

Peripheral Groups of Polyhedral Oligomeric Silsesquioxane (POSS)

Core Based Dendrimers: Crucial Factor for Higher-level Supra-architecture Building

(Supporting information)

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1. Synthesis and characterization of POSS-Lys-X derivatives

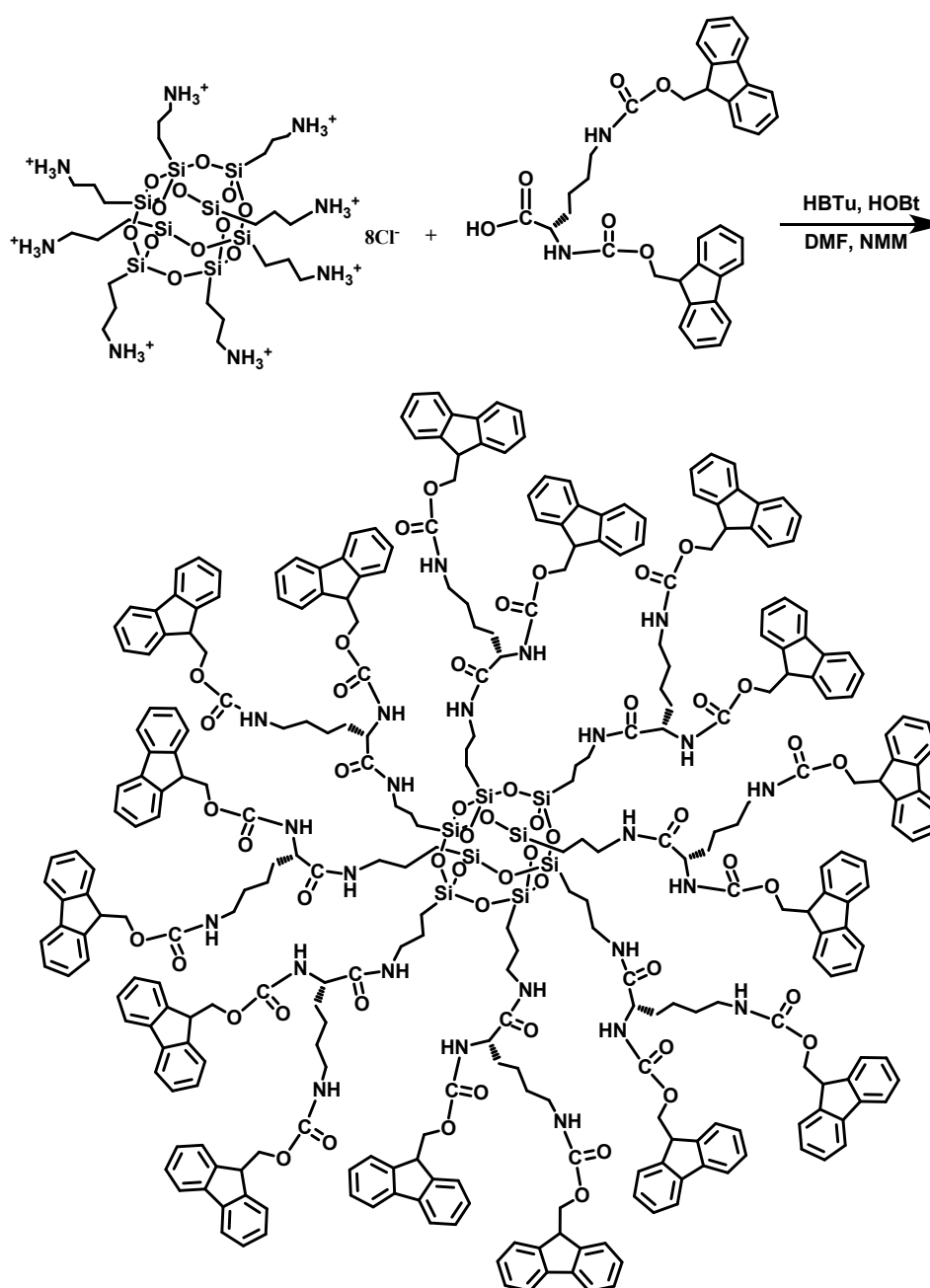
1.1 Materials

All materials employed in the paper were commercially available. Octa (3-aminopropyl) silsesquioxanes hydrochloride (Octa-Ammonium POSS-HCl) was purchased from hybrid plastic (Hattiesburg, MS). N,N,N,N'-Tetramethyl-O-(1H-benzotriazol-1-yl)uroniumhexafluorophosphate (HBTU), 1-hydroxybenzotriazole(HOBt), Z-Asp(OBzl)-OH, N,N-Diisopropylethylamine (DIPEA) L-Lysine methyl ester dihydrochloride, triethylamine (TEA), benzoic acid, N-Methylmorpholine (NMM), N-(3-Dimethylaminopropyl)-N'-ethylcarbodiimide hydrochloride (EDC) and N,N-Diisopropylethylamine (DIPEA), were supplied by Aladdin (Shanghai, China) and used as received. All solvents used in the synthesis were analytical pure and used without further purification. Silica column chromatography was carried out using silica gel (200-300 mesh) provided by Qingdao Haiyang Chemical (Qingdao, China). Thin layer chromatography was performed on commercially available glass backed silica plates.

