Supplementary materials

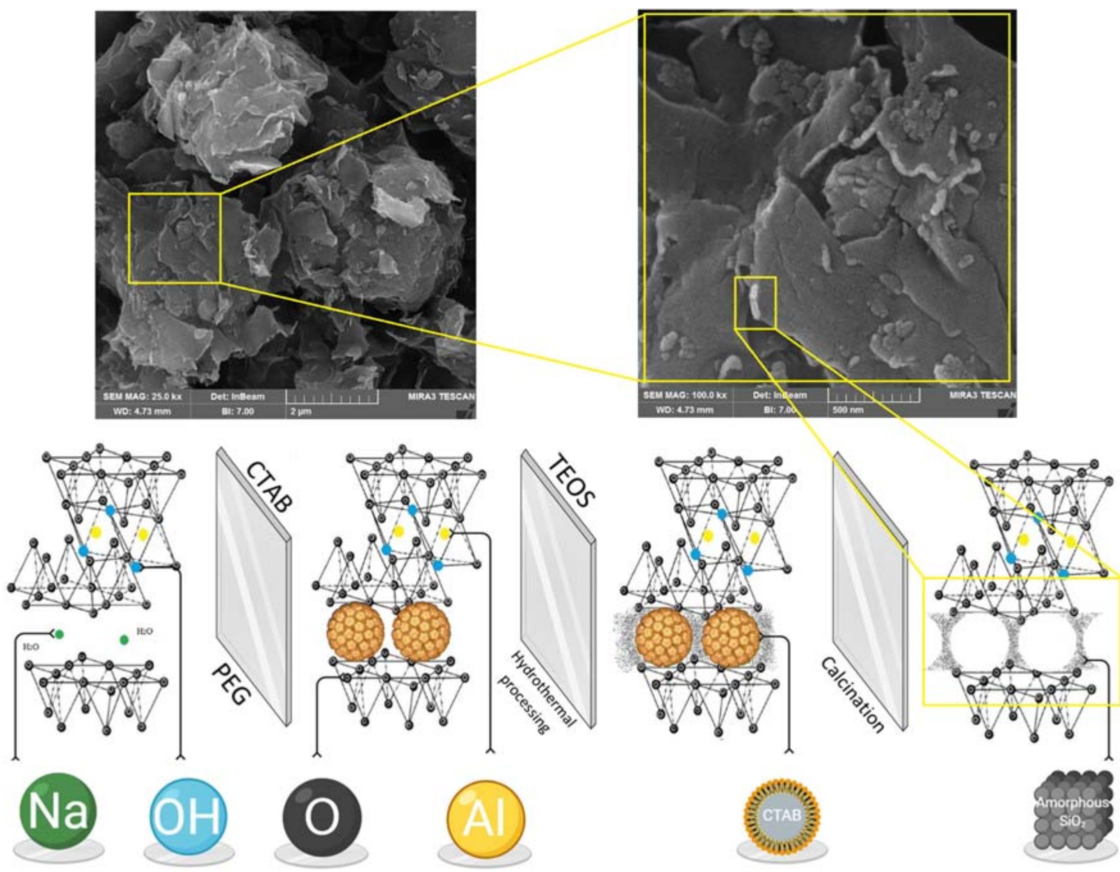

Figure S1: Schematic illustration of multistep synthesis of CS-NPs.

