Synthesis of novel periodic mesoporous organosilicas with large content of lysine-bridged organosilane skeleton

Jianqiang Wang[1] ✉, *Changqing Gu*[1], *Man Zhou*[1], *Wenqi Zhang*[1], *Zhiwei Wang*[1], *Mengyuan Lv*[1], *Cheng Guo*[1], *Linbing Sun*[2]

[1]*College of Chemistry and Molecular Engineering, Nanjing Tech University, 30 Puzhu South Road, Jiangsu, Nanjing 211816, People's Republic of China*
[2]*College of Chemical Engineering, State Key Laboratory of Materials-Oriented Chemical Engineering, Nanjing Tech University, Nanjing 210009, People's Republic of China*
✉ *E-mail: jqwang@njtech.edu.cn*

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Novel periodic mesoporous organosilicas (PMOs) as functional nanomaterials based on the skeleton of lysine were synthesised by the co-condensation of lysine-bridged organosilicane (Lys-BOS) and tetraethyl orthosilicate in acidic medium using P123 as template. Furthermore, a large content of Lys-BOS was incorporated into the silica framework. Amino acid organosilicane (Lys-BOS) was first prepared by the multi-step reaction between traditional orgnaosilicane [(3-aminopropyl) triethoxysilane] and carboxyl protected lysine. The small-angle X-ray diffraction and N_2 adsorption–desorption isotherms indicate that these PMO materials still retain ordered mesostructure in the high molar concentration of Lys-BOS. Fourier-transform infrared spectroscopy confirms that lysine is incorporated in the framework of the PMO materials.

1. Introduction: Amino acids are important biological compounds for life and naturally available renewable resources due to broaden application in many fields [1, 2]. Lysine with two amino groups including one single side-chain amine group is one of the most essential 20 amino acids [3]. However, lysine has been used in a large number of studies because of important biological value such as absorption of calcium, production of carnitine, conversion of fatty acid, reduction of cholesterol and formation of collagen [4]. Furthermore, lysine as organic moieties is incorporated into various materials to increase cell adhesion, biocompatibility and aqueous stability, which is used as biosensors and targeted radiation [5–7]. Owing to this, lysine has been used in synthesising and functionalising nanomaterials [8, 9].

It is well known that mesoporous materials are often used as the inorganic scaffold to immobilise different organic moieties, resulting in the formation of organic–inorganic hybrid functional materials. Commonly, the functionalisation of mesoporous materials is achieved through three methods: grafting, co-condensation and periodic mesoporous organosilicas (PMOs) [10]. Among them, the PMO materials can reduce the shortcomings (such as inhomogeneous distribution of organic groups, blocking of pore entrance or channel and disordered/amorphous structure) by incorporating organic moieties into the framework [11, 12]. In 1999, three independent research groups of Stein, Ozin and Inagaki have reported for the first time the synthesis of PMO as special hybrid functional materials by surfactant-mediated self-assembly process under acid/basic conditions in the presence of bridged organosilane (BOS) of the type $[(R'O)_3Si–R–Si(OR')_3$; R: bridged organic groups, R' = methyl or ethyl] as precursors [13–15]. R in BOS precursor is a key organic functional group to undergo the surfactant self-assembly process and create the flexibility, rigidity and functionality of the framework of stable PMO structure after removing of surfactant [16]. In the previous study of PMO, many different components of R are used to create kinds of BOSs to meet the requirements in kinds of field. For example, molecular structure with heteroatoms (N, S, P, O etc.), metal complexes or nanoparticles and chiral bridges were introduced into the framework of PMO materials [17–20].

