asphalt by adding nano-SiO_2, while free asphalt is seen to keep the same amount by adding nano-TiO_2. As a general result, the improvement of the performance of mortar or concrete by nano-SiO_2 is attributed to the increased formation of C-S-H gel caused by the pozzolanic reaction of nano-SiO_2 with calcium hydroxide [25]. However, nano-TiO_2 is believed to be a non-reactive filler and had no pozzolanic activity [44, 45]. Therefore, the free asphalt is consumed by the large amount of C-S-H gel in CAM with nano-SiO_2, while free asphalt still exists in CAM with nano-TiO_2 since no excessive C-S-H gel was produced. The experimental results of strength and microstructure of CAM with nanoparticles show that incorporation of nano-SiO_2 can reduce the temperature sensitivity of CAM, while incorporation of nano-TiO_2 is adverse to the temperature sensitivity of CAM.

4. Conclusions

The temperature sensitivity of flexural strength and compressive strength of CAM with and without nanoparticles was investigated in this paper. Based on the experimental observations, the conclusions are drawn as follows:

(1) Both compressive strength and flexural strength of CAM are not significantly improved by the inclusion of nanoparticles in CAM in this paper. The reduction of strength at a high ratio of nanoparticles is possibly attributed to the poor workability caused by the agglomeration of nanoparticles.

(2) The flexural strength and compressive strength of CAM with and without nanoparticles decreased with the increasing temperature. However, the decreasing trend is different for CAM with different type and dosage of nanoparticles. The temperature sensitivity factor I_{TS} of strength based on Arrhenius model was introduced to describe the dependence of strength on temperature. Based on the results of temperature sensitivity factor, it was found that the temperature sensitivity of strength of CAM was mitigated by incorporation of nano-SiO_2, while nano-TiO_2 seemed not helpful to improve the performance of CAM.

(3) The SEM observations showed that the presence of free asphalt is crucial to the temperature sensitivity of CAM. The amount of free asphalt membrane in CAM with nano-SiO_2 was significantly less than that in CAM without nanoparticles, while a massive area of free asphalt membrane was found in the hardened CAM with nano-TiO_2.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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