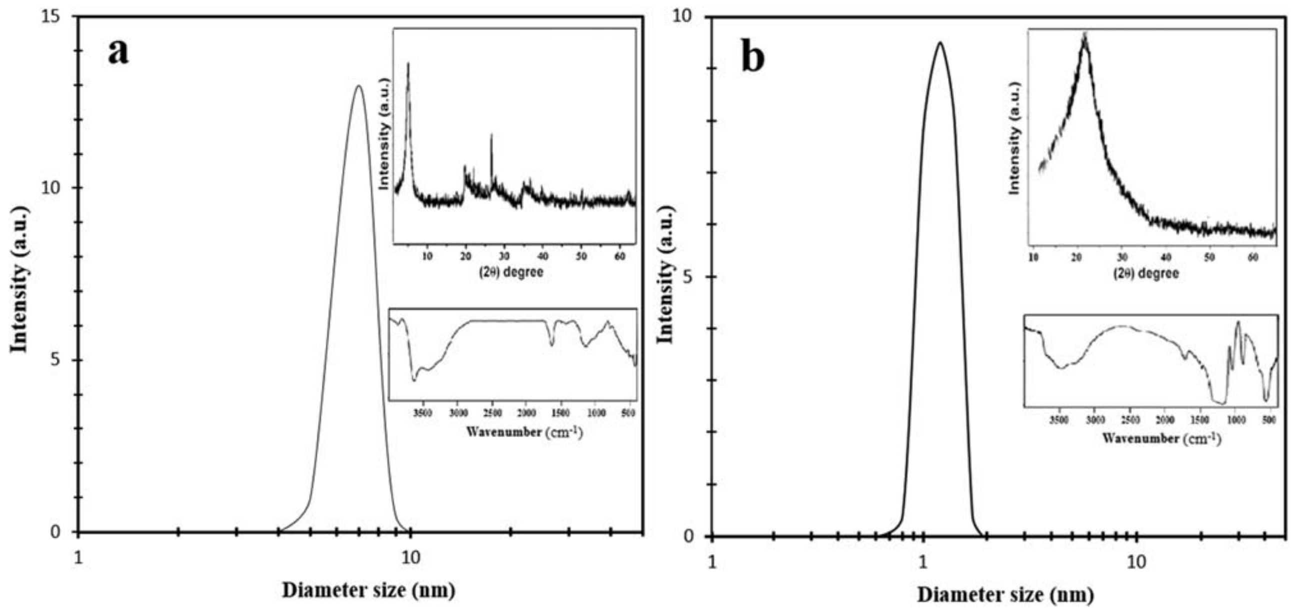

Figure S2: DLS distribution, XRD pattern, and Fourier transform infrared spectra of (a) clay and (b) fumed silica.

