Heterogeneous Organocatalysis at Work: Functionalization of Hollow Periodic Mesoporous Organosilica Spheres with MacMillan Catalyst

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Abstract: We report a new method for the synthesis of hollow-structured phenylene-bridged periodic mesoporous organosilica (PMO) spheres with a uniform particle size of 100–200 nm using α -Fe₂O₃ as a hard template. Based on this method, the hollowstructured phenylene PMO could be easily functionalized with MacMillan catalyst (H-*Ph*PMO-Mac) by a co-condensation process and a "click chemistry" post-modification. The synthesized H-*Ph*PMO-Mac catalyst has been found to exhibit high catalytic activity (98% yield, 81% enantiomeric excess (*ee*) for *endo* and 81% *ee* for *exo*) in asymmetric Diels–Alder reactions with water as solvent. The catalyst could be

Keywords: asymmetric catalysis • heterogeneous catalysis • hollow structures • organocatalysis • mesoporous materials reused for at least seven runs without a significant loss of catalytic activity. Our results have also indicated that hollowstructured PMO spheres exhibit higher catalytic efficiency than solid (nonhollow) PMO spheres, and that catalysts prepared by the co-condensation process and "click chemistry" postmodification exhibit higher catalytic efficiency than those prepared by a grafting method.

Introduction

Complementing metal- and biocatalysis, organocatalysis has become one of the most rapidly growing research areas in synthetic organic chemistry during the past decade.^[1] Many types of asymmetric organocatalysts have been developed for applications in a wide range of organic methodologies, most prominently those providing efficient and environmentally benign access to chiral compounds such as drugs and bioactive natural products. For example, imidazolidinone, the so-called MacMillan catalyst^[2] (Scheme 1), is one of the most versatile organocatalysts, and has been utilized in a variety of highly enantioselective reactions, such as the Diels-Alder reaction,^[2a,e] 1,3-dipolar cycloaddition,^[2b] Friedel-Crafts alkylation,^[2c] and so on. However, the practical application of asymmetric organocatalysis is generally hindered due to the requirement for high catalyst loadings and the difficulty in separating the catalyst from the product. Accordingly, immobilization of organocatalysts on solid supports, such as polymers,^[3] porous materials,^[4] or magnetic nanoparticles,^[5] has been further explored to achieve asymmetric catalysis under heterogeneous conditions.

It is being increasingly recognized that hollow structures with a large fraction of void space and high surface area are advantageous for catalytic applications.^[6] Most of the report-

 [a] J. Y. Shi, C. A. Wang, Z. J. Li, Q. Wang, Y. Zhang, Prof. Dr. W. Wang State Key Laboratory of Applied Organic Chemistry College of Chemistry and Chemical Engineering Lanzhou University, Lanzhou 730000 (P.R. China) Fax: (+86)9318915557 E-mail: wang_wei@lzu.edu.cn ed work has focused on the construction of hollow-structured catalysts for metal catalysis. For example, Kim et al.^[7] reported that hollow Pd spheres exhibit good catalytic activity in Suzuki cross-coupling reactions. Liang et al.^[8] synthesized hollow Pt nanospheres, which showed good electrocatalytic activity in the oxidation of methanol. Ikeda and coworkers prepared Pt^[9a] and Rh^[9b] nanoparticles encapsulated in hollow mesoporous carbon shells, which served as excellent heterogeneous hydrogenation catalysts. Song and coworkers^[10] also prepared Pd nanoparticles inside hollow mesoporous silica spheres, which exhibited superior activity in Suzuki coupling reactions. To immobilize organocatalysts, Yang and co-workers^[11a] pioneered the research by preparing ethane-silica hollow nanospheres with microwindows in the shells through a "polymeric micelles" method. Through a post-modification process, these authors further offered the first two examples of hollow nanospheres functionalized with chiral diamine^[11b] or prolinamide^[11c] organocatalysts, which showed promise as highly efficient, water-tolerant catalysts. An important aspect yet to be developed is enlargement of the micropores in the shells of such hollow structures to mesopores, which will extend catalytic applications to large reactants or products.