1.2 Synthesis and characterization

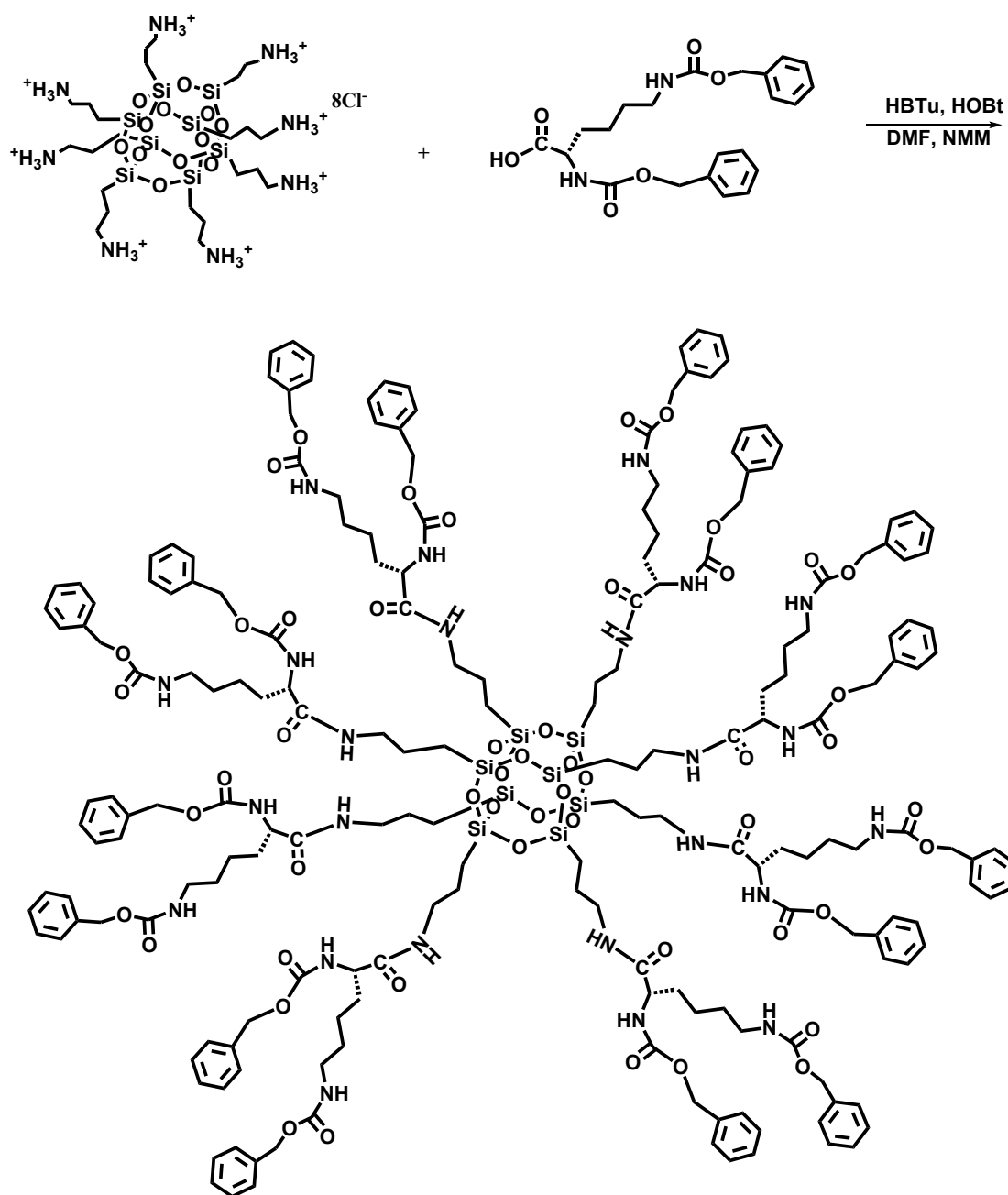
POSS-Lys-Fmoc (Fmoc): The structure and synthetic route of POSS- Lys-Fmoc were presented on Scheme S1 as same as the literature reported before¹. 2.36 g (4.0 mmol) Fmoc-Lys(Fmoc)-OH, 1.52 g (4.0 mmol) HBTU and 0.65 g (4.8 mmol) HOBt were dissolved in 20 mL DMF. After 5 min, 0.73 g (7.2 mmol) NMM and 0.47g (0.4mmol) Octa-Ammonium POSS-HCl were added. The mixture was stirred at room temperature for 24 h, and then 150 mL (0.5M) citric acid aqueous solution was added to get a white solid. The crude product was obtained by filtration

under reduced pressure and purified by column chromatography (silica, CH₂Cl₂: MeOH= 9:1 R_f=0.80) to get a white solid with the yield of 52.3 %. The structure of the POSS-Lys-Fmoc was determined by NMR (Bruker Avance III, 500 MHz), ESI-TOF MS (Agilent 6210). ¹H NMR (DMSO-d₆, ppm), δ 7.96 (8H, s, CONH), 7.89-7.90 (32 H, d, Ph), 7.84-7.86 (32 H, d, Ph), 7.41-7.44 (32 H, t, Ph), 7.34-7.37 (32 H, t, Ph), 6.71 (8 H, s, CONH), 4.20-4.32 (40 H, m, COCH(R)NH; CH₂CH(Ph)₂), 3.17 (32 H, s, CH₂NH), 1.61-1.11 (80 H, m, CH₂CH₂; CH₂CH₂CH₂), 0.82 (16 H, s, SiCH₂). ESI-MS: The calculated [M+8H]⁸⁺/8 of POSS-Lys-Fmoc was 683.2 and the test result was 684.2, results fit with the calculation.