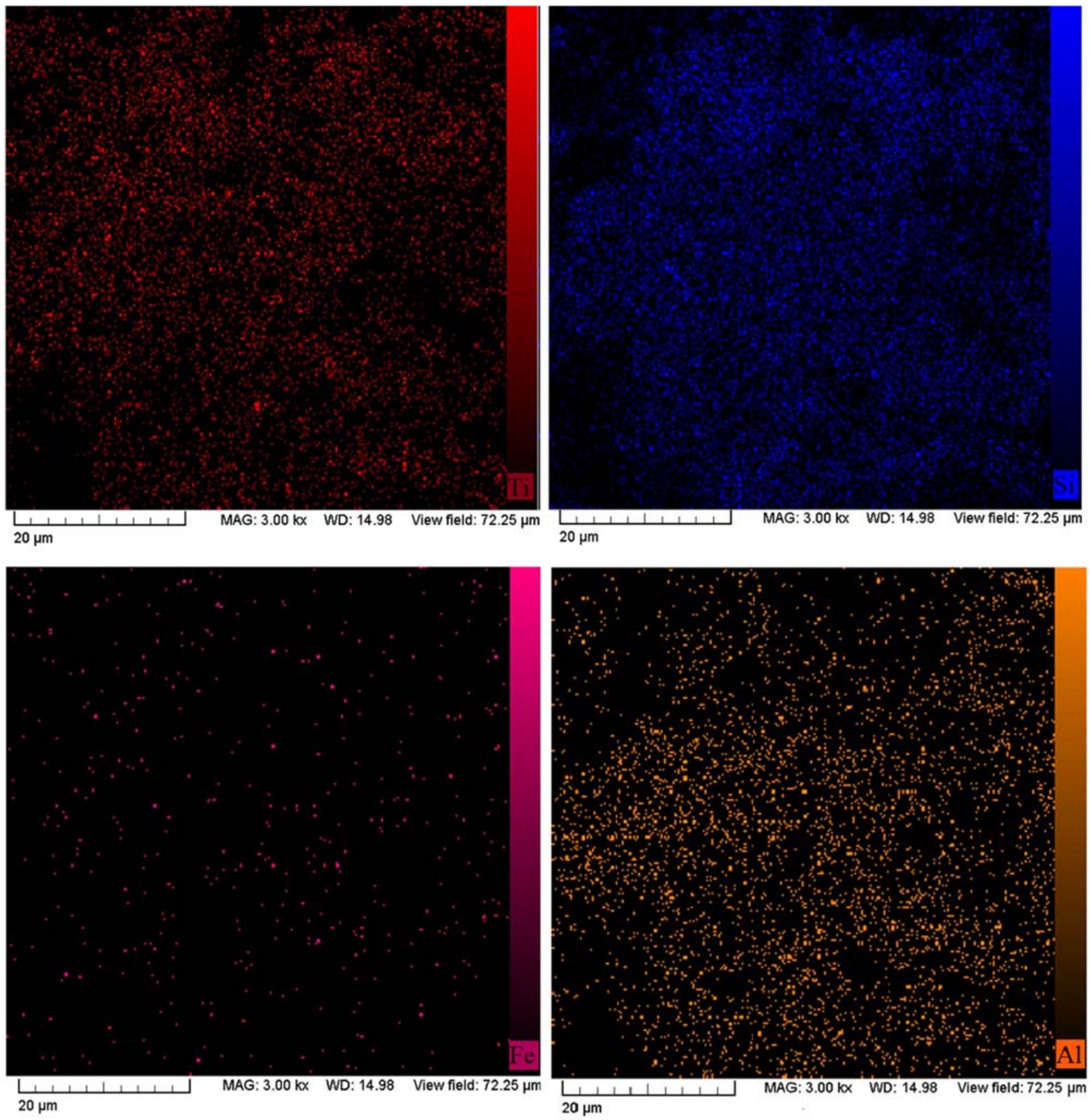

Figure S3: Energy dispersive X-ray (EDX) mapping analysis of binders modified with CS nanoparticles. Elemental spot maps of Ti, Fe, Si, and Al.