Previously, lysine as functional molecule was immobilised within the channels of mesoporous materials by post-grafting method [21]. The mesoporous structure was kept well but the channels were narrowed or even completely blocked by functional molecule to affect the usage of these materials. To solve these problems, we propose that lysine is introduced into the framework of mesoporous structure to form PMO materials. In this Letter, lysine is first selected to prepare new amino acid BOS precursor via condensation reaction with (3-aminopropyl) triethoxysilane (APTES) in the premise of carboxyl protecting. We try to develop novel PMO materials with the framework of lysine by using the above prepared BOS precursor. Moreover, an attempt was made to introduce the large content of lysine-bridged organosilane (Lys-BOS) functionality in the framework of PMO materials. The Lys-BOS precursor and ordered pore structure of PMO materials were confirmed by kinds of spectra. Furthermore, due to special characters of lysine, these PMO materials are applied in many fields such as enzymatic immobilisation, drug delivery, adsorption of poisonous metal ions etc.

2. Experimental section

2.1. Reagents and materials: Triblock poly ethylene oxide (EO)–poly propylene oxide–poly EO copolymer Pluronic P123 (composition of $EO_{20}PO_{70}EO_{20}$) with the average molecular weight of 5800 was purchased from Aldrich. Other reagents such as lysine, triphosgene, piperidine, APTES, tetraethyl orthosilicate (TEOS), and organic solvents were obtained from Chemical Reagent Company in China. All reagents and solvents were of analytical regent (AR) grade without further purification.

2.2. Preparation of Lys-BOS: The Lys-BOS was prepared by the following process (as shown in Fig. 1): a solution of thionyl chloride (15 ml) was slowly dropped into the solution of ethanol (100 ml) under the ice bath. Lysine (14.6 g, 0.1 mol) was added into the above mixtures under vigorous stirring conditions at −10°C. Then, the reactants were heated at reflux for 4 h under oil bath. On completion, the reaction system was cooled. The crude products were filtrated and washed with cold ethanol. After that, the crude products were dissolved in ethanol. Evaporation of

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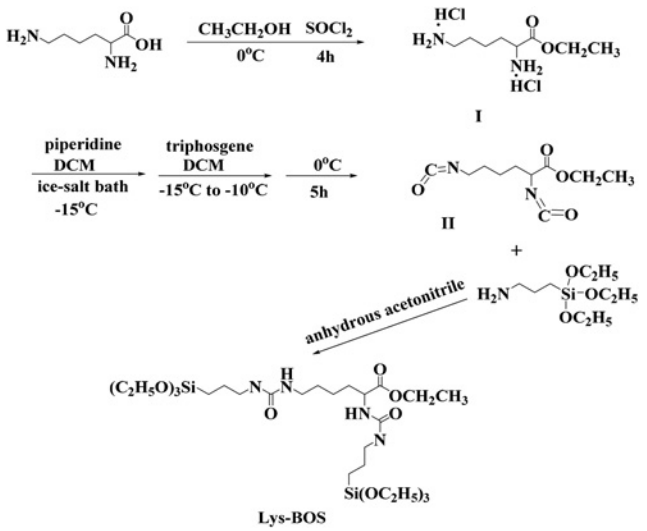