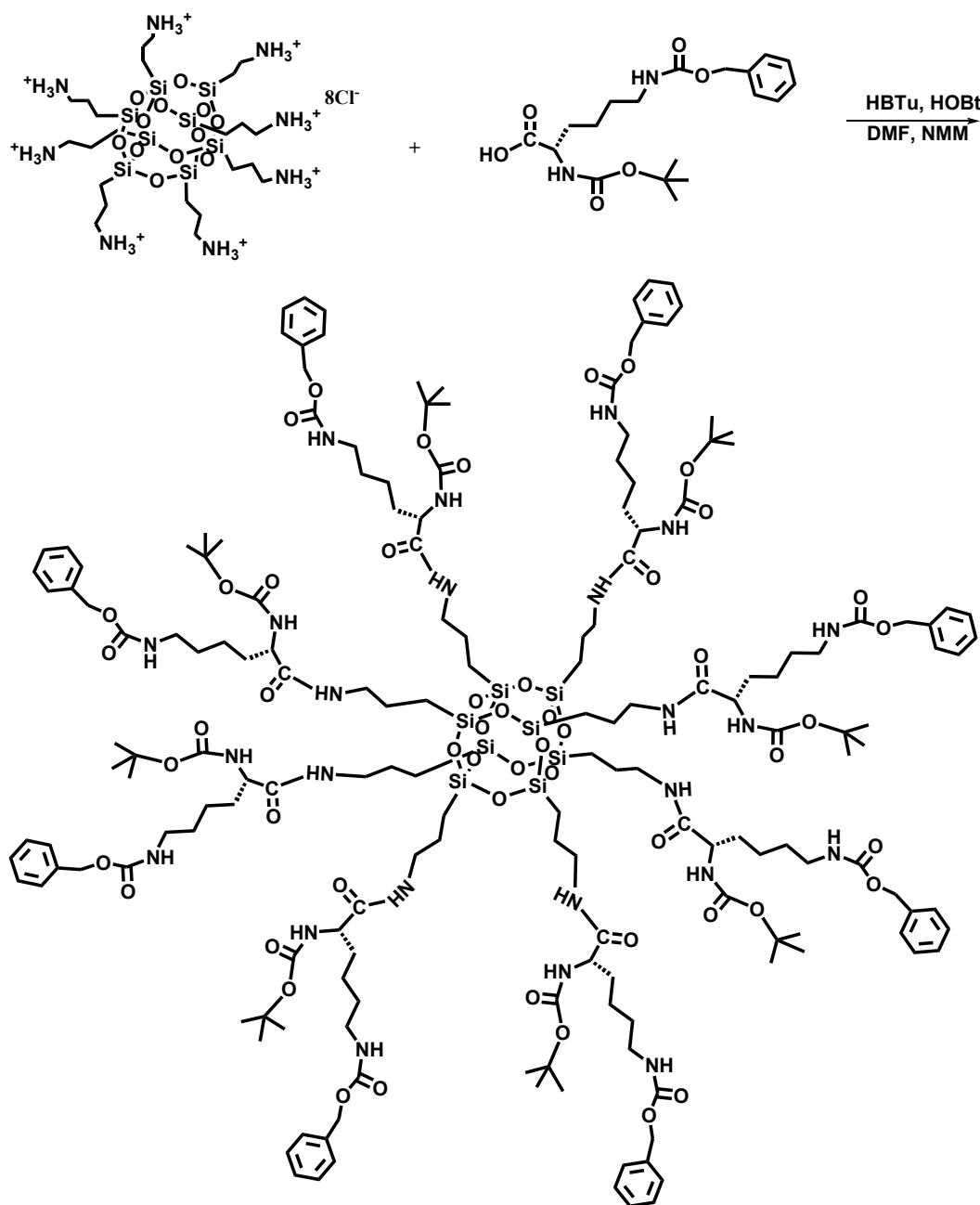
Scheme S1 Synthesis of POSS-Lys-Fmoc (**Fmoc**)

POSS-Lys-Cbz (**Cbz** Scheme S2): 1.66 g (4.0 mmol) Z-Lys(Z)-OH, 1.52 g (4.0 mmol) HBTU and 0.65 g (4.8 mmol) HOBt were dissolved in 20 mL DMF. After 5 min, 0.73 g (7.2 mmol) NMM and 0.47g (0.4mmol) OctaAmmonium POSS-HCl were added. The mixture was stirred at room temperature for 24 h, and then 150 mL (0.5M) citric acid aqueous solution was added to get a white solid. The crude product was obtained by filtration under reduced pressure and purified by column chromatography (silica, CH₂Cl₂: MeOH= 9:1 R_f=0.72) to get a white solid with the yield of 70.6 %. ¹H NMR (DMSO-d₆, ppm), δ: 7.91 (8 H, s, CONH), 7.25-7.39 (80 H, m, Ph), 6.69 (8 H, s, CONH), 4.99 (32H, d, OCH₂C₆H₅), 3.92 (8H, d, COCH(NH)CH₂), 2.94 (32 H, t, CH₂NH), 1.63-1.15 (64 H, m, CH₂-CH₂-NH), 0.57 (16 H, s, SiCH₂). ESI-MS: The calculated [M+2H]²⁺/2 of POSS-Lys-Cbz was 2072.5 and the test result was 2072.8, results fit with the calculation.



