

Supporting Information (SI)

Synthesis of porous hollow silica nanostructures using hydroxyapatite nanoparticle templates

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General procedures.

All chemicals used in these experiments were obtained from commercial sources as analytical reagents and used without further purification unless otherwise indicated. Ultra pure water ($18.2 \text{ m}\Omega \text{ cm}^{-1}$) was used throughout.

A simple and versatile method for hydroxyapatite nanoparticle production is wet chemical precipitation, described herein for HAp2. Ammonium dihydrogenphosphate (0.3M) was added to a calcium nitrate (0.5M) solution dropwise. These concentrations were chosen to achieve a 1.67 Ca/P ratio. The reaction was allowed to proceed at 60°C for 4 h followed by an overnight aging period during which the suspension was allowed to stand at room temperature. After washing and drying at 60°C overnight the precipitate was heated in a furnace at 550°C for 6 h, to produce nanocrystalline HAp2. X-ray diffraction studies show that the predominant crystalline phase is indeed hydroxyapatite, confirmed by comparison with standard JCPDS files.

HAp1 refers to hydroxyapatite obtained from Sigma Aldrich (<200 nm) catalogue number 677418

Preparation of HAp2 (calcined hydroxyapatite)

To a solution of $0.5\text{M Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ in H_2O (30 mL) was added $0.3\text{M } (\text{NH}_4)_2\text{HPO}_4$ in H_2O (30 mL) drop-wise. The solutions were adjusted to pH 10 with 28% ammonium hydroxide prior to mixing. The reaction mixture was stirred for 4 h at 60°C , and left to stand overnight. The precipitate was washed four times with ethanol (20 mL) with centrifugation at 8,000 rpm to remove the washings. The product was dried at 60°C overnight and sintered in a furnace at 550°C for 6 h yielding a fine white powder.

Preparation of HAp3 (hydrothermally treated hydroxyapatite)

To a solution of $0.5\text{M Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ in H_2O (30 mL) was added $0.3\text{M } (\text{NH}_4)_2\text{HPO}_4$ in H_2O (30 mL) drop-wise. Solutions were adjusted to pH 10 with 28% ammonium hydroxide prior to mixing. The reaction mixture was stirred for 4 h at 60°C , and left to stand overnight. The precipitate was washed four times with ethanol (20 mL) with centrifugation at 8,000 rpm to remove the washings. After washing and drying at 60°C overnight the HAp powder was suspended in water (15 mg/mL) and placed in an acid digestion bomb (Parr), and heated in an oven at 200°C for 24 h followed by freeze drying.

Preparation of HAp4 (citrate coated hydroxyapatite)

HAp 1 (200 mg) was suspended in sodium citrate dehydrate 0.2M (50 mL), adjusted to pH 6 with HCl (0.1 M), and stirred for 12 h. The solid was washed four times with H_2O with centrifugation at 8,000 rpm to remove unbound citrate. The resultant white powder was freeze dried.

Preparation of hollow silica structures (HPS): General method

Hydroxyapatite nanoparticles (30 mg) were added to ethanol (4 mL) and sonicated for 10 min. To the sonicated suspension was added CTAC (cetyltrimethylammonium chloride) 25% (0.08 mL) followed by stirring for 10 min and the addition of H_2O (0.34 mL), ammonium hydroxide 28% (0.15 mL), and TEOS (tetraethyl orthosilicate, 0.41 mM) (0.08 mL). The reaction mixture was stirred at room temperature for 3 h and washed four times with ethanol (5 mL) with centrifugation at 15,000 rpm to remove washings. The particles were left to dry in air overnight and calcined in the presence of air in a furnace at 550°C for 6 h. The powder thus prepared was suspended in dilute HCl (0.1 M) and stirred for 12 h to remove the core hydroxyapatite. The suspension was washed four times with H_2O (5 mL) with centrifugation at 15,000 rpm to remove washings. The resulting solid was then freeze dried producing a fine white powder.

