RSC Advances

Synthesis, characterization and catalytic activity of novel large network polystyrene-immobilized organic bases

Journal:	*RSC Advances*
Manuscript ID	RA-ART-10-2015-021140.R3
Article Type:	Paper
Date Submitted by the Author:	23-Nov-2015
Complete List of Authors:	Vaccaro, Luigi; Università di Perugia, Dipartimento di Chimica Biologia e Biotecnologie Chen, Jihua; Oak Ridge National Laboratory, Center for Nanophase Materials Sciences Barkakaty, Balaka; Oak Ridge National Laboratory, Center for Nanophase Materials Sciences Hensley, Dale; Oak Ridge National Laboratory, Center for Nanophase Materials Sciences Adriaensens, Peter; Hasselt University, Chemistry Carleer, Robert; Hasselt University, Chemistry Tassi, Marco; Hasselt University, Chemistry Bartollini, Elena; University of Perugia, Department of Chemistry Bianchi, Luca; Unversità di Perugoa, Dipartimento di Chimica Biologia e Biotecnologie Marrocchi, Assunta; University of Perugia,
Subject area & keyword:	Catalysis < Organic

SCHOLARONE™
Manuscripts

Please do not adjust margins

Journal Name

ARTICLE

Synthesis, characterization and catalytic activity of novel large network polystyrene-immobilized organic bases

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Marco Tassi,[1] Elena Bartollini,[2] Peter Adriaensens,*[1] Luca Bianchi,[2] Balaka Barkakati,[3] Robert Carleer,[1] Jihua Chen,[3] Dale K. Hensley,[3] Assunta Marrocchi,*[2] and Luigi Vaccaro*[2]

In view of searching for efficient polymeric supports for organic bases to be used in environmentally friendly reaction conditions, novel gel-type cross-linked polystyrenes functionalized with diethylamine and 1,5,7-triazabicyclo[4.4.0]dec-5-ene, have been prepared. The structural properties and morphology of these catalysts have been determined by extensive solid state NMR experiments, FTIR spectroscopy and SEM/TEM microscopy. SPACeR-supported bases were found to exhibit high catalytic activity in the epoxide ring opening by phenols. A range of β-substituted alcohols have been readily and regioselectively synthesized.

Introduction

Supported catalysts have played essential roles in many chemical processes. The current global environmental and resource problems are motivating further research and development of supported catalysts. They constitute a more sustainable, cost-effective alternative to the traditional non-supported counterparts enabling the simplification of the isolation of products and easy recyclability.[1] The most versatile materials used for catalysts supports are organic insoluble (cross-linked) polymers. Despite this fact, such catalytic systems may suffer from lower activities and selectivities when compared with their non-supported analogues. Diffusion effects, accessibility of the catalytic sites by the reagents in solution, and site heterogeneity are in part responsible for these results.[1]

To address such issues, an accurate choice is required to select the ideal supports in terms of e.g. polymer backbone rigidity, the nature of the cross-linker, catalyst site density/loading, influence on the catalyst stability/efficiency.

For many years we have been optimizing synthetic procedures by employing eco-friendly reaction protocols, including the use of water, solvent-free conditions (SolFC), and supported organocatalysts, proving that significant improvements in both chemical efficiency and process sustainability can be achieved.[2] Particularly, we have recently directed our interest[2] towards the development of novel polymer supports more suitable than classic Merrifield[3] and Janda-Jel[4] resins for being used in sustainable reaction media, including solvent-free conditions.

Thus, in this work, three novel chloromethylated polystyrene-based SPACeR (SP) gel-type resin supports **1** featuring different network loading capacities (***a-c***) were successfully prepared by suspension polymerization and used to immobilize 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) and diethylamine bases to access catalytic systems SP-TBD **2*a-c*** and SP-TEA **3*a-c***, respectively (Figure 1).