Scheme S2 Synthesis of POSS-Lys-Cbz (**Cbz**)

POSS-Lys-ZB (**ZB** Scheme S3). 1.52 g (4.0 mmol) N-Boc-N'-Cbz-Lys-OH, 1.52 g (4.0 mmol) HBTU and 0.65 g (4.8 mmol) HOBt were dissolved in 20 mL DMF. 5 mins later, 0.73 g (7.2 mmol) NMM and 0.47g (0.4mmol) OctaAmmonium POSS-HCl were added. The mixture was stirred at room temperature for 24 h, and then 150 mL (0.5M) citric acid aqueous solution was added to get a white solid. The crude product was obtained by filtration under reduced pressure and purified by column chromatography (silica, CH₂Cl₂: MeOH= 9:1 R_f=0.70) to get a white solid with the yield of 63.5 %. ¹H NMR (DMSO-d₆, ppm): δ 7.91 (8 H, s, CONH), 7.28-7.39 (40 H, m, Ph), 7.21 (8H, t, CONH), 6.78 (8 H, s, CONH), 4.99 (16H, m, OCH₂C₆H₅), 3.83 (8H, d, COCH(NH)CH₂), 2.97-3.04 (32 H, t, CH₂NH), 1.54 -1.23 (136 H, m, CH₂-CH₂-NH), 0.57 (16 H, s, SiCH₂). ESI-MS: The calculated [M+Na+H]²⁺/2 of POSS-Lys-ZB was 1902.0 and the test result was 1901.4, results fit with the calculation.



Scheme S3 Synthesis of POSS-Lys-ZB (**ZB**)

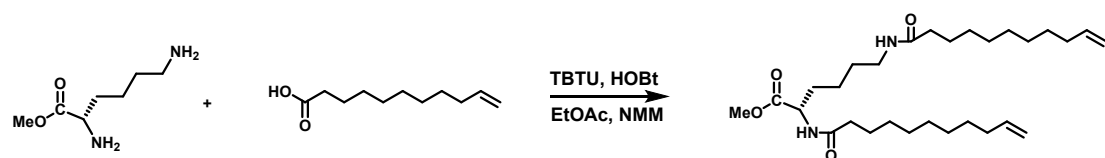
POSS-Lys-Dod:

POSS-Lys-Dod was synthesized in a three-step method, the structure and synthetic route were presented on Scheme S4.

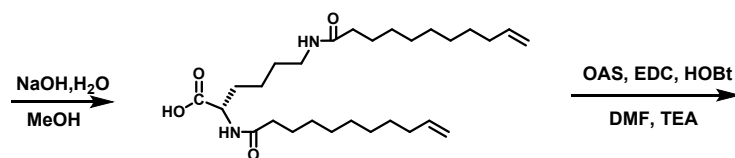
Lys-Dod-COOMe: 1.89 g (10.2 mmol) 10-undecenoic acid, 1.51 g HOBt (11.2 mmol), 2.15 g EDC (11.2 mmol) and 1.45 g (11.2 mmol) DIPEA were dissolved in 30 mL ethyl acetate and stirred under the ice bath. After 20 min, 1 g (4.6 mmol) L-lysine hydrochloride and 1.10 g (8.5 mmol) DIPEA were added in the mixture. The ice bath was removed 1h later and stirred at room temperature for 24 h. The organic layer in the mixture was washed by saturated sodium hydrogencarbonate solution (100 mL), sodium hydrogen sulfate solution (100 mL, 8.0 g/50 mL), saturated sodium hydrogen carbonate solution (50 mL) and deionized water (200 mL), respectively. The remained water in solvent were removed by anhydrous magnesium sulfate. The solvent was dried by rotary evaporation to obtain the crude products. Lys-Dod-COOMe was obtained after purified by column chromatography (ethyl acetate: petroleum ether = 1.5:1), to give a pale yellow solid 1.61g, R_f = 0.38, yield 76.3%. Lys-Dod-COOMe: ^1H NMR δH (500 MHz, CDCl_3): 6.21 (d, 1H; *NH*), 5.82 (m, 2H; CH_2CHCH_2), 4.95 (m, 4H; CHCH_2), 4.57 (d, 1H; $\text{COCH}(\text{NH})\text{CH}_2$), 3.74 (s, 3H; CHOCO), 3.24 (m, 2H; CH_2NH), 2.23 (t, 2H; $\text{CH}_2\text{NHCOCCH}_2$), 2.18 (s, 2H; CHNHCOCCH_2), 2.17 (d, 2H; CHCH_2CH_2), 2.03 (t, 4H; CH_2CHCH_2), 1.54 (m, 6H; CH_2), 1.36 (m, 22H; CH_2). ESI-MS: The calculated $M=492$, and the result of Lys-Dod-COOMe was $[\text{M}+\text{H}]^+=493$, $[\text{M}+\text{Na}]^+=515$, results fit with the calculation.

Lys-Dod-COOH: 1.47 g (2.98 mmol) Lys-Dod-COOMe was dissolved in 10 mL of methanol, and then 8.94 mL of aqueous sodium hydroxide (1 M, 8.94 mmol) was added under the ice bath, stirred under a nitrogen atmosphere for 24 hours. After the reaction was completed, the methanol was removed by a rotary evaporator, and the mixture was adjusted to pH=3 with sodium hydrogen sulfate. The Lys-Dod-COOH was extracted with ethyl acetate and dry by rotary evaporator to obtained a whiter solid, yield 96.5%. ^1H NMR (500 MHz, $\text{DMSO}-d_6$): 7.99 (1H, d; CHNHCO), 7.74 (1H, t, CH_2NHCO), 5.78 (2H, m; CH_2CHCH_2), 4.98 (4H, m; CHCH_2), 4.12 (1H, m; COCH), 2.99 (2H, m; CH_2NHCO), 2.04 (2H, m; CHNHCOCCH_2), 2.00 (6H, m; CH_2), 1.66 (2H, m; CHCH_2), 1.55 (4H, m; CH_2), 1.48 (22H, m; CH_2). ESI-MS: the calculated $M=478$, and the result were $[\text{M}+\text{H}]^+=479.1$ $[\text{M}+\text{Na}]^+=511.8$, results fit with the calculation.