Characterisation

The morphology and structure of the products were analysed by transmission electron microscopy (TEM) using an FEI Tecnai T12 instrument at 120 kV. Samples were drop cast and dried on carbon film copper grids. Elemental analysis was performed by energy dispersive spectroscopy using an EDAX spectrometer in conjunction with the same microscope. X-ray diffraction patterns (XRD) were recorded on a PANalytical X'Pert Pro Multi Purpose diffractometer. Zeta potential and hydrodynamic particle size measurements were made using a Delsa Nano C particle analyser. Particles were suspended in water (1 mg/mL) at pH7. All measurements were performed at 25°C at a measurement angle of 90° . Samples were also analysed by infrared spectroscopy (FT-IR) using a Perkin-Elmer Spectrum RXI FT-IR spectrometer.

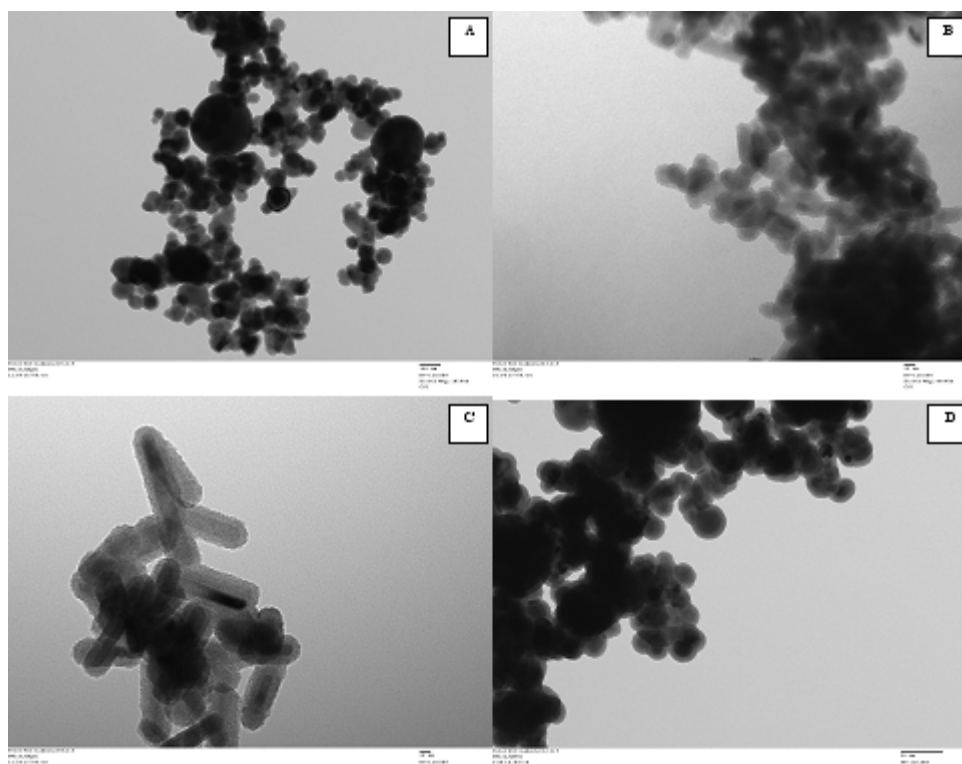


Figure 1. TEM of HAP_silica composites. A, HAp1_Si. B, HAp2_Si. C, HAp3_Si. D, HAp4_Si