Fig. 1 *Preparation of Lys-BOS*

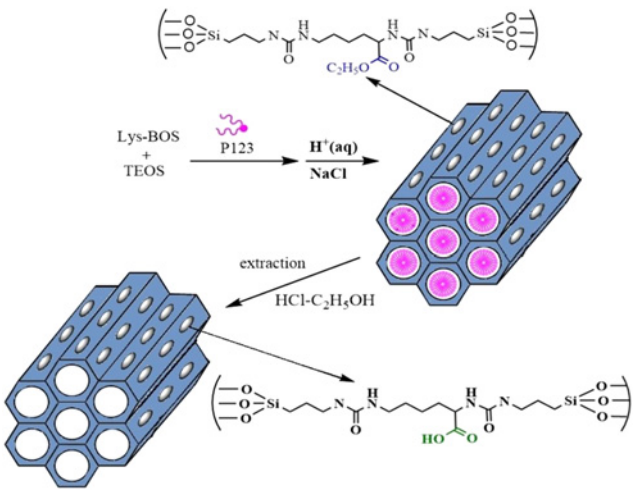

Fig. 2 *Preparation of Lys-PMO*

the solvent gave the pure lysine ethylester dihydrochloride (compound *I*) as a white solid. Next, 3.55 g of lysine ethylester dihydrochloride (compound *I*, 25 mmol) was dispersed into the mixed solutions of dichloromethane (100 ml) and piperidine (25 ml) at 10°C. The solutions of triphosgene (20 g, 70 mmol) dissolved in dichloromethane (50 ml) were slowly dropped into the mixtures at the same temperature. The reaction system was heated and kept at 0°C for 5 h. The reactants were washed with cold diluted hydrochloric acid (0.5 M, 150 ml) for two times. The layers of dichloromethane were collected and dried with anhydrous magnesium sulphate for one night. The product of lysine diisocyanate (compound *II*) as an oil liquid was obtained by evaporation of solutions under reduced pressure. Finally, 0.22 g of lysine diisocyanate (1 mmol) was added into the mixed solutions of APTES (0.44 g, 2 mmol) and anhydrous acetonitrile (2 ml). The reactant system was stirred at room temperature overnight. The resulting white solid product of Lys-BOS compound was obtained by vacuum distillation of acetonitrile with a yield of 65%. The product was denoted as Lys-BOS. ^{1}H nuclear magnetic resonance (NMR) (300 MHz, DMSO-d_6, TMS) δ: 0.509(*t*, $SiCH_2$, $J=3$ Hz, 4 H), 1.201(*t*, CH_3, $J=11.1$ Hz, 18 H), 1.216(*t*, $CHCH_2CH_2$, $J=5.5$ Hz, 2 H), 1.335(*t*, $COOCH_2CH_3$, $J=5.1$ Hz, 3 H), 1.408(*t*, $CHCH_2CH_2CH_2$, $J=3.2$ Hz, 2 H), 1.562(*t*, $SiCH_2CH_2$, $J=12$ Hz, 4 H), 2.077 (*t*, $CHCH_2$, $J=0.6$ Hz, 2 H), 2.935(*t*, $NHCH_2$, $J=6.9$ Hz, 6 H), 3.733(*q*, CH_3CH_2, $J=2$ Hz, 12 H), 4.393(*t*, CH, $J=1.8$ Hz, 1 H), 4.704(*q*, $COOCH_2$, $J=2$ Hz, 2 H), 5.751–5.848(*m*, NHCONH, 2 H), 6.006(*t*, CHNHCONH, $J=4.35$ Hz, 1 H), 6.168(*d*, CHNH, $J=0.9$ Hz, *H*)electrospray ionization mass spectrometry (ESI-MS)**:** m/z = 691.37($M+Na^+$).

2.3. Preparation of Lys-PMOs: Lys-PMOs were prepared using Lys-BOS as the organic bridging group, TEOS as the inorganic silica source and P123 as a templating agent in acidic solution. In a typical synthesis as shown in Fig. 2, Pluronic P123 (1.0 g) was first dissolved in 33.0 g of distilled water containing 5.0 g of concentrated hydrochloric acid at room temperature in a flask with slow stirring. Once the template was dissolved, 4.68 g of sodium chloride was added. When the resulting solution was homogenised, it was continuously stirred under water bath and heated up to 35°C. Subsequently, specified amounts of TEOS and Lys-BOS in solution of methanol were added at once with rapid stirring and kept at 35°C for 24 h. Thereafter, the mixtures were transferred into a stainless steel reactor with polytetrafluorethylene liner and aged at 100°C for another 24 h. Finally, the solid product was recovered by filtration, washed with distilled water and dried in air at room temperature. The template was removed from the material by successive reflux extraction in ethanol/HCl (1.0 g of the product in the mixed solutions of 250 ml absolute ethanol and 5 ml of 2 M hydrochloric acid) for 48 h. The obtained materials were denoted as Lys-PMO-*n*, where *n* ($n=10$, 20, 30%,) is the molar per cent of Lys-BOS/(Lys-BOS + TEOS).