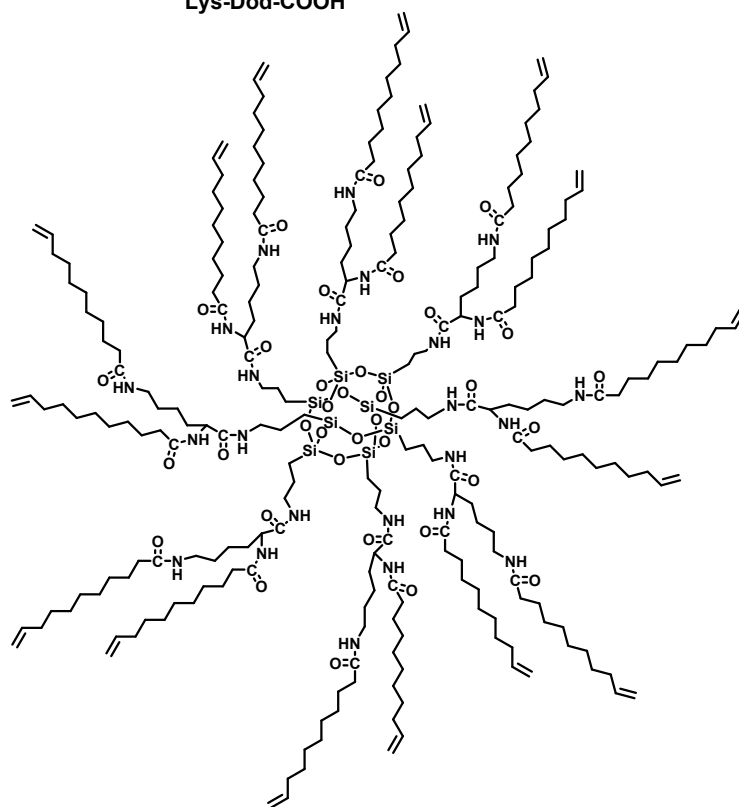
POSS-Lys-Dod (**Dod**): 1.38 g (2.88 mmol) Lys-Dod-COOH, 0.6 g (6 mmol) NMM, 1.09 g (2.88 mmol) HBTU and 0.43 g (3.16 mmol) HOBt was dissolved in 20 ml of DMF. 5 min later, 0.24g (0.21mmol) OctaAmmonium POSS-HCl were added. The reaction mixture was stirred at room temperature for 16 h, and then 150 mL (0.5M) citric acid aqueous solution was added to get a white solid. The crude product was purified by column chromatography (silica, CH_2Cl_2 : $\text{MeOH}=9:1$) to get a white solid with the yield of 32.6 %. ^1H NMR (CDCl_3 , ppm), δ : 7.48 (8 H, s, CONH), 7.06 (8 H, s, CONH), 6.38 (8 H, s, CONH), 5.82 (16 H, m, $\text{CH}=\text{CH}_2$), 5.02 (32 H, m, $\text{CH}=\text{CH}_2$), 4.51 (8 H, brm, $\text{COCH}(\text{R})\text{NH}$), 3.20 (32 H, brs, $\text{CH}_2\text{CH}_2\text{NH}$), 2.18 (32 H, m, $\text{CH}_2\text{CH}=\text{CH}_2$), 2.05 (32H, m, COCH_2), 1.77-1.29 (256 H, m, CH_2), 0.63 (16 H, s, SiCH_3). ESI-TOF-MS: The calculated $[\text{M}+\text{OH}]^-/1$ of POSS-Lys-Dod was 4580 and the test result was 4579.2, results fit with the calculation.



Lys-Dod-COOMe



Lys-Dod-COOH



POSS-Lys-Dod

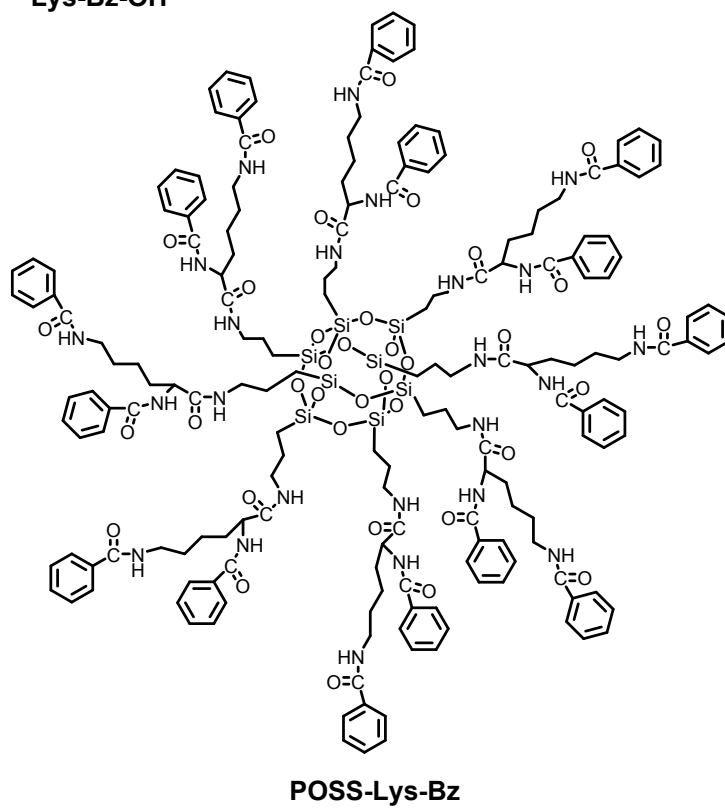
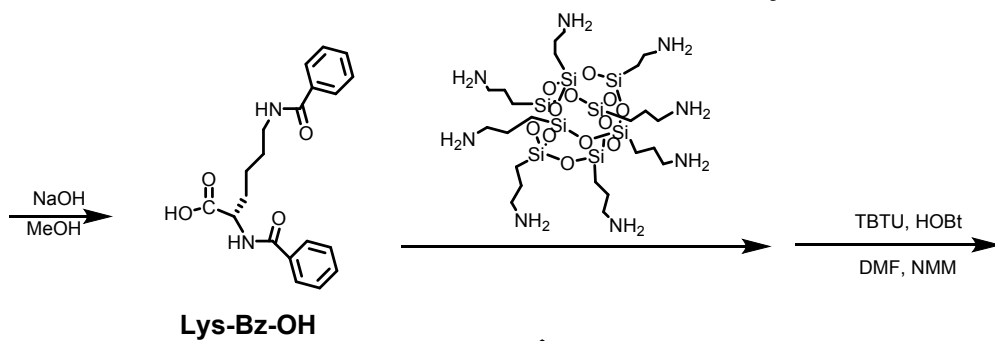
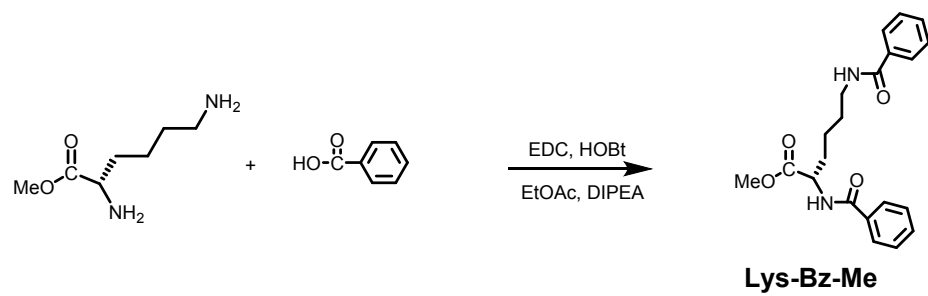
Scheme S4. Synthesis of POSS-Lys-Dod (Dod)