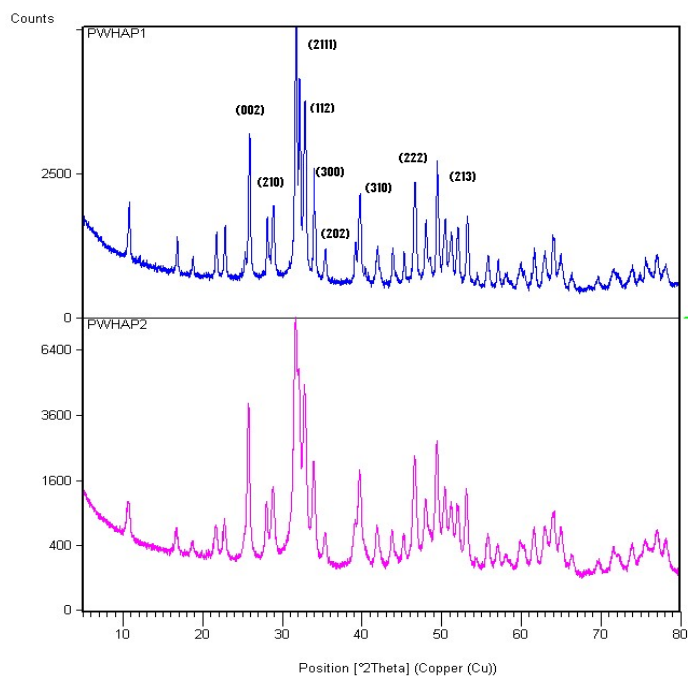


Figure 2. Typical XRD HAP1 (top) and HAP2 (bottom)files.