Periodic mesoporous organosilicas (PMOs) are synthesized from organo-bridged precursors (R'O)₃Si-R-Si(OR')₃ in the presence of a surfactant.^[12] Due to their combined advantages of ordered mesoporous structure, unique pore-wall functionality, and tunable surface properties,^[13] PMO materials are of potential importance in catalytic applications.^[13e] Accordingly, many efforts have been directed towards the designed synthesis and catalytic applications of chiral PMOs.^[14] Mesoporous materials in nanoparticle size, especially with a hollow nanostructure, may decrease diffusion

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Scheme 1. Schematic representation of the synthesis of hollow-structured phenylene PMO (H-*Ph*PMO, path A) and further functionalization with Mac-Millan catalyst (H-*Ph*PMO-Mac, path B) through a co-condensation process and click chemistry post-modification.

lengths, increase accessibility to active sites, and thus enhance catalytic activity.^[6b,15] The first example of the preparation of PMO materials with hollow nanospheres was reported by Lu's group, in which a dual-templating approach was explored.^[16] Ha and co-workers^[17] also prepared mesoporous ethane–silica hollow nanospheres through a hard-templating route using polystyrene latex spheres. Fröba and co-workers^[18] reported the synthesis of core–shell PMO materials with a solid silica core and a phenylene PMO shell. However, no catalytic application of these hollow PMO materials was reported.

Herein, we report a hard-templating route for the preparation of hollow phenylene-bridged PMO (denoted as H-PhPMO) by using hematite nanoparticles as the hard template. Based on this new method, the hollow-structured phenylene PMO could be easily functionalized with Mac-Millan catalyst (denoted as H-PhPMO-Mac) through a cocondensation process and "click chemistry" post-modifica-

tion. The hydrophobic surface properties of PMO^[13c,e] and accessible mesopores between the inner and outer surfaces of the hollow structures^[6] accelerate the mass-transport process, which renders the H-*Ph*PMO-Mac catalyst highly active in asymmetric Diels–Alder reactions.

Results and Discussion

Synthesis of hollow-structured phenylene PMO (H-PhPMO): As depicted in Scheme 1 (path A), hollow-structured phenylene PMO was synthesized for the first time by using hematite (α -Fe₂O₃) nanoparticles as a hard template. The α -Fe₂O₃ nanoparticles were prepared according to a procedure described in the literature.^[19] As determined from scanning electron microscope (SEM) images, the obtained α -Fe₂O₃ nanoparticles had a diameter of (100±20) nm (Figure S1 in the Supporting Information). These α -Fe₂O₃ nanoparticles were dispersed in an aqueous solution containing cetyltrimethylammonium bromide (CTAB) and NaOH, to which 1,4-bis(triethoxysilyl)benzene (BTEB) was then added. The hydrolyzed BTEB molecules self-assembled with CTAB micelles around the α -Fe₂O₃ nanoparticles, resulting in the formation of ordered PMO shells. After extraction of the surfactant and acid etching, the hollow-structured phenylene-bridged PMO (H-*Ph*PMO) was obtained.

For comparison, the powder X-ray diffraction (XRD) patterns of PMO samples synthesized without (Figure 1a) and with (Figure 1b) α -Fe₂O₃ as the core template are shown in



Figure 1. Powder XRD patterns of a) *PhPMO* and b) H-*PhPMO*, TEM images of c) *PhPMO* and d) H-*PhPMO*, and SEM images of e) *PhPMO* and f) H-*PhPMO*.

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Figure 1. In each case, the single reflection peak seen in the low-angle region is typical of mesoporous materials. A transmission electron microscope (TEM) image of solid (nonhollow) phenylene PMO (denoted as PhPMO) indicates a spherical morphology with most diameters in the range 100-200 nm (Figure 1c). As revealed in Figure 1d, the hollowstructured phenylene PMO (H-PhPMO) was successfully synthesized. The particle size of the product was mostly in the range 100-200 nm, with a hollow core diameter of about 90 nm. These hollow-structured PMO particles were largely monodispersed, with some exceptions of two or more cores due to the unsatisfactory dispersion of α -Fe₂O₃ nanoparticles. SEM images (Figure 1e, f) also showed that both PhPMO and H-PhPMO had spherical morphologies, with particle sizes in the range 100-200 nm. The nitrogen adsorption-desorption isotherms (Figure 2) indicate that both PhPMO and H-PhPMO show type IV behavior, which is also characteristic of mesoporous solids. A hysteresis loop for H-PhPMO was observed in the range 0.4–1.0 P/P_0 , which may be attributed to the delayed evaporation of nitrogen from the hollow voids blocked by the surrounding mesopores.^[20] The mesostructural properties of *Ph*PMO and H-PhPMO are listed in Table 1, which indicate that H-PhPMO has higher surface area, and larger pore size and pore volume. Solid-state ¹³C cross-polarization magic-angle spinning (CP/MAS) NMR and ²⁹Si MAS NMR measurements (Figures S2 and S3 in the Supporting Information) confirmed that the pore walls of H-PhPMO were composed of covalently-bonded O1.5Si-C6H4-SiO1.5 units. As revealed by thermogravimetric analysis (Figure S4 in the Supporting Information), the benzene groups remained intact in the PMO network at up to 550 °C in air.