POSS-Lys-Bz:

POSS- Lys-Bz (Bz) was also synthesized in a three-step method, the structure and synthetic route were presented on Scheme S5. Firstly, 1.26 g (10.3 mmol) of benzoic acid was dissolved in 30 mL ethyl acetate, and then 1.51 g (21.2 mmol) HOBt, 2.15 g (11.2 mmol) EDC and 1.45 g (14.3 mmol) TEA were added and stirred under the ice bath. 20 min later, 1.00 g (3.4 mmol) lysine methyl ester hydrochloride and 1.10 g (10.9 mmol) TEA was added. After stirring for 1 h the ice cubes were naturally melted, the reaction was continued in room temperature for 23 h. The mixture was washed by saturated sodium hydrogencarbonate solution (100 mL), sodium hydrogen sulfate solution (100 mL, 8.00 g/50.00 mL), saturated sodium hydrogen carbonate solution (50 mL) and deionized water (200 mL), respectively, to obtain the organic layer. The remained water in solvent were removed by anhydrous magnesium sulfate. The solvent was dried by rotary evaporation to obtain the crude products. After purified by column chromatography (first elution with ethyl acetate/petroleum ether 1:1, the desired product was eluted with ethyl acetate/petroleum ether 3:1), to give a white solid 1.36g, $R_f = 0.50$, yield 86.6%. Lys-Bz-Me: ^1H NMR (500 MHz, CDCl_3): δ 7.81 (4H, s; $\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 7.50 (2H, m; $-\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 7.42 (4H, m; $-\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 6.93 (1H, d; CHNH), 6.44 (1H, s; CH_2NHCO), 4.83 (1H, d; COCH), 3.79 (3H, s; CH_3CO), 3.52 (2H, m; CH_2NH), 2.01 (2H, m; CHCH_2), 1.92 (2H, m; $\text{CH}_2\text{CH}_2\text{NH}$), 1.70 (2H, m; CHCH_2CH_2).

Lys-Bz-COOH: 1.36 g (3.69 mmol) Lys-Bz-Me was dissolved in 30 mL methanol and then 11.10 mL of NaOH (1 M, 11.1 mmol) aqueous solution was added under the ice bath. After stirred under a nitrogen atmosphere for 24 hours, the methanol was removed by rotary evaporation at 65 °C. Subsequently, about 20 mL water was added to the reaction product to get an aqueous solution, NaHSO_4 solution was added to adjust the pH value of solution until insoluble matter was formed (oily, pale yellow). The insoluble organic matter was obtained *via* extraction by ethyl acetate. After washed with water for two times, and dried with MgSO_4 , solvent was removed by rotary evaporators to get a white solid with the yield of 97 %. ^1H NMR (500 MHz, CDCl_3) δ : 7.81 (s, 4H, $\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 7.50 (m, 2H, $\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 7.42 (4H, m; $\text{C}(\text{CH})_2(\text{CH})_2\text{CH}$), 6.93 (1H, d; CHNH), 6.44 (1H, s; CH_2NHCO), 4.83 (1H, d; COCH), 3.79 (3H, s; CH_3CO), 3.52 (2H, m; CH_2NH), 2.01 (2H, m; CHCH_2), 1.92 (2H, m; $\text{CH}_2\text{CH}_2\text{NH}$), 1.70 (2H, m; CHCH_2CH_2).