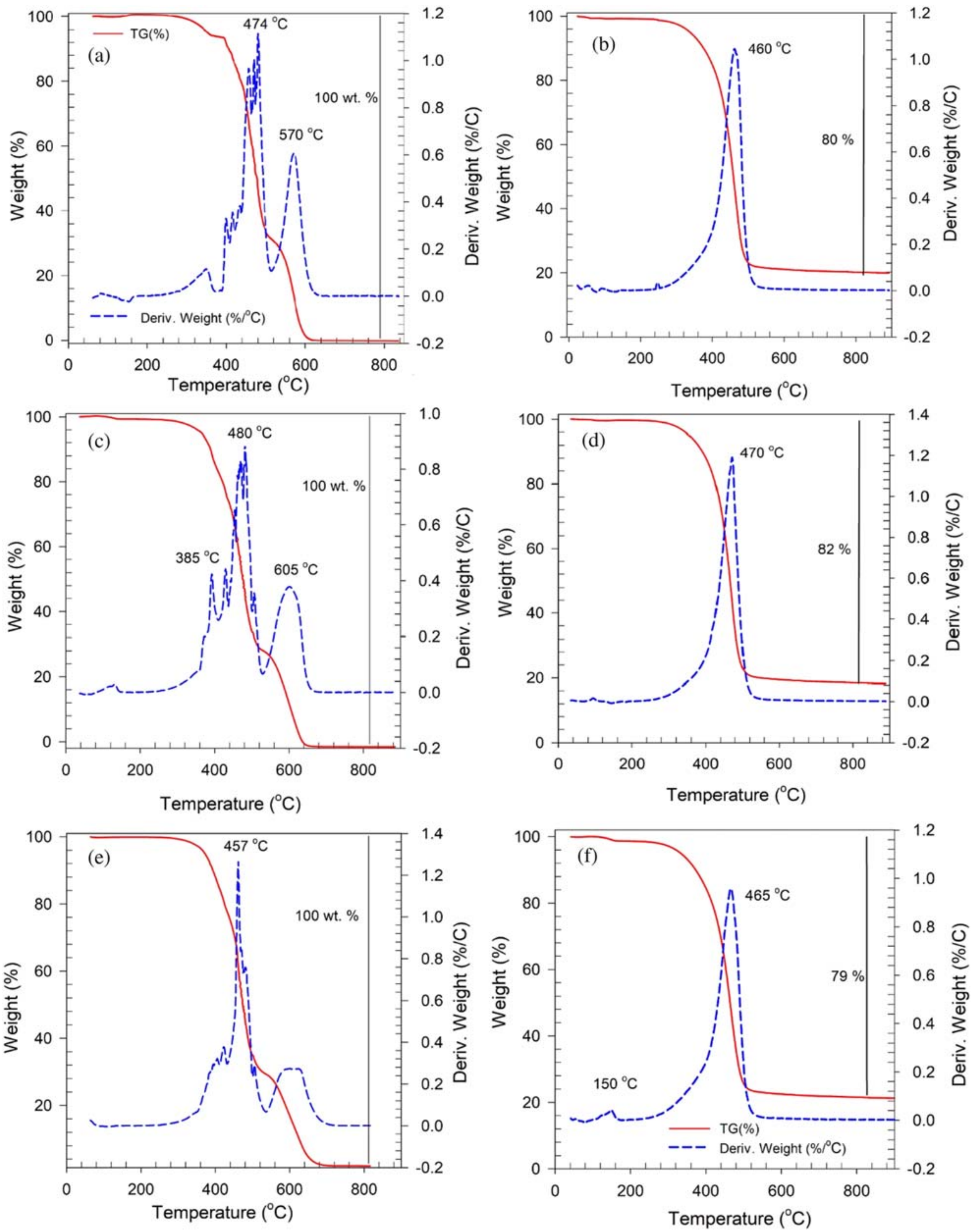

Figure S4: Thermal Gravimetric Analysis (TGA) and Derivative Thermo-Gravimetry (DTG) curve: (a) unaged binder, (b) unaged binder modified by fumed silica NPs, (c) short-term aged binder, (d) fumed silica NPs-modified binder after short-term aging, (e) long-term aged binder, and (f) fumed silica NPs-modified binder after long-term aging.