2.4. Sample characterisation: Small-angle X-ray diffraction (XRD) detection of samples were performed on ARL XTRA diffractometer using copper Kα radiation ($\lambda=1.5418$ Å) at 40 kV and 20 mA in the 2θ range of 0.5–8° to investigate mesoscopic order. Nitrogen adsorption–desorption isotherms were measured on a Micrometrics ASAP2020 to determine textural properties, and the samples were degassed at 373 K overnight in the degassing port of the adsorption analyser prior to testing. The specific surface area was calculated from nitrogen adsorption data using the Brunauer–Emmet–Teller (BET) method. Pore size distributions were calculated using the Barret–Joyner–Halenda (BJH) algorithm on the adsorption branch. The most probable pore size was defined as the peak positions of the distribution curves. The pore volume was determined from the amount adsorbed at the P/P_0 of 0.973. ^{1}H NMR (300 MHz) spectra were obtained using a Bruker AV-300 Avance spectrometer and all chemical shifts (*d*) are reported in parts per million downfield from TMS; *J* values are given in hertz (Hz). Fourier-transform infrared spectroscopy (FTIR) spectra were recorded on a Thermo iS5 FT instrument in the region from 4000 to 400 cm^{-1} at 298 K, and the sample was mixed with potassium bromide at the ratio of 3 : 97 (mol/mol) and then pressed as transparent disc. High-resolution mass spectra were run on Agilent 1100-LC-MSD-Trap/SL.

3. Results and discussion

3.1. Structural characterisation of PMOs Lys-PMO: Lys-PMOs were synthesised by direct co-condensation method as described in the experimental section. The amounts of lysine group in the framework were modulated by varying the concentrations of BOS Lys-BOS in the initial mixture of silicon source. Small-angle powder XRD patterns of the solvent-extracted PMO samples including Lys-PMO-10%, Lys-PMO-20% and Lys-PMO-30% are shown in Fig. 3. All samples showed the main peak (100) reflection in the lower 2θ°, suggesting the formation of ordered mesoporous materials. Lys-PMO-10% sample displays a sharp (100) peak, which obviously exhibits at 2θ of 0.9. Only a broad (100) reflection peak appears in the XRD patterns of

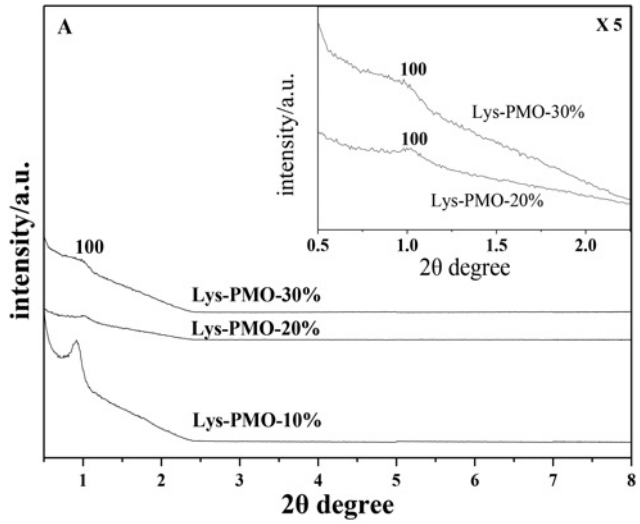

Fig. 3 *Small-angle powder XRD patterns of PMOs Lys-PMO-n (n=10%, 20%, 30%). The insert: five times XRD patterns of PMOs lys-PMO-n*