POSS-Lys-Bz: 1.15 g (3.25 mmol) Lys-Bz-COOH, 1.04 g (2.75 mmol) HBTU and 0.48 g (3.53 mmol) HOBt were dissolved in 20 mL DMF. 5 min later, 0.16 g (1.58 mmol) NMM and 0.24 g (0.21 mmol) POSS-HCl were added. The mixture was stirred at room temperature for 20 h, and then 100 mL deionized water was added to get a white precipitation. The crude product was purified by column chromatography (silica, CH_2Cl_2 : MeOH= 10:1, $R_f=0.60$) to get a white solid with the yield of 43.7 %. The structure of the POSS-Lys-Bz. ^1H NMR (DMSO-d_6 , ppm), δ : 8.43 (8H, s, CH_2NHCO), 8.38 (8H, s, NHCOC_6H_5), 7.85 (8H, s, NHCOC_6H_5), 7.80-7.37 (80H, m, C_6H_5), 4.39 (8H, d, COCH(R)NH), 3.21 (16H, m, $\text{CH}_2\text{NHCOC}_6\text{H}_5$), 3.00 (16H, d, $\text{SiCH}_2\text{CH}_2\text{CH}_2\text{NH}$), 1.73-1.30 (64H, m, CH_2), 0.56 (16H, s, SiCH_2). ESI-TOF-MS: The calculated $[\text{M}+\text{Na}]^+/1$ of POSS-Lys-Bz was 3592.4 and the test result was 3592.4, results fit with the calculation.



Scheme S5 Synthesis of POSS-Lys-Bz

2. Gelation behaviors of dendrimers

Table S1. Gelation ability of dendrimers in different solvents^a

Solvents	End group of POSS-Lys-X							Dendrimer
	E ^T (N)	<i>Dod</i>	<i>Bz</i>	<i>Fmoc</i>	<i>Boc</i>	<i>Cbz</i>	<i>Boc+Cbz</i>	<i>Phe</i>
N-hexane	-0.01	P	P	P	P	P	P	P
Cyclohexane	0.02	P	P	P	P	P	P	P
Toluene	0.20	P	P	S	TG (4)	S	TG (6.3)	TG (14.3)
Chlorobenzene	0.22	P	P	S	TG (4)	S	TG (8.5)	TG (20.0)
O-xylene	0.26	P	P	S	TG (0.5)	S	TG (6.7)	TG (12.5)
Styrene	0.29	P	P	S	TG (3)	S	TG (5.4)	TG (16.7)
MMA	N/A	P	P	P	TG (5)	P	TG (10.0)	P
Ethylacetate	0.21	P	P	P	TG (5)	P	TG (9.0)	P
Butylacetate	0.18	P	P	P	TG (4)	P	TG (9.5)	P
Acetone	0.37	S	S	S	TG (5)	P	S	OG (3.3)
THF	0.30	P	P	P	S	OG (9.5)	S	S
DMSO	0.22	S	P	S	S	OG (10.8)	S	S
DCM	0.46	S	S	S	S	OG (9.5)	S	S
DMF	0.41	S	S	S	S	S	S	S
Ethyl alcohol	0.67	P	P	S	S	P	S	S
Methanol	0.60	P	P	S	S	OG (40)	S	S

^aP = precipitate, TG = transparent gel, OG = Opaque gel, S = solution. N/A = not available. The data in brackets represents the minimal gel concentration (MGC), mg/mL. E^T(N) is the empirical polarity parameter².

3. The construction features of loofah-like network structure

According to our previous research^{1,3-4} and the theoretical study from Prof. Liu⁵⁻⁷, the possible hierarchical assembly mechanism of loofah-like superstructure was inferred as shows in Figure S1. After the dendrimers self-organized into primary fibers, the existing hydrogen bonding driving these fibers follows a hierarchical assembly process, finally formed an ordered network structure with discrete fibers entangle with each other through physical crosslinking to create sample-spanning networks. Therefore, the construction features of loofah-like network structure are that the fibers grew together inherently to form a continuous and integral network without physical crosslinking of individual fibers and one thick mother-fiber branches off into two relatively thin daughter-fibers, forming a unique Y-limb.

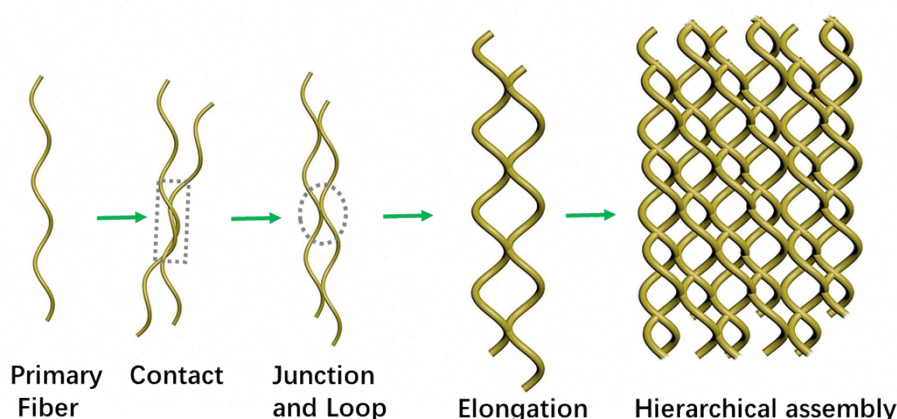


Figure S1. The possible hierarchical assembly mechanism of dendrimer *Boc* from primary fiber to loofah-like network structure.