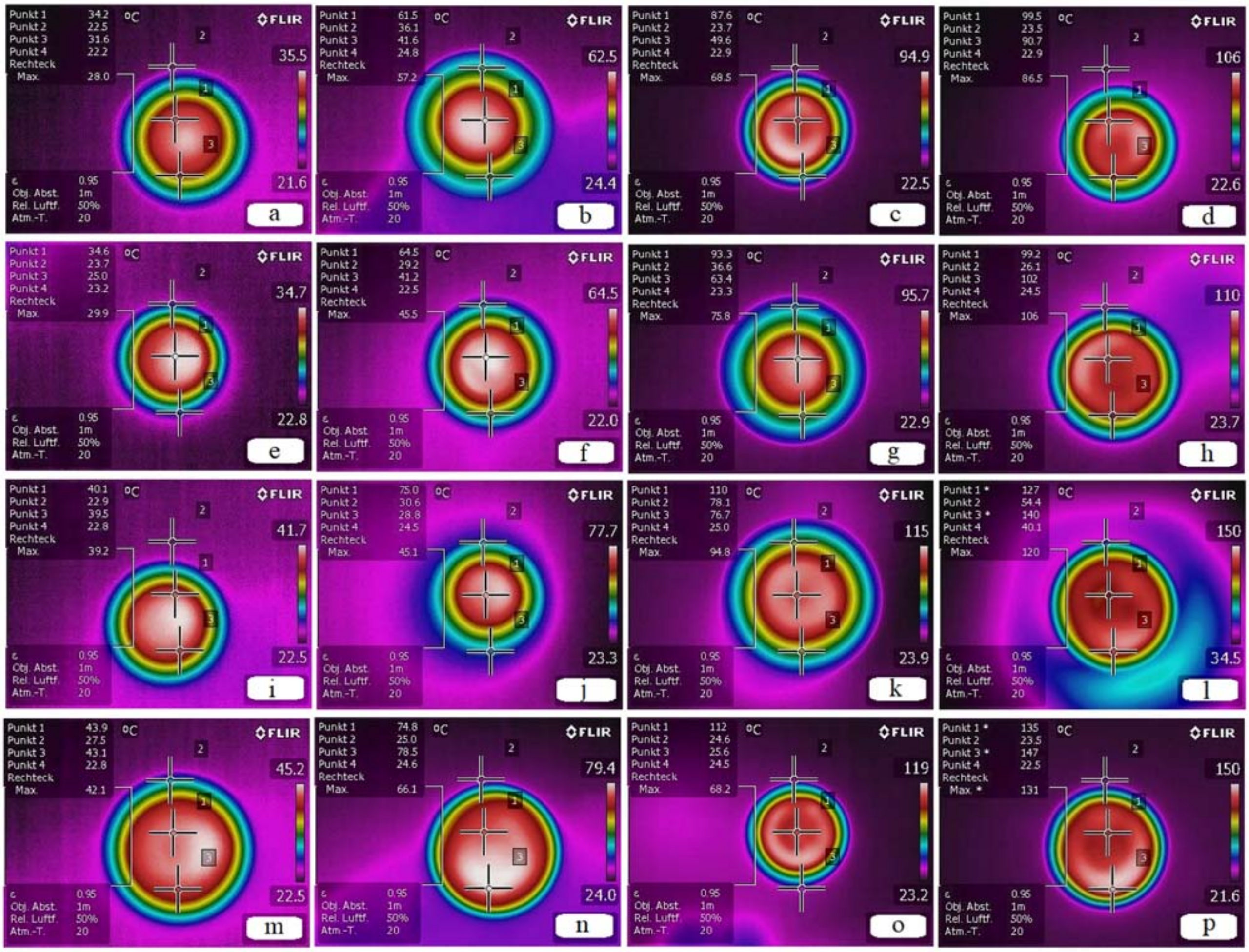

Figure S5: Infrared thermal images evaluation of asphalt binder specimens of: (a–d) warm mix additive and FSN, (e–h) warm mix additive and without FSN, (i–l) FSN and without warm mix additive, and (m–p) without warm mix additive and without FSN; in different thermal zones: (a, e, I, and m) 30 s, (b, f, j, and n) 60 s, (c, g, k, and o) 90 s, and (d, h, l, and p) 120 s. The diameter of the specimen is 18 mm.