Lys-PMO-20%. When the precursor content is increased to 30%, the (100) reflection peak becomes weak in the insert of Fig. 3. These results indicate that the mesoporosity of materials still is kept in the maximum amount of organic bridged compounds in the pore wall, which might be important for further applications. Moreover, the concentrations of BOS in the initial sol–gel mixtures directly affect the degree of mesostructural ordering of the Lys-PMO framework. In addition, the (100) peak intensity of the resulting Lys-PMO decreased gradually with increasing the concentration of the Lys-BOS. This suggests that the presence of Lys-BOS with large molecular size in the formation disturbs self-assembly of surfactant aggregates during the co-condensation process, leading to poor mesostructural ordering of the PMO materials. In addition, the (100) peak intensity of the resulting Lys-PMO decreased gradually with increasing the concentration of the Lys-BOS. This suggests that the presence of Lys-BOS with large molecular size in the formation disturbs self-assembly of surfactant aggregates during the co-condensation process, leading to poor mesostructural ordering of the PMO materials.

The N_2 adsorption–desorption isotherms and the pore size distribution curves of Lys-PMOs-*n* with the different concentration of Lys-BOS are shown in Fig. 4. As shown in Fig. 4*a*, the material Lys-PMO-10% shows type-IV isotherms with a clear H_1 type hysteresis loop at high relative pressure (P/P_0) from 0.4 to 0.7, which is a characteristic of the material with mesoporous structure according to the International Union of Pure and Applied Chemistry classification.

With the increasing amounts of Lys-BOS in initial mixtures, the materials Lys-PMO-20% and Lys-PMO-30% exhibit type-IV with a clear H_4 hysteresis loop at the different range of relative pressure, which indicates that mesopore and micropore are simultaneously founded within the channels of these materials. These results further reveal that the Lys-BOS with large molecule size strongly influences the porous structure of Lys-PMO-*n* materials.

Furthermore, the corresponding structural parameters of these PMO materials also illustrate the viewpoint, as are listed in Table 1. The BET surface areas and pore volumes decreased progressively from Lys-PMO-10% to Lys-PMO-30% with increasing the BOS loading, which is seen in Table 1. BET surface areas of these PMO materials are in the range from 356 to 63 m^2g^{-1}, and the total pore volumes vary from 0.49 to 0.09 $cm^3\ g^{-1}$.

The pore size decreased with increasing the loading concentration of Lys-BOS in these materials, showing that the functional moieties occupy the mesoporous walls. This was anticipated because of the geometrical constrictions to accommodate a high