4. Correlation of the rheological property and loofah-like superstructure

According to Prof. Liu's reports⁵, soft materials with a fiber network, the storage modulus, G' , is directly associated with the network structure. To linking the rheological property and fibrous structure of supramolecular gel, an important parameter correlation length ξ (Figure S2a) determined by the average mesh size of fiber networks was introduced. It follows a power law that $G'_{\max} \approx \xi^{-p}$ ($p \approx 0.5-1.7$ depending on the type of networks), with G' decreases initially sharply as the correlation length ξ for cyclic networks increases (or increases initially sharply with the junction density). Linking to our loofah-like network (Figure S2c) and dynamic strain sweep data (Figure S2b), the statistical ξ is *ca.* 330 nm and the $G'_{\max} \approx 140$ Pa, the calculated $p \approx 0.9$ which fit with the structural features of mesh network with fibers fully connected (loofah-like network). Therefore, these results strongly indicating that the loofah-like structure is existing in wet gels and the physical properties fit with the superstructure underlying network.

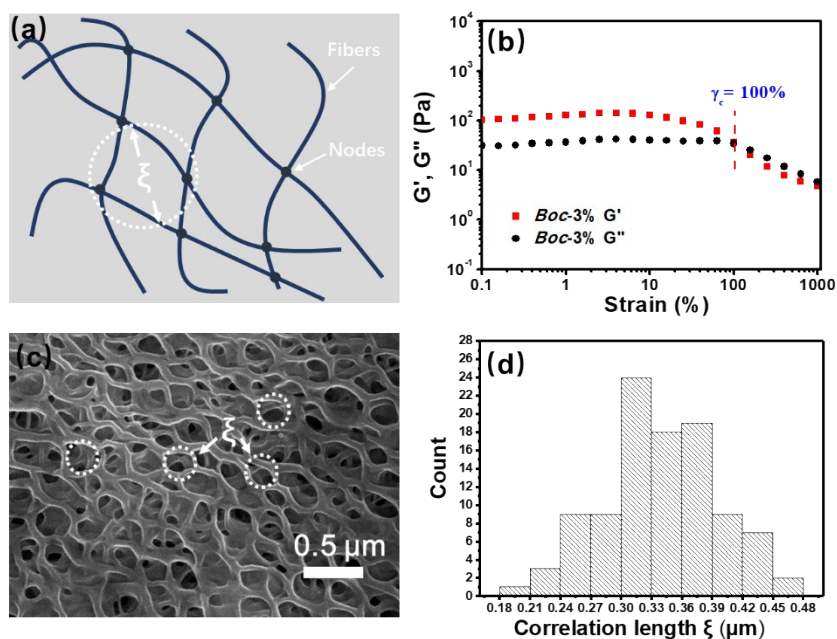


Figure S2. (a) Interconnecting fiber network consisting of fibers and joints (or nodes) with closed loops. (b) Strain dependence of G' and G'' for *Boc* gel in MMA, the concentration of gelators is 30 mg/mL. (c) the SEM image of *Boc* xerogel obtained from MMA. (d) The distribution of correlation length ξ obtained from (c).

5. The molecular packing modes in xerogel or gel state are the same.

The molecular packing models of *Boc* in xerogel or gel state were obtained from XRD and wide-angle X-ray scattering (WAXS) as Figure. S3 shows. From the XRD results, dendrimers were following a hexagonal columnar packing pathway which have been confirmed and reported¹. From the WAXS pattern of the wet gel (XENOCSS, SAXS/WAXS SYSTEM), the scattering peaks form a ratio of $1: \sqrt{3}: 2$ for q_1 to q_3 , a feature that suggests a hexagonal columnar structure. From patterns, the strongest diffraction peak in XRD corresponding to d-spacing of 23.9 \AA , and the strongest scattering peak in WAXS corresponding to d-spacing of 23.8 \AA . The same d-spacings indicated that the molecular packing for xerogel and gel state is the same. The drying effect shows no influence on the stacking of dendrimers, and the loofah-like structure can be confirmed exist in the gel.

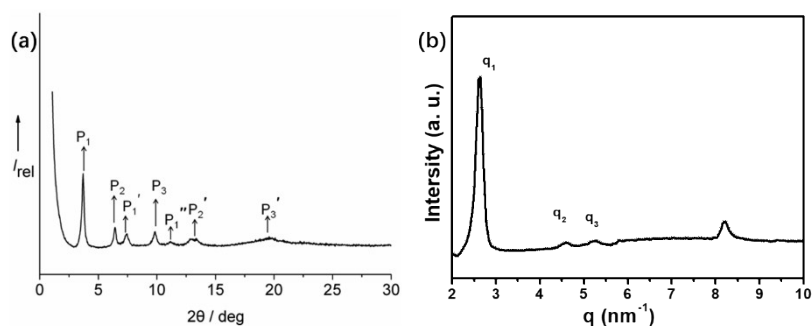


Figure. S3 the XRD and WAXS pattern of *Boc* obtained from MMA. For the XRD¹(a), the sample is the xerogel after dry with the concentration in 3 mg/mL. For the WAXS (b), the sample is the wet gel with the concentration in 3 mg/mL.

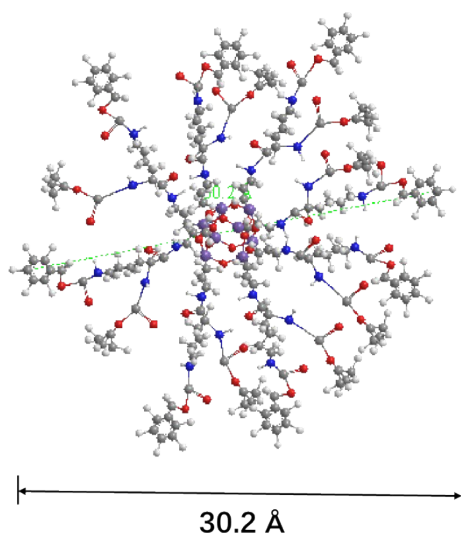


Figure S4. Molecular model and size of **ZB** obtained by Chem Draw.

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