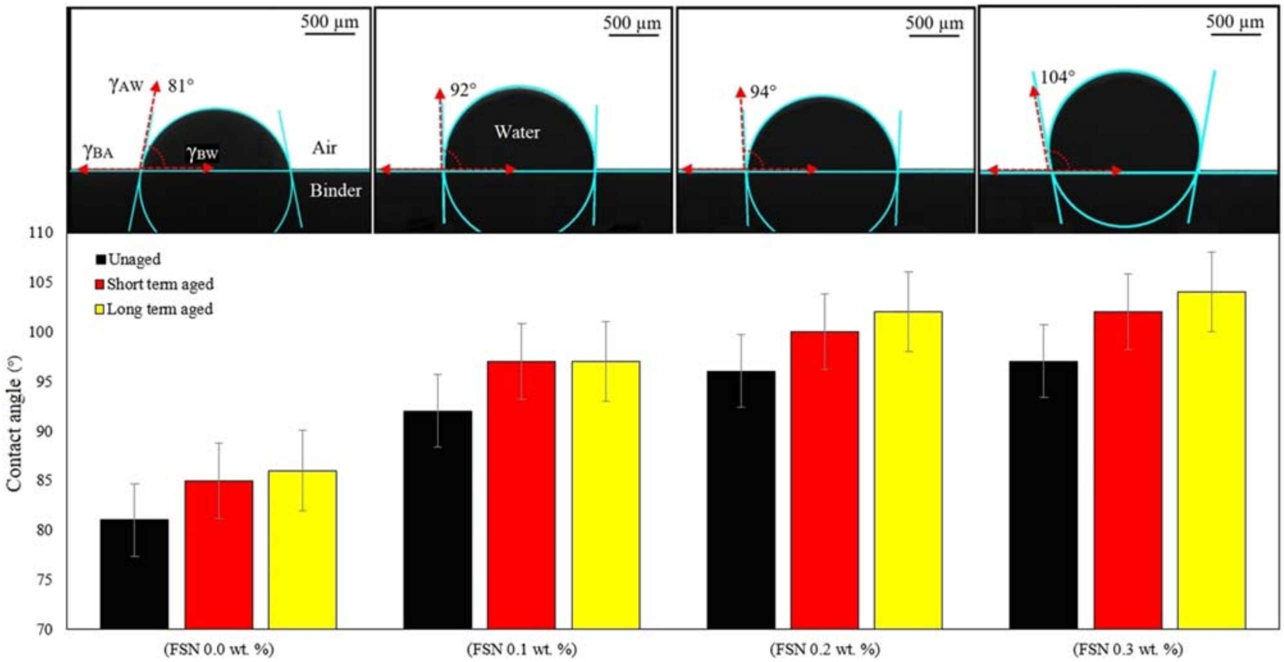

Figure S6: Contact angles of modified asphalt binders in different concentrations of fumed silica NPs.