Figure 2. N2 adsorption-desorption isotherms of PhPMO and H-PhPMO.

Functionalization of hollow-structured PMO materials with MacMillan catalyst (H-PhPMO-Mac): On account of its large fraction of void space, high surface area, and good thermal stability, the hollow-structured H-PhPMO may act as an excellent support for the immobilization of organocatalysts. Accordingly, we set out to prepare hollow PMO spheres functionalized with a typical symmetric organocatalyst, namely the MacMillan catalyst. As depicted in Scheme 1 (path B), by a co-condensation procedure employing α -Fe₂O₃ as a hard template, we first synthesized hollow phenylene PMO material functionalized with organic azide (denoted as H-PhPMO-N₃). On the basis of the click chemistry approach (1,3-dipolar cycloaddition of organic

Table 1. Description and mesostructural properties of phenylene PMO samples.

Sample name	Sample description	Pore size ^[a] [nm]	BET surface area $[m^2g^{-1}]$	Pore volume [cm ³ g ⁻¹]	N content ^[b] [%]	Mac content ^[c] [mmol g ⁻¹]
<i>Ph</i> PMO	Phenylene PMO	$2.9(3.1^{[d]})$	1017 (1197 ^[d])	0.66 (0.81 ^[d])	- (- ^[d])	- (- ^[d])
H-PhPMO	Hollow-structured phenylene PMO	3.8 (3.3 ^[e])	1219 (1224 ^[e])	$0.75 (0.88^{[e]})$	- (- ^[e])	- (- ^[e])
H-PhPMO-N ₃	Azide-functionalized hollow-structured <i>Ph</i> PMO, prepared by co-condensation process	2.9	1212	0.81	3.38	_
H-PhPMO-Mac	MacMillan-catalyst-functionalized hollow-structured <i>Ph</i> PMO, prepared by click chemistry	3.1	644	0.47	4.09	0.50
<i>Ph</i> PMO-N ₃	Azide-functionalized <i>Ph</i> PMO, prepared by co-condensation process	2.8	1188	0.70	3.26	-
PhPMO-Mac	MacMillan-catalyst-functionalized <i>Ph</i> PMO, prepared by click chemistry	4.7	480	0.38	3.89	0.47
PhPMO-Mac-G	MacMillan-catalyst-functionalized <i>Ph</i> PMO, prepared by a grafting method	4.4	265	0.26	4.17	0.59
H-PhPMO-Mac-G	MacMillan-catalyst-functionalized hollow-structured <i>Ph</i> PMO, prepared by a grafting method	6.9	253	0.36	3.71	0.53
H-PhPMO-Mac-R7	H-PhPMO-Mac catalyst recycled after seven runs of Diels-Alder reaction	3.5	400	0.26	2.07	0.27

[a] Calculated from the adsorption branch of the isotherms. [b] Nitrogen content in the sample, determined by elemental analysis. [c] Loading amount of MacMillan catalyst, determined by elemental analysis or semi-quantitative IR estimation. [d] Another batch of *Ph*PMO sample, used for further grafting of MacMillan catalyst to prepare *Ph*PMO-Mac-G. [e] Another batch of H-*Ph*PMO sample, used for further grafting of MacMillan catalyst to prepare H-*Ph*PMO-Mac-G.

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Figure 3. Powder XRD patterns of a) H-*Ph*PMO- N_3 and b) H-*Ph*PMO-Mac, TEM images of c) H-*Ph*PMO- N_3 and d) H-*Ph*PMO-Mac, and SEM images of e) H-*Ph*PMO- N_3 and f) H-*Ph*PMO-Mac.

azides to alkynes),^[21] the hollow-structured phenylene PMO could be easily functionalized with the MacMillan catalyst. The product obtained is denoted as H-PhPMO-Mac (Scheme 1). The XRD patterns of H-PhPMO-N₃ (Figure 3a) and H-PhPMO-Mac (Figure 3b) indicate that each PMO material has a mesoporous structure. TEM images of H-*Ph*PMO-N₃ (Figure 3c) and H-*Ph*PMO-Mac (Figure 3d) confirmed that monodispersed and hollow-structured PMO materials were successfully obtained after the co-condensation procedure (for H-PhPMO-N₃) and the click reaction (for H-PhPMO-Mac). SEM images (Figure 3e and f) also showed both H-PhPMO-N₃ and H-PhPMO-Mac to be composed of monodispersed particles. Nitrogen adsorption-desorption isotherms (Figure 4) of H-PhPMO-N₃ and H-PhPMO-Mac revealed that each PMO material had a welldefined mesostructure giving rise to a type IV isotherm pattern. Hysteresis loops in the range 0.4–1.0 P/P_0 indicate that both had a hollow structure with a mesoporous shell. After the click reaction, the surface was reduced from area 1212 m²g⁻¹ (for H-*Ph*PMO-N₃) to 644 m²g⁻¹ (for H-PhPMO-Mac) and the pore volume was reduced from 0.81 to $0.47 \text{ cm}^3 \text{g}^{-1}$ (Table 1). All of these data indicate the successful incorporation of MacMillan catalyst into the hollow-structured PMO material.