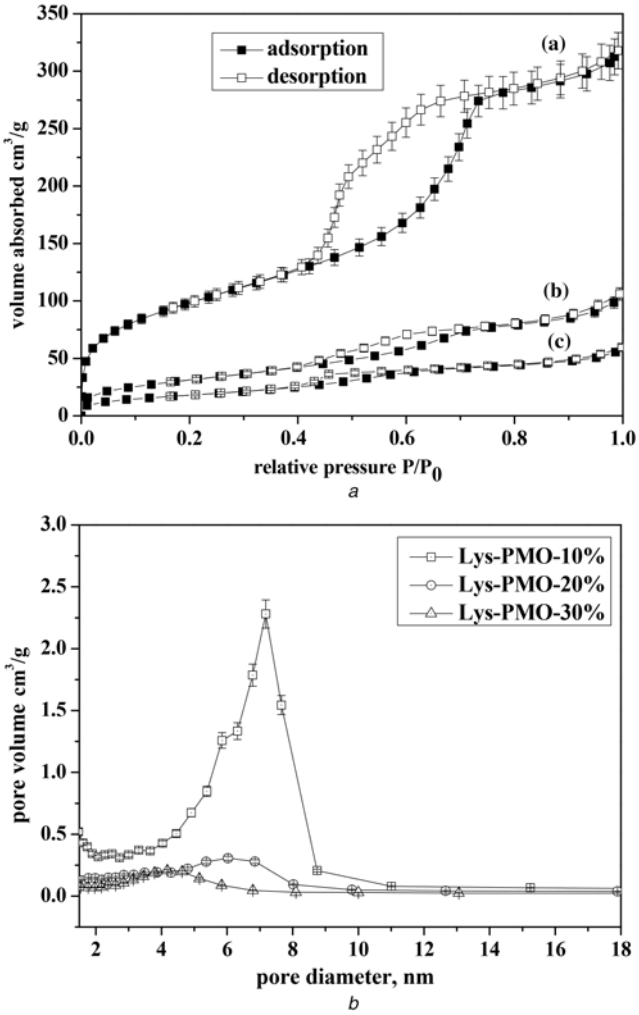

Fig. 4 *Material Lys-PMO-10% shows type-IV isotherms*
a Nitrogen adsorption-desorption isotherms of PMOs Lys-PMO-n (n= (a) 10%, (b) 20%, (c) 30%) and
b Pore size distribution of PMOs Lys-PMO

Table 1 Textual parameters of PMOs Lys-PMO-*n*

Sample	d^a_{100}, nm	α^b_0, nm	S_{BET}, m^2/g	Pore volume[c], cm^3/g	Pore size[d], nm
Lys-PMO-10%	9.7	11.2	356	0.49	7.2
Lys-PMO-20%	8.7	10.0	109	0.16	6.0
Lys-PMO-30%	9.0	10.4	63	0.09	3.8

[a]Interplanar spacing of the (100) plane, as obtained from the XRD analysis.
[b]α_0 is unit cell parameter, calculated from $\alpha_0 = 2d_{100}/\sqrt{3}$.
[c]Pore volume is determined from the N_2 adsorption and desorption isotherms.
[d]Pore diameter is calculated using the BJH model based on the desorption branch of the isotherm.

loading content of Lys-BOS precursor with large molecular size in the framework of Lys-PMO materials. The other textural parameters (d_{100}, α_0) of Lys-PMO-*n* are also summarised in Table 1. The results of N_2 sorption analysis show that all Lys-PMO-*n* samples with high amounts of Lys-BOS are mesoporous materials with uniform pore size distributions.

3.2. Spectroscopic analysis of PMOs Lys-PMO: To confirm the chemical bonds and the presence of organic moieties in the

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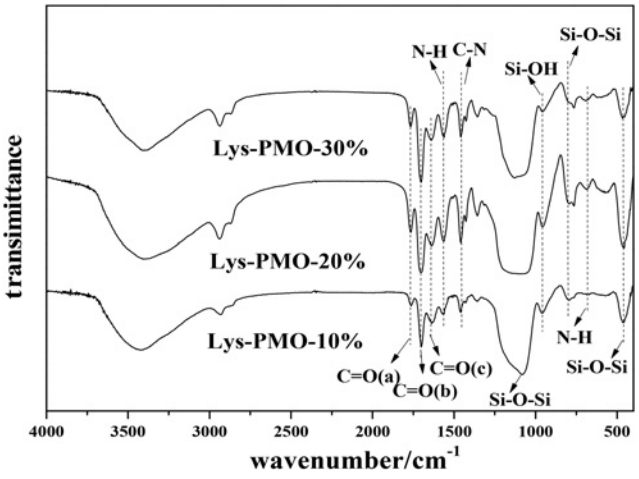

Fig. 5 *FTIR spectra of PMOs Lys-PMO-n (n = 10, 20, 30%; C = O in the different chemical groups)*
a Easer group
b Carboxyl
c Urea group