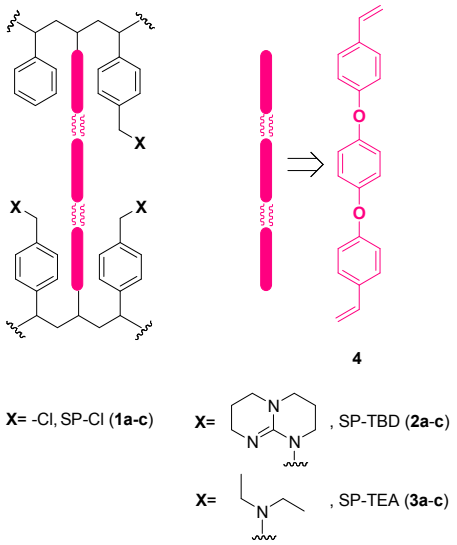


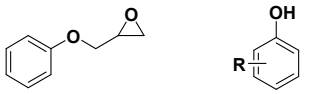
Figure 1. Schematic of SPACeR (SP) resins supports **1*a-c*** and corresponding SP-supported catalysts **2*a-c*** and **3*a-c***. Chemical structure of 1,4-bis(4-vinylphenoxy)benzene cross-linker **4**.

[a] Hasselt University - Applied and Analytical Chemistry, Agoralaan-Building D, Belgium BE-3590 Diepenbeek
[b] Laboratory of Green Synthetic Organic Chemistry, CEMIN – Dipartimento di Chimica, Biologia e Biotecnologie, Università di Perugia Via Elce di Sotto, 8, 06123 Perugia, Italy.
[c] Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Supplementary Information (ESI) available: synthetic procedures/spectroscopic data, FTIR/^{13}C-CP/MAS SS-NMR analysis of supports/catalytic systems, SEM/TEM images of supports/catalytic systems. See DOI: 10.1039/x0xx00000x

This journal is © The Royal Society of Chemistry 20xx

Notably, the investigated supports **1*a-c*** contain the 1,4-bis(4-vinylphenoxy)benzene cross-linker **4** (Figure 1), which is a novel large spacer more polar but less flexible than the Janda's cross-linker. These polymers are therefore more "SPACed" and "Rigid" than Janda-Jel resins,[4] and we named them SPACeR (SP). The supports as well as the resulting catalysts were characterized in terms of their structural and morphological features. In this regards, Fourier-Transform Infrared Spectroscopy (FTIR), solid-state NMR, Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM) were performed. Finally, the use of SP-immobilized base catalysts **2*a-c*** and **3*a-c*** in the reaction of the epoxide 5 with a variety of phenols **6-13** (Scheme 1) has been explored, and compared with the performance of commercially available polystyrene supported TBD (PS-TBD) and polystyrene supported triethylamine (PS-TEA), both 2% cross-linked with divinylbenzene. Attention has been directed to the epoxide phenolysis process since it is of great importance in organic synthesis. Indeed, it could offer a suitable route towards a variety of β-substituted alcohols for different uses.[5] However, the poor nucleophilicity of phenols requires suitable activation protocols. Although there have been several reports related to these homogeneous as well as heterogeneous catalytic methods,[6] there are still many problems including the use of expensive reagents, catalyst activation difficulties, long reaction time, low selectivity, environmental hazards, and catalyst recycling problems. In this regard, developing new heterogeneous catalytic systems and improving the performance of such reaction is highly desirable.
Our results demonstrated that the novel matrices may be very attractive to realize efficient, regioselective epoxide ring opening procedures.



5

6 R= H
7 R= 4-I
8 R= 4-F
9 R= 4-*i*Pr
10 R= 4-CHO
11 R= 2-CHO
12 R= NO_2
13 R= CF_3

Scheme 1. Phenyl glycidyl ether (**5**) and phenols **6**-**13** used in this study.