The incorporation of functional groups into the hollowstructured PMO was further confirmed by solid-state ¹³C

CP/MAS NMR spectroscopy (Figure 5). In the ¹³C CP/MAS NMR spectrum of azide-functionalized hollow PMO (H-*Ph*PMO-N₃, Figure 5a), the peak at δ =133 ppm relates to the carbon atoms of the benzene ring. The three signals at δ =53, 22, and 9 ppm correspond to different methylene groups of propyl azide. In the ¹³C CP/MAS NMR spectrum of MacMillan-catalyst-functionalized hollow PMO (H-*Ph*PMO-Mac, Figure 5b), the signals at δ =174, 158, 114, 76,



Figure 4. N2 adsorption-desorption isotherms of H-PhPMO-N3, H-
PhPMO-Mac, and H-PhPMO-Mac-R7 (H-PhPMO-Mac catalyst recycled
after seven runs of Diels-Alder reaction).sev

Relative Pressure (P/P)

0.6

H-PhPMO-Mag

H-PhPMO-Mac-R7

0.8

1.0

Figure 5. ¹³C CP/MAS NMR spectra of a) H-*Ph*PMO-N₃, b) H-*Ph*PMO-Mac, and c) H-*Ph*PMO-Mac-R7 (H-*Ph*PMO-Mac catalyst recycled after seven runs of Diels–Alder reaction). Asterisks denote spinning sidebands. The assignments of ¹³C chemical shifts are indicated in the chemical structures.

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500

400

300

200

100

0.0

0.2

0.4

Volume Adsorbed cm³ g⁻¹

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59, 40, 30, 26, 20, and 13 ppm can be assigned to the skeleton carbons of the MacMillan catalyst. The signal at δ = 144 ppm due to the carbon atoms of the newly formed triazole ring also indicates the successful functionalization through the click reaction. The peak at δ =50 ppm is ascribed to surface methoxy groups (Si–OCH₃) formed in the process of Soxhlet extraction using methanol. Therefore, the ¹³C CP/MAS NMR spectra recorded for H-*Ph*PMO-N₃ and H-*Ph*PMO-Mac provide convincing evidence for the incorporation of organic azide and the MacMillan catalyst, respectively, into the framework of the hollow PMOs. Moreover, the IR spectrum of H-*Ph*PMO-N₃ (Figure 6a) displays



Figure 6. IR spectra of a) H-*Ph*PMO- N_3 , b) H-*Ph*PMO-Mac, and c) H-*Ph*PMO-Mac-R7 (H-*Ph*PMO-Mac catalyst recycled after seven runs of Diels-Alder reaction).

a strong absorbance at 2104 cm⁻¹, which is characteristic of the stretching vibration of azide groups. Based on elemental analysis, the loading amount of azide groups in H-*Ph*PMO- N_3 was 0.80 mmolg⁻¹. After the click reaction, the IR ab-

sorption intensity of the azide group band at 2104 cm⁻¹ decreased dramatically and a carbonvl stretching band at 1675 cm^{-1} appeared (Figure 6b), indicating covalent attachment of the MacMillan catalyst to the hollow-structured PMO. Applying a semi-quantitative estimation developed by Malvi et al.,^[22] we determined that around 79% of the azide groups in H-PhPMO-N3 were converted during the click reaction. Accordingly, the loading amount of MacMillan catalyst in H-PhPMO-Mac was 0.50 mmol g^{-1} (Figure S5 and Table S1 in the Supporting Information).