framework, the materials Lys-PMOs were detected by FTIR spectroscopy. Fig. 5 presents the FTIR spectra of solvent-extracted Lys-PMO-*n* samples. A broad adsorption band at 1000–1250 cm^{-1} and two bands of 794 and 459 cm^{-1} are observed in all the materials, which are attributed to stretching vibration and bending vibration of Si–O–Si bond, respectively. The results indicate the formation of Si–O–Si siloxane bonds to construct porous framework of Lys-PMO. The vibration band for the residual silanol groups was obtained at 960 cm^{-1}. The weak intensity signal at 1428 cm^{-1} is attributed to the P123 template residues, which suggest the almost complete removal of surfactant from the materials by extraction in the solutions of ethanol and hydrochloric acid. The characteristic peaks at 2937 and 2869 cm^{-1} are assigned to the C–H stretching frequencies of $–CH_2–CH_2–CH_2–$ groups. A sharp and intense band at 1700 cm^{-1} is ascribed to the C = O stretching vibration of the carboxyl group in lysine. A very weak peak at 1765 cm^{-1} is attributed to the C = O stretching vibration of the ester group in the protecting group of Lys-BOS.

The results suggest that the most protecting groups (ester groups) are removed in the extraction of template P123. In addition, the C = O stretching vibration and C–N of the urea groups (–NH–CO–NH–) are observed at 1637 and 1458 cm^{-1} [22], respectively. The stretching vibration mode of N–H (–NH–CO–NH–) in Lys-BOS is confirmed by the adsorption bands located at 1565 and 688 cm^{-1} [23]. The intensity of these peaks including of C = O (–COOH), C = O and NH (–NH–CO–NH–) are enhanced with increasing concentrations of Lys-BOS in initial mixtures. Thus, the FTIR spectra confirmed the successful loading of lysine in the framework of Lys-PMO materials.

4. Conclusions: Novel PMOs (Lys-PMO) as distinctively functionalised materials were developed by introducing lysine, an amino acid in framework by the co-condensation of TEOS and protected Lys-BOS in the presence of triblock copolymer Pluronic P123 as a template. Lys-BOS is also prepared by the reaction between protected amino acid and conventional OS for the first time. Moreover, lysine in framework was directly recovered by removing the protecting groups in the extraction process of Lys-PMO without extra methods. The resulting PMO materials were confirmed by small-angle XRD, N_2 adsorption–desorption isotherm and FTIR. A large content of Lys-BOS was incorporated into the silica framework, which indicates that specific functional ligands with large molecule size and amount can be successfully formed ordered mesoporous material. Therefore, the material with large concentration of lysine has potential application due to important value and wide application of the amino acid.