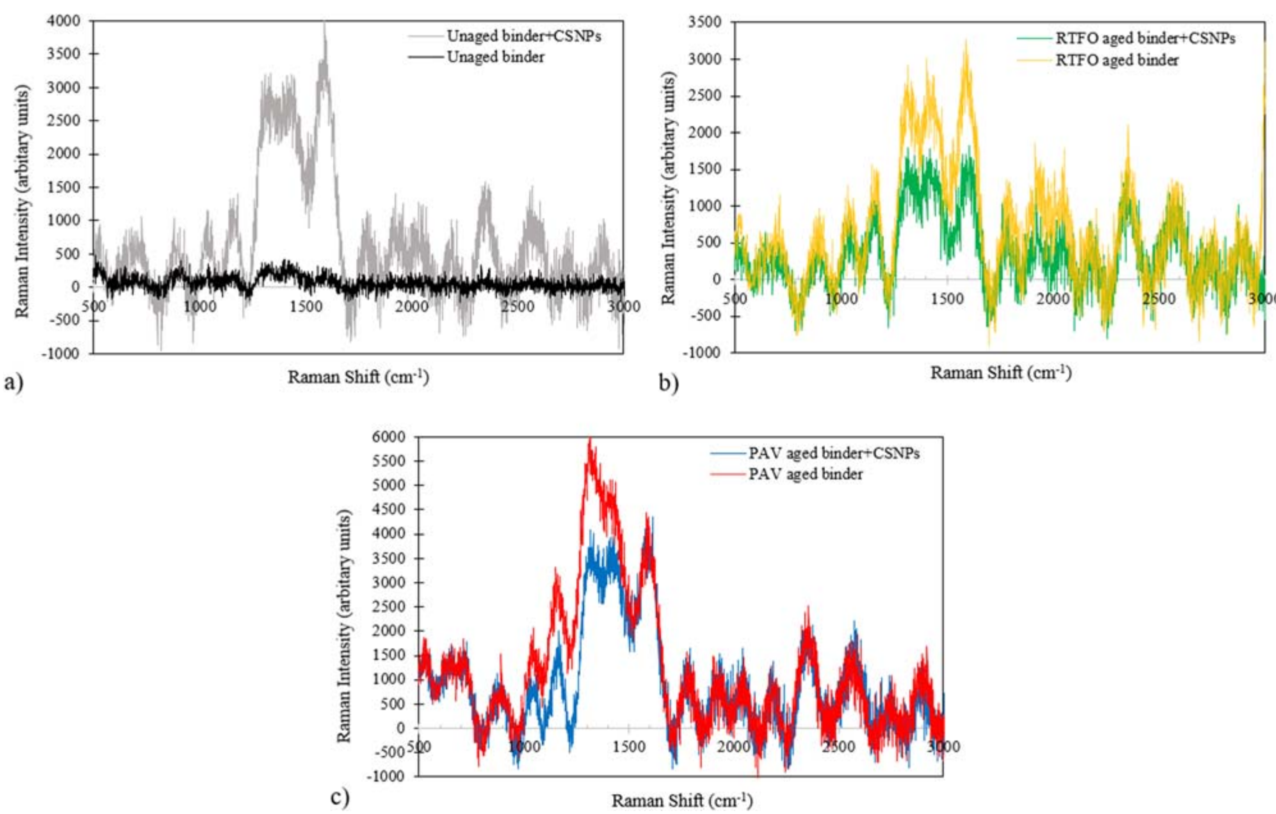

Figure S7: Raman spectra of the binder samples after coating on the microscope slides (a) unaged, (b) short-term aging, and (c) long-term aging.

Table S1: Properties of nanomaterials

Properties	Fumed silica	Clay
Specific surface area (m^2/g)	270–330	90–800
pH (°C)	3.7–4.5	4.5–7
Appearance (Color)	White	Light Beige
Appearance (Form)	Powder	Powder
Loss on drying	≤1.5%	≤18.0%

Table S2: Samples with different additives and aging process

Sample	NPs additives	Aging process	Sample	Additives	Aging process
S1	0.0 wt% CSNPs	Unaged	S7	0.2 wt% CSNPs	RTFO
S2	0.1 wt% CSNPs	Unaged	S8	0.3 wt% CSNPs	RTFO
S3	0.2 wt% CSNPs	Unaged	S9	0.0 wt% CSNPs	PAV
S4	0.3 wt% CSNPs	Unaged	S10	0.1 wt% CSNPs	PAV
S5	0.0 wt% CSNPs	RTFO	S11	0.2 wt% CSNPs	PAV
S6	0.1 wt% CSNPs	RTFO	S12	0.3 wt% CSNPs	PAV

Table S3: Physical properties of bitumen sample

Physical properties	Value	Standard
Ductility (@25°C, cm)	100	ASTM D113
Softening point (°C)	48.6	ASTM D36
Penetration (@25°C, 0.1 mm)	63	ASTM D5
Density (kg/m^3)	1.03	ASTM D70

Table S4: Physical properties of bitumen sample

$$I_{CH=CH} = \frac{\text{Area of ethylene band centered around 966/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (1)$$

$$I_{S=O} = \frac{\text{Area of sulfoxide band centered around 1030/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (2)$$

$$I_{C-H\ of\ CH_3} = \frac{\text{Area of aliphatic band centered around 1376/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (3)$$

$$I_{C-H\ of (CH_3)n} = \frac{\text{Area of aliphatic band centered around 1460/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (4)$$

$$I_{C=C} = \frac{\text{Area of aromatic band centered around 1600/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (5)$$

$$I_{C=O} = \frac{\text{Area of carbonyl band centered around 1690/cm}}{\sum \text{Area of spectral bands around 2000 and 600/cm}} \quad (6)$$

$$CR = \left(\frac{\text{Index of bitumen after} - \text{Index of bitumen before}}{\text{Index of bitumen before}}\right) \times 100 \quad (7)$$

$$IVA = \frac{\text{Viscosity of bitumen after aging} - \text{Viscosity of bitumen before aging}}{\text{Viscosity of bitumen before aging}} \quad (8)$$