To compare the catalytic activity with that of H-PhPMO-Mac, solid (non-hollow) spheres of MacMillan-catalyst-functionalized phenylene PMO (denoted as PhPMO-Mac) were also prepared. In the absence of α -Fe₂O₃, solid spheres of azide-functionalized phenylene PMO (denoted as PhPMO- N_3) were synthesized through the co-condensation procedure, and PhPMO-Mac was obtained after the click reaction. The XRD patterns (Figure S6 in the Supporting Information) and nitrogen adsorption-desorption isotherms (Figure S7 in the Supporting Information, results summarized in Table 1) confirmed that both PhPMO-N₃ and PhPMO-Mac had mesoporous structures. SEM images (Figure S8 in the Supporting Information) show that both had largely monodispersed spherical morphologies with the majority of the particles in the size range 100-200 nm. IR and ¹³C CP/MAS NMR (Figures S9 and S10a in the Supporting Information) confirmed that the MacMillan catalyst had been successfully incorporated into PhPMO. According to elemental analysis and semi-quantitative IR estimation, about 77% of the azide groups in *Ph*PMO-N₃ were converted during the click reaction, and the loading amount of MacMillan catalyst in PhPMO-Mac was 0.47 mmol g⁻¹ (Table S1 in the Supporting Information).

For comparison, we also synthesized hollow-structured MacMillan-catalyst-functionalized *Ph*PMO (denoted as H-*Ph*PMO-Mac-G) and solid spheres (denoted as *Ph*PMO-Mac-G) by a grafting method. The synthetic procedure is outlined in Scheme 2. XRD patterns (Figures S11 and S12 in the Supporting Information) and nitrogen adsorption–desorption isotherms (Figures S13 and S14 in the Supporting Information, results summarized in Table 1) confirmed that both H-*Ph*PMO-Mac-G and *Ph*PMO-Mac-G had mesoporous structures. SEM images (Figures S15 and S16 in the Supporting Information) showed that they were composed of monodispersed particles. IR (Figure S17 in the Supporting Information) and ¹³C CP/MAS NMR spectra (Figure S10 b and c in the Supporting Information) confirmed that the



Scheme 2. Schematic representation of the immobilization of MacMillan catalyst on solid *Ph*PMO spheres (denoted as *Ph*PMO-Mac-G) and on hollow spheres (denoted as H-*Ph*PMO-Mac-G) by a grafting method.

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loss of the reaction yield (from

98% to 86%). These results suggest that H-PhPMO-Mac catalyst may be advantageously applied as a remarkably watertolerant catalyst for asymmetric Diels-Alder reactions. After the H-PhPMO-Mac catalyst had been recycled seven times, the loading amount of the Mac-Millan moiety in the recycled catalyst had decreased from 0.50 to 0.27 mmol g^{-1} (Table S1 in the Supporting Information). An XRD pattern (Figure S18 in the Supporting Information) in-

dicated that the recycled cata-

lyst retained a mesoporous

MacMillan catalyst was immobilized on the surface of the PhPMO materials. According to elemental analysis, the loading amounts of MacMillan catalyst were 0.53 mmolg⁻¹ on H-PhPMO-Mac-G and 0.59 mmolg⁻¹ on PhPMO-Mac-G, respectively.

Catalytic performance of hollow-structured PhPMO materials functionalized with MacMillan catalyst (H-PhPMO-Mac): To evaluate the catalytic activity of H-PhPMO-Mac catalyst, the Diels-Alder cycloaddition of 1,3-cyclopentadiene with trans-cinnamaldehyde was selected as a model reaction. Table 2 summarizes the catalytic performances of

(entries 9 and 10). The MacMillan catalyst immobilized by the grafting method may have been inhomogeneously distributed on the PhPMO support, possibly with most such moieties being located on the surface or near the pore mouths of the PMO material,^[23] and this would have hindered the mass-transport process, thereby rendering the catalyst poorly active and giving only low enantioselectivity.^[15b]

The recyclability of the H-PhPMO-Mac catalyst in the asymmetric Diels-Alder reaction was further investigated and the results are listed in Table 3. The H-PhPMO-Mac catalyst could be reused for at least seven runs without a noticeable decrease in enantioselectivity (from 81% ee to 78% ee), although with some

Table 2. Comparison of catalytic performances of the MacMillan catalyst on different PhPMO supports.

	Ph	- + C	Cat. (20 mol%), TF.		Ph +	.CHO h	
Entry	Catalyst	<i>t</i> [h]	Solvent	Yield [%] ^[b]	exo endo/exo ^[c]	endo ee ^[d] [%]	exo ee ^[d] [%]
1	1	24	CH ₃ CN/H ₂ O ^[a]	97	1:1.1	95	92
2	H-PhPMO-Mac	24	CH ₃ CN/H ₂ O ^[a]	58	1:1.1	89	86
3	PhPMO-Mac	24	CH ₃ CN/H ₂ O ^[a]	42	1:1.1	87	85
4	H-PhPMO-Mac-G	24	CH ₃ CN/H ₂ O ^[a]	46	1:1.0	72	69
5	PhPMO-Mac-G	24	CH ₃ CN/H ₂ O ^[a]	38	1:1.0	70	68
6	1	24	H ₂ O	80	1:1.4	93	91
7	H-PhPMO-Mac	12	H ₂ O	98	1:1.1	81	81
8	PhPMO-Mac	12	H ₂ O	84	1:1.1	79	78
9	H-PhPMO-Mac-G	12	H_2O	86	1:1.2	63	62
10	PhPMO-Mac-G	12	H_2O	80	1:1.1	59	62