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6 References

[1] Lai H., Chen X., Lu Q., *ET AL.*: 'A new strategy to synthesize bottlebrushes with a helical polyglutamate backbone via N-carboxyanhydride polymerization and RAFT', *Chem. Commun.*, 2015, **50**, pp. 14183–14186
[2] Mori H., Endo T.: 'Amino-acid-based block copolymers by RAFT polymerization', *Macromol Rapid Commun.*, 2012, **33**, pp. 1090–1107
[3] Guo C.C., Holland G.P.: 'Investigating lysine adsorption on fumed silica nanoparticles', *J. Phys. Chem. C*, 2014, **118**, pp. 25792–25801
[4] Perez R.B., Calvo A.M., Álvarez P.G., *ET AL.*: 'Enantioselective adsorption of ibuprofen and lysine in metal–organic frameworks', *Chem. Commun.*, 2014, **50**, pp. 10849–10852
[5] Kuddannaya S., Bao J.N., Zhang Y.L.: 'Enhanced in vitro biocompatibility of chemically modified poly(dimethylsiloxane) surfaces for stable adhesion and long-term investigation of brain cerebral cortex cells', *ACS Appl. Mater. Interfaces*, 2015, **7**, pp. 25529–25538
[6] Shan C.S., Yang H.F., Han D.X., *ET AL.*: 'Water-soluble graphene covalently functionalized by biocompatible poly-L-lysine', *Langmuir*, 2009, **25**, pp. 12030–12033
[7] Dhainaut J., Daou T.J., Bats N., *ET AL.*: 'Synthesis of FAU and EMT-type zeolites using structure-directing agents specifically designed by molecular modelling', *Microporous Mesoporous Mater.*, 2013, **170**, pp. 117–125
[8] Pearce B.L., Berg N.G., Jiang L., *ET AL.*: 'Aqueous stability of nanostructured aluminum and gallium oxyhydroxide before and after functionalization with lysine', *Mater. Lett.*, 2016, **184**, pp. 278–281
[9] Hoffmann F., Cornelius M., Morell J., *ET AL.*: 'Silica-based mesoporous organic–inorganic hybrid materials', *Angew. Chem., Int. Ed.*, 2006, **45**, pp. 3216–3251
[10] Burleigh M.C., Markowitz M.A., Spector M.S., *ET AL.*: 'Amine-functionalized periodic mesoporous organosilicas', *Chem. Mater.*, 2001, **105**, pp. 4760–4766
[11] Guan L.Y., Di B., Su M.X., *ET AL.*: 'Immobilization of b-glucosidase on bifunctional periodic mesoporous organosilicas', *Biotechnol. Lett.*, 2013, **35**, pp. 1323–1330
[12] Melde B.J., Holland B.T., Blanford C.F., *ET AL.*: 'Mesoporous sieves with unified hybrid inorganic/organic frameworks', *Chem. Mater.*, 1999, **11**, pp. 3302–3308
[13] Asefa T., MacLachan M.J., Coombs N., *ET AL.*: 'Periodic mesoporous organosilicas with organic groups inside the channel walls', *Nature*, 1999, **402**, pp. 867–871
[14] Inagaki S., Guan S., Fukushima Y., *ET AL.*: 'Novel mesoporous materials with a uniform distribution of organic groups and inorganic oxide in their frameworks', *J. Am. Chem. Soc.*, 1999, **121**, pp. 9611–9614
[15] Hunks W.J., Ozin G.A.: 'Challenges and advances in the chemistry of periodic mesoporous organosilicas (PMOs)', *J. Mater. Chem.*, 2005, **15**, pp. 3716–3724
[16] Voort P.V.D., Esquivel D., Canck E.D., *ET AL.*: 'Periodic mesoporous organosilicas: from simple to complex bridges; a comprehensive overview of functions, morphologies and applications', *Chem. Soc. Rev.*, 2013, **42**, pp. 3913–3955
[17] Liu X.A., Wang P.Y., Zhang L., *ET AL.*: 'Chiral mesoporous organosilica nanospheres: effect of pore structure on the performance in asymmetric catalysis', *Chem. Eur. J.*, 2010, **16**, pp. 12727–12732
[18] Corma A., Das D., Garcia H., *ET AL.*: 'A periodic mesoporous organosilica containing a carbapalladacycle complex as heterogeneous catalyst for Suzuki cross-coupling', *J. Catal.*, 2005, **229**, pp. 322–331
[19] Polarz S., Kuschel A.: 'Preparation of a periodically ordered mesoporous organosilica material using chiral building blocks', *Adv. Mater.*, 2006, **18**, pp. 1206–1209

[20] Ma J.X., Wang Z., Shi Y., *ET AL.*: ' Synthesis and characterization of lysine-modified SBA-15 and its selective adsorption of scandium from a solution of rare earth elements', *RSC Adv.*, 2014, **4**, pp. 41597–41604
[21] Franville C., Sambon D., Mahiou R., *ET AL.*: 'Luminescence behavior of sol–gel-derived hybrid materials resulting from covalent grafting of a chromophore unit to different organically modified alkoxysilanes', *Chem. Mater.*, 2000, **12**, pp. 428–435
[22] Lee S.H., Park S.S., Parambadath S., *ET AL.*: 'Sulphonic acid functionalized periodic mesoporous organosilica with the bridged bissilylated urea groups for high selective adsorption of cobalt ion from artificial seawater', *Microporous Mesoporous Mater.*, 2016, **226**, pp. 179–190
[23] Pla-Roca M., Isa L., Kumar K., *ET AL.*: 'Selective (bio)functionalization of solid-state nanopores', *ACS Appl. Mater. Interfaces*, 2015, **7**, pp. 6030–6035

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