2. Experimental

2.1. General Remarks

All chemicals were purchased and used without any further purification unless otherwise noted. 4-Vinylbenzylchloride (VBC) was extracted three times with a 5% w/w NaOH solution to remove the polymerization inhibitor (tert-butyl catechol). Dibenzoylperoxide was re-crystallized from methanol. Suspension polymerizations were run using a three-neck cylinder-shaped glass vessel, equipped with a mechanical stirrer, condenser, and nitrogen inlet.[7] A silicon oil bath was used as heating source. Commercial polystyrene- bound TBD (PS-TBD) was purchased at Sigma-Aldrich Co. (2.6 mmol TBD/g). Polystyrene-supported triethylamine (PS-TEA) was prepared following a previously reported procedure[8] (3.4 mmol TEA/g). Gas Chromatographic (GC) analyses were performed by using Hewlett-Packard HP 5890A series system equipped with capillary column DB-35MS (30 m, 0.53 mm), and a FID detector, hydrogen was the gas carrier. GLC-EIMS analyses were carried out by using a Hewlett-Packard HP 6890N Network GC system/5975 Mass Selective Detector equipped with an electron impact ionizer at 70 eV.

2.2. Characterization Techniques

Elemental microanalyses were performed using a Fison's EA1106CHN analyzer using atropine, 2,5-bis-2-(5-tert-butylbenzoxazol-yl)-thiophene (BBOT) and phenanthrene as reference standard, with an accuracy of ca. 2μmol/g.
FTIR spectra were recorded using a Bruker Optics Vertex 70 spectrometer. Bulk polymer samples were analyzed via ATR-FTIR using a Harrick Scientific MVP Star accessory equipped with a diamond internal reflection element (IRE); a standard deuterated L-alanine doped triglycine sulfate (DLaTGS) detector was used. A background spectrum was collected as the average of 64 scans of the clean ATR crystal while spectra were collected as the average of 64 scans with 4 cm-1 resolution and subsequently baseline corrected.
Scanning Electron Microscopy (SEM) was performed with a Zeiss Merlin at a voltage less than 2kV. Transmission Electron Microscopy (TEM) samples were embedded in a low viscosity resin (Ted Pella) before microtoming into ~75-nm-thick slices and examined with a Zeiss Libra 120 at 120kV.
All standard ^{1}H-NMR and ^{13}C-NMR analysis in liquid medium were performed at 400 MHz and 100.6 MHz, respectively, using a convenient deuterated solvent (reported in the characterization charts) and the residual peak as internal chemical shift reference, or TMS in the case of CDCl3. Characterization data for all compounds are given in the Supporting Information.
^{13}C CP/MAS SS-NMR spectra were acquired at ambient temperature on Agilent VNMRS DirectDrive 400 MHz spectrometer (9.4 T wide bore magnet) equipped with a T3HX 3.2 mm probe dedicated for small samples volumes and high decoupling powers. MAS was performed at 13 kHz. Hexamethylbenzene was used to calibrate the carbon chemical shift scale to 132.1 ppm. Acquisition parameters used were: a spectral width of 50 kHz, a 90° pulse of 2.5 μs, a spin-lock field for Cross Polarization of 100 kHz, a contact time for CP of 1250 μs, an acquisition time of 15 ms, a recycle decay of 8 s and a number of accumulations between 2000 and 3000. High power proton dipolar decoupling during the acquisition time has been set to 100 kHz. The Hartmann-Hahn condition for CP was calibrated accurately on the samples themselves.

2.3. Materials Synthesis

2.3.1. Synthesis of 1,4-bis(4-vinylphenoxy)benzene (4). In a round bottom flask equipped with a condenser and a magnetic stirrer, 4-fluorobenzaldehyde **14** (3.18 g, 25.6 mmol), hydroquinone **15** (1.54 g, 14.0 mmol) were dissolved in

This journal is © The Royal Society of Chemistry 20xx

dimethylacetamide (20.0 mL), and potassium carbonate (4.84 g, 35.0 mmol) was added. The reaction mixture was left under stirring at 160°C for 6 h, then poured into cold water (20 mL) and filtered to afford 4,4'-[1,4-phenylen-bis-(oxy)]dibenzaldehyde **16** (4.0 g, 12.6 mmol, 90% yield) as brown solid, which was pure according to NMR analysis and was used without further purification. ^{1}H-NMR ($CDCl_3$) δ 7.04-7.16 (m, 8H), 7.84-7.93 (m, 4H), 9.99 (s, 2H); ^{13}C-NMR ($CDCl_3$) δ 117.9, 118.5, 129.8, 131.3, 150.1, 162.7, 190.6.