[a] CH₃CN/H₂O, 95:5 (v/v). [b] Yield of the isolated product. [c] Determined by ¹H NMR spectroscopy. [d] Determined by HPLC. TFA = trifluoroacetic acid.

the MacMillan catalyst on different supports. We also chose a homogeneous catalyst (1) as a reference. Catalyst 1 gave a 97% yield (with 95% enantiomeric excess (ee) for endo, 92% ee for exo) in CH₃CN/H₂O (Table 2, entry 1) and an 80% yield (with 93% ee for endo, 91% ee for exo) in H_2O (Table 2, entry 6). When CH₃CN/H₂O was used as solvent, both PhPMO-Mac and H-PhPMO-Mac gave good ee values, but with poor yields (Table 2, entries 2 and 3). To our delight, when H₂O was used as solvent, a high yield of 98% and high enantioselectivities of 81% ee (endo) and 81% ee (exo) were obtained for H-PhPMO-Mac catalyst (Table 2, entry 7). Under all conditions tested, the hollow-structured PhPMO catalysts (H-PhPMO-Mac, Table 2, entries 2 and 7) exhibited higher catalytic activity than their solid (nonhollow) counterparts (PhPMO-Mac, entries 3 and 8). The accessible mesopores within the walls of the hollow spheres may provide plentiful channels between the inner and outer surfaces, which facilitate the diffusion of solvents, reactants, and products, and thus accelerate chemical reactions.^[6]

For comparison, H-PhPMO-Mac-G (hollow spheres) and PhPMO-Mac-G (solid spheres) prepared by the grafting method were also tested in the Diels-Alder cycloaddition of 1.3-cvclopentadiene and trans-cinnamaldehvde. Both samples exhibited low catalytic activity with low enantioselectivity in CH₃CN/H₂O (Table 2, entries 4 and 5) and in H₂O

Table 3. Recyclability of H-PhPMO-Mac catalyst.								
Ph CHO + $H - PhPMO-Mac (20 mol%)$ H ₂ O, TFA, RT H_2 O, TFA, RT H_2O, TFA, RT H_2 O, TFA, RT H_2O, TFA, RT H_2O, TFA, R								
Entry	Recycle	Time [h]	Yield ^[a] [%]	endo/exo ^[b]	endo ee ^[c] [%]	exo ee ^[c] [%]		
1	Fresh	12	98	1:1.1	81	81		
2	1st	12	96	1:1.1	83	81		
3	2nd	12	90	1:1.1	83	82		
4	3rd	12	92	1:1.2	81	82		
5	4th	12	76	1:1.2	84	83		
6	5th	21	94	1:1.1	80	81		
7	6th	21	86	1:1.2	79	79		

[a] Yield of the isolated product. [b] Determined by ¹H NMR spectroscopy. [c] Determined by HPLC.

1:1.1

78

78

86

structure, but with decreased order in the mesostructure. N₂ adsorption-desorption isotherms (Figure 4, bottom) indicated that its surface area had been reduced to $400 \text{ m}^2\text{g}^{-1}$ and that the pore volume had been reduced to $0.26 \text{ cm}^3 \text{g}^{-1}$ (Table 1). The ¹³C CP/MAS NMR spectrum showed additional signals at $\delta = 44$ and 26 ppm (Figure 5c), while the IR spectrum remained almost unchanged (Figure 6c). A TEM image further revealed that the hollow structure of H-

8

7th

21

*Ph*PMO-Mac had been destroyed (Figure S19 in the Supporting Information). The loss of catalytic active sites and damage of the hollow structure may be the main reasons for the loss of catalytic activity after seven runs.