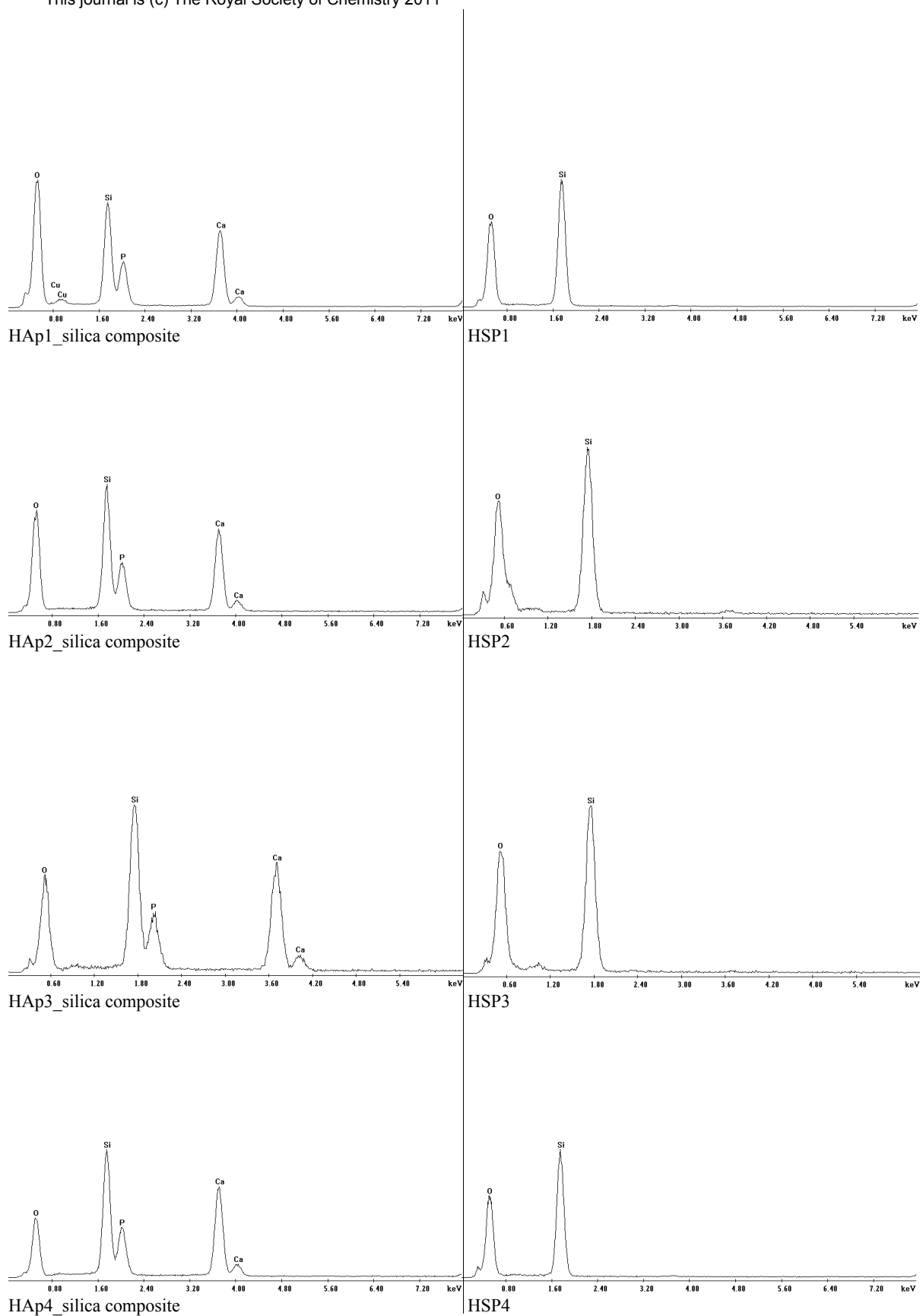


Figure 3. EDX spectrometry for HAp silica composites1-4 (left) and HSP1-4 (right). Identifies the presence of Ca, P, Si and O in composite samples; and removal of hydroxyapatite core, leaving only Si and O in HSP samples.