In a three-neck round bottom flask, equipped with a magnetic stirrer and a nitrogen inlet/outlet, methyltriphenylphosphonium bromide (13.40 g , 37.5 mmol) was dissolved in dry THF (150 mL) at 0°C. A solution of nBuLi (3.8 mL, 1.6 M in n-hexane, 95.3 mmol) was then added dropwise, and the reaction mixture was left under stirring at 0°C for 3 h, then allowed to warm at room temperature. Next, a solution of 4,4'-[1,4-phenylenebis(oxy)]dibenzaldehyde **16** (4.0 g , 12.6 mmol) in dry THF (30.0 mL) was added, and this mixture was stirred at room temperature for an additional 24 h. After this time, THF was removed under vacuum, and the residue was recrystallized from methanol, affording 1,4-bis(4-vinylphenoxy)benzene **4** (3.17 g, 80% yield) as a white solid (m.p. 146-146.5°C); ^{1}H- NMR ($CDCl_3$) δ 5.18- 5.21 (d, 1H, J= 11.08 Hz), 5.64-5.68 (d, 1H, J= 17.52 Hz), 6.65-6.72 (dd, 1H, J= 11.08, 17.52 Hz) , 6.95-6.97 (d, 2H, J= 8.64 Hz), 7.00 (s, 2H), 7.36-7.39 (d, 2H, J = 8.64 Hz); ^{13}C-NMR ($CDCl_3$) δ 112.79, 118.25, 120.43, 127.54, 132.65, 135.95, 152.62, 157.40. An. Calcd. for $C_{22}H_{18}O_2$: C, 84.05; H, 5.77% . Found: C, 84.11; H, 5.76%.

2.3.2. Preparation of SP-Cl supports 1*a-c*

2.3.2.1. SP-Cl 1*a*. A three-neck cylinder-shaped glass vessel, equipped with a mechanical stirrer, a condenser, and a nitrogen inlet was charged with an aqueous NaCl (2% wt) solution containing acacia gum (4 % wt) (120 mL). After deoxygenation by purging with nitrogen, a mixture of vinylbenzylchloride (9.68 g, 63.7 mmol), 1,4-bis(4-vinylphenoxy)benzene (0.41 g, 1.3 mmol), chlorobenzene (8mL), and dibenzoylperoxide (0.20 g , 0.83 mmol, 2 % wt/wt) was rapidly added to the solution. Next, this reaction mixture was kept under stirring at room temperature for an additional 30 min, then heated at 85°C for 24 h. Subsequently, the reaction mixture was cooled at room temperature, and the polymer beads were isolated by filtration, washed with water (50 mL), extracted by using water (100 mL), THF (100 mL), and n-hexane (100 mL) in a Soxhlet apparatus. Finally, the resin **1*a*** was dried under vacuum for 15 h at room temperature (7.96 g,4.86 mmol Cl/g, 79% yield).

2.3.2.2. SP-Cl 1*b*. A three-neck cylinder-shaped glass vessel, equipped with a mechanical stirrer, a condenser, and a nitrogen inlet was charged with an aqueous NaCl (2% wt) solution containing acacia gum (4% wt) (120 mL). After deoxygenation by purging with nitrogen, a mixture of styrene (2.98 g, 28.6 mmol), vinylbenzylchloride (5.36 g, 35.1 mmol), 1,4-bis(4-vinylphenoxy)benzene (0.409 g, 1.3 mmol), chlorobenzene (8mL), and dibenzoylperoxide (178 mg, 0.72 mmol, 2 % wt/wt) was rapidly added to the solution. Next, this reaction mixture was kept under stirring at room temperature for an additional 30 min, then heated at 85°C for 24 h. Subsequently, the reaction mixture was cooled at room temperature, and the polymer beads were isolated by filtration, washed with water (50 mL), extracted by using water (100 mL), THF (100 mL), and n-hexane (100 mL) in a Soxhlet apparatus. Finally, the resin was dried under vacuum for 15 h at room temperature (6.78 g, 3.41 mmol Cl/g, 78% yield).

2.3.2.3. SP-Cl 1*c*. Prepared by following the procedure described above for **