Conclusion

We have developed a new method for the synthesis of hollow-structured PMO spheres using α -Fe₂O₃ as a hard template. Based on this method, hollow-structured phenylene PMO (H-PhPMO) could be easily functionalized with the MacMillan catalyst (H-PhPMO-Mac) through a co-condensation process and a click chemistry post-modification. Results have indicated that these hollow-structured MacMillan-catalyst-functionalized PhPMO spheres, that is, H-PhPMO-Mac catalyst, exhibit higher catalytic activity than solid (non-hollow) PhPMO-Mac catalyst and may be advantageously applied as a water-tolerant and highly efficient catalyst for asymmetric Diels-Alder reactions. Moreover, the H-PhPMO-Mac catalyst can be reused for at least seven runs without significant loss of catalytic activity. Our results have also indicated that the catalysts (PhPMO-Mac and H-PhPMO-Mac) prepared by the co-condensation process are superior in terms of catalytic activity to immobilized catalysts (H-PhPMO-Mac-G and PhPMO-Mac-G) prepared by a grafting method.

Experimental Section

Chemicals and reagents: 1,4-Bis(triethoxysilyl)benzene (BTEB),^[24] 3-azidopropyl-trimethoxysilane,^[25] and hematite nanoparticles^[19] were prepared according to the respective literature procedures.

Synthesis of phenylene PMO (*PhPMO*): In a typical synthesis, CTAB (0.1 g) was dissolved in deionized water (48 mL) and 0.5 M NaOH (1.4 mL). The system was then kept at a constant temperature of 80 °C, and BTEB (0.48 mL) was slowly added under vigorous stirring. After stirring for 2 h at 80 °C, the white solid product was collected by filtration, washed thoroughly with water and ethanol, and dried at room temperature. After twofold extraction with a solution of 36 wt % HCl (2 mL) in ethanol (60 mL) at 60 °C for 6 h, a surfactant-free sample was obtained.

Synthesis of hollow-structured phenylene PMO (H-*Ph*PMO): Hematite nanoparticles (0.20 g) were dispersed by ultrasound in a solution containing CTAB (0.1 g), deionized water (48 mL), and 0.5 M NaOH (1.4 mL). The system was then heated to a constant temperature of 80 °C, where upon BTEB (0.48 mL) was slowly added under vigorous stirring. After stirring for 2 h at 80 °C, the white solid product was collected by filtration, washed thoroughly with water and ethanol, and dried at room temperature. After twofold extraction with a solution of 36 wt % HCl (2 mL) in ethanol (60 mL) at 60 °C for 6 h, and etching in a solution of 2 M HCl at 80 °C for 2 h, a surfactant-free and hematite-free sample was obtained.

Synthesis of azide-functionalized phenylene PMO (*Ph*PMO-N₃): CTAB (0.5 g) was dissolved in deionized water (240 mL) and 0.5 M NaOH (7.0 mL). The system was then heated to a constant temperature of 80 °C, whereupon BTEB (2.16 mL) was slowly added under vigorous stirring. After 15 min, 3-azidopropyltrimethoxysilane (0.27 g) was slowly added. After stirring at 80 °C for 105 min, the white solid product was collected by filtration, washed thoroughly with water and ethanol, and dried at room temperature. After twofold extraction with a solution of 36 wt %

HCl (6 mL) in ethanol (200 mL) at 60 $^{\circ}\mathrm{C}$ for 6 h, a surfactant-free sample was obtained.

Synthesis of hollow-structured azide-functionalized PMO (H-*Ph*PMO- N_3): Hematite nanoparticles (1.2 g) were dispersed by ultrasound in a solution containing CTAB (0.5 g), deionized water (240 mL), and 0.5 m NaOH (7.0 mL). The system was then heated to a constant temperature of 80°C, whereupon BTEB (2.16 mL) was slowly added under vigorous stirring. After 15 min, 3-azidopropyltrimethoxysilane (0.27 g) was slowly added. After stirring at 80°C for 105 min, the white solid product was collected by filtration, washed thoroughly with water and ethanol, and dried at room temperature. After twofold extraction with a solution of 36 wt% HCl (6 mL) in ethanol (200 mL) at 60°C for 6 h, and etching in a solution of 2M HCl at 80°C for 2 h, a surfactant-free and hematite-free sample was obtained.

Synthesis of MacMillan-catalyst-functionalized PMOs (*Ph*PMO-Mac and H-*Ph*PMO-Mac) by click chemistry: An azide-functionalized sample (*Ph*PMO-N₃ or H-*Ph*PMO-N₃) (1.8 g) and CuI (0.11 g, 0.54 mmol) were suspended in THF (10 mL). A solution of 1 (1.70 g, 5.4 mmol) in THF (25 mL) was added under Ar, and then *N*,*N*'-diisopropylethylamine (DIPEA) (1.9 mL, 11 mmol) was added dropwise. The suspension was stirred at 50 °C for 3 days. The solid was then collected by filtration, washed thoroughly several times with acetonitrile and methanol, subjected to by Soxhlet extraction with methanol for 48 h, and then dried under vacuum at 60 °C.