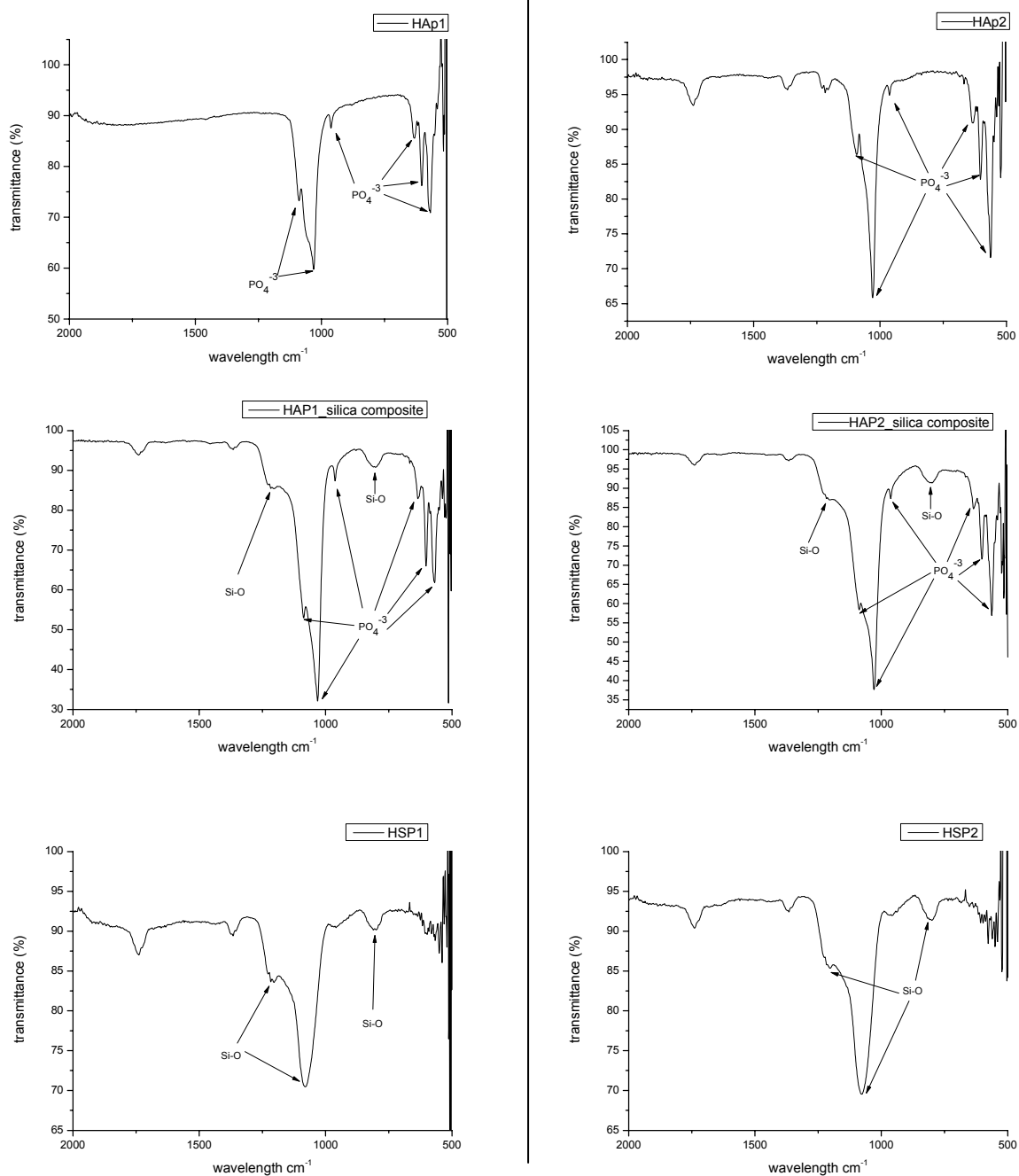


Figure 4. FT-IR of HAp1, HAp2, HAp_silica composite1, HAp silica composite2, HSP1 and HSP2

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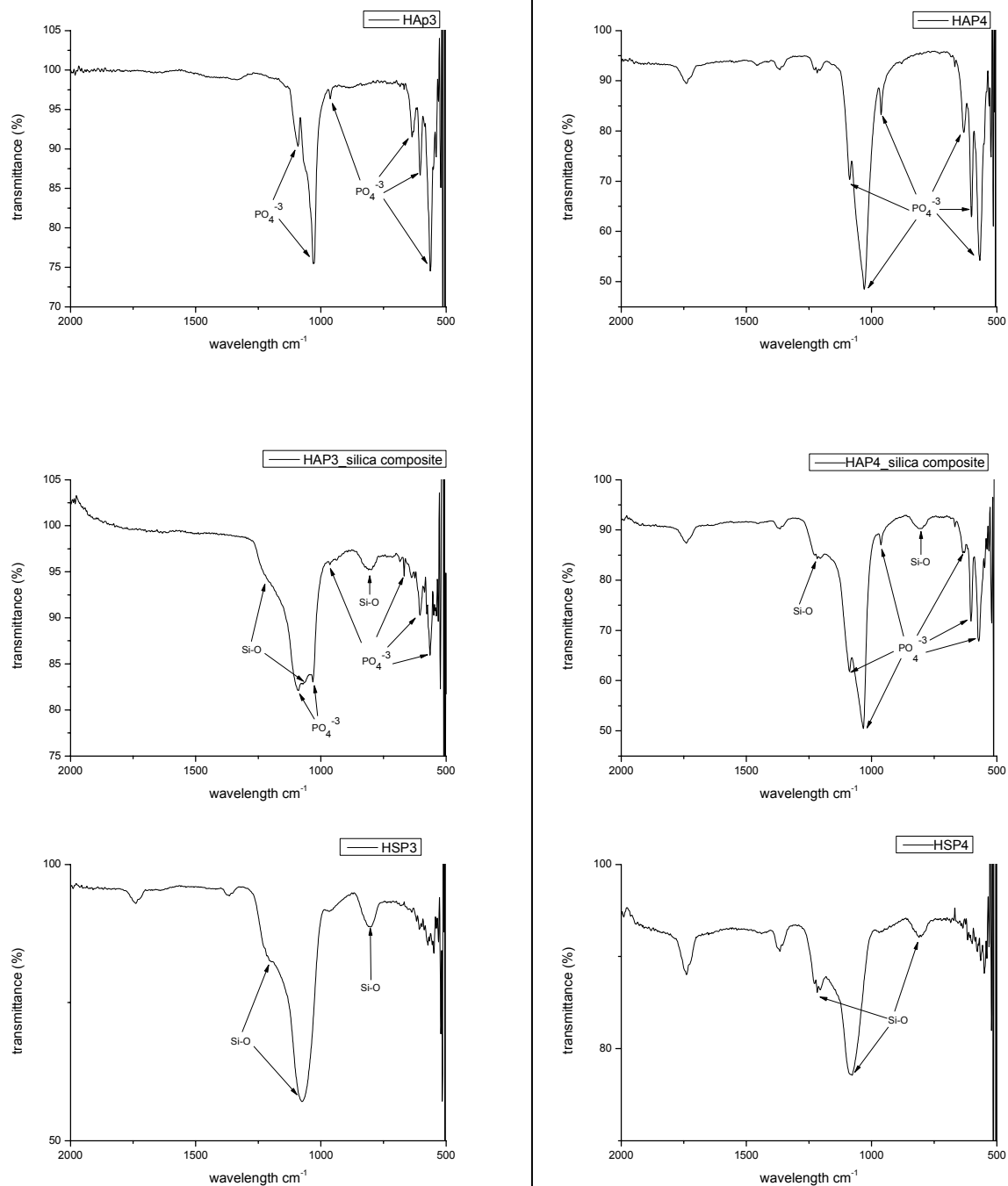
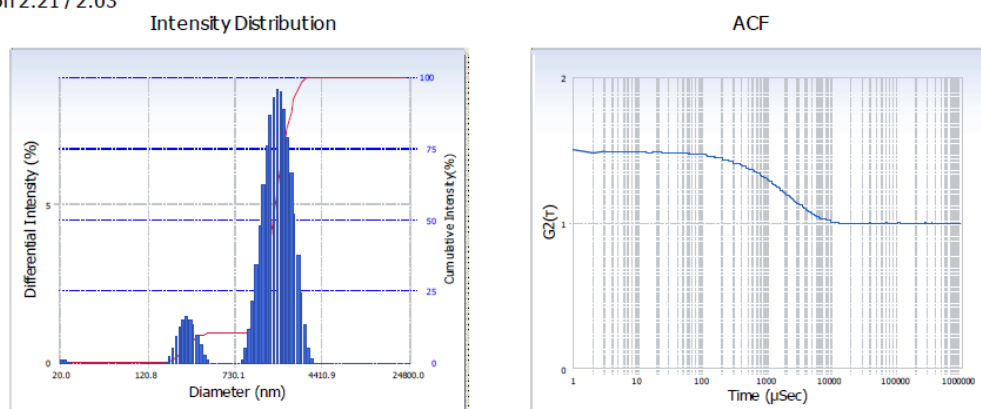


Figure 5. HAp3, HAp4, HAp silica composite3, HAp silica composite 4, HSP3 and HSP4

	HAp1	HAp2	HAp3	HAp4	HSP1	HSP2	HSP3	HSP4
d/nm	-	-	-	-	2076.6 ± 154.1	1286.5 ± 77.7	1070.5 ± 95.2	2311.1 ± 141.3
Polydispersity	-	-	-	-	0.346 ±	0.341 ±	0.226 ±	0.354 ±
index					0.007	0.025	0.015	0.013
ζ/ mV	-10.7 ± 0.8	-15.8 ± 0.2	-6.0 ± 0.6	-41.8 ± 0.7	-32.2 ± 0.5	-21.7 ± 0.1	-26.5 ± 0.5	-36.0 ± 0.6

Table 1. Average hydrodynamic radius and zeta potential; obtained from Delsa Nano particle analyser.

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Distribution Results (Contin)			Cumulants Results		
Peak	Diameter (nm)	Std. Dev.	Diameter (d)		(nm)
1	21.3	1.1	Polydispersity Index (P.I.)	0.298	
2	273.2	48.9	Diffusion Const. (D)	3.901e-009	(cm ² /sec)
3	1,810.4	495.6	Measurement Condition		
4	0.0	0.0	Temperature	25.0	(°C)
5	0.0	0.0	Diluent Name	WATER	
Average	1,655.4	660.7	Refractive Index	1.3328	
Residual :	1.182e-003	(O.K)	Viscosity	0.8878	(cP)
			Scattering Intensity	37115	(cps)

Figure 7. Typical DLS result for HSP2.