Synthesis of MacMillan-catalyst-immobilized PMOs (*PhPMO-Mac-G* and H-*PhPMO-Mac-G*) by a grafting method: The MacMillan catalyst was anchored onto the surface of phenylene PMO samples according to a strategy described in the literature (Scheme 2).^[26] CuI (3.2 mg, 0.017 mmol) and DIPEA (0.35 mL, 2 mmol) were added to a solution of **1** (0.33 g, 1.05 mmol) and 3-azidopropyltrimethoxysilane (0.203 g, 1.0 mmol)) in THF (10 mL) protected by Ar. The resulting mixture was stirred at room temperature for 24 h, the solvent was removed under reduced pressure to quantitatively afford **2** as a light yellow oil, and this was used directly in the next step without further purification. The resulting crude yellow product was mixed with a PMO sample (1.0 g) and toluene (30 mL), and the suspension was heated at 90 °C for 2 days under Ar. The solid was collected by filtration, washed thoroughly several times with acetonitrile and methanol, subjected to Soxhet extraction with methanol for 48 h, and then dried under vacuum at 60 °C.

General procedure for asymmetric Diels-Alder reactions catalyzed by MacMillan catalysts on different supports: Trifluoroacetic acid (0.05 mmol) was added to a stirred solution of catalyst (0.05 mmol) in H₂O (1 mL) and the mixture was stirred for 5 min at room temperature. (E)-Cinnamaldehyde (31.8 µL, 0.25 mmol), used soon after purification, was added, followed by cyclopentadiene (104 µL, 1.25 mmol). The mixture was stirred at room temperature for a specified time. After the addition of CH₃CN, the catalyst was separated by centrifugation and the liquid layer was removed by decantation. The catalyst was washed with four portions of Et2O, the washings were pooled with the aforementioned liquid layer, and then the combined liquid phase was extracted four times with Et₂O. After evaporation of the solvent under vacuum, the residue was purified by column chromatography on silica gel (hexane/ethyl acetate, 12:1, v/v) to give the product as a colorless oil. The endo to exo ratio was determined by ¹H NMR (400 MHz). The product was converted into the corresponding alcohol with NaBH4 and the enantiomers were separated by HPLC using a Daicel chiral OJ-H column (hexane/iPrOH, 70:30; flow rate 1.0 mLmin⁻¹). The recovered H-PhPMO-Mac catalyst was employed for the next run after evacuation under vacuum.

Characterization: Solution ¹H and ¹³C NMR spectra were recorded in CDCl₃ on a Bruker Avance III 400 MHz NMR spectrometer using tetramethylsilane (TMS) as an internal standard. Powder X-ray diffraction (XRD) measurements were made with a PANalytical X'Pert Pro with X'Celerator detector (step size: 0.008°, step time: 38.34 s). The nitrogen adsorption and desorption isotherms were measured at 77 K using a Micromeritics ASAP 2020M system. The samples were degassed at 120 °C for 8 h before the measurements. Surface areas were calculated from the adsorption data using the Brunauer–Emmett–Teller (BET) method. The pore size distribution curves were obtained from the adsorption branches

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using the Barrett-Joyner-Halenda (BJH) method. The morphology and size of the obtained samples were characterized with a JEOL-6701F field-emission scanning electron microscope (SEM) operated at 10 kV. Transmission electron microscope (TEM) images were obtained with a JEOL JEM-2010 instrument operating at 200 kV. Solid-state NMR measurements were performed on a Bruker WB Avance II 400 MHz spectrometer. ¹³C CP/MAS NMR spectra were recorded with a 4 mm doubleresonance MAS probe at a sample spinning rate of 10.0 kHz; a contact time of 2 ms (ramp 100) and a pulse delay of 3 s were applied. ²⁹Si highpower proton-decoupling (HPDEC) MAS NMR spectra were recorded with a 4 mm double-resonance MAS probe and a sample spinning rate of 10.0 kHz; a $\pi/4$ single-pulse excitation of 2.0 µs and a pulse delay of 30 s were applied. FTIR spectra were recorded on a Nicolet NEXUS 670 instrument. Elemental analysis was carried out on an Elementar Analysensysteme GmbH VarioEL V3.00 elemental analyzer. Thermogravimetric analysis (TGA) was performed on an STA 449C Jupiter instrument over the temperature range from ambient to 900 °C under air atmosphere (heating rate 10°Cmin⁻¹). Enantiomeric excesses were determined by HPLC on a Waters 1525 Delta system with a Daicel chiral OJ-H column (eluents: iPrOH and n-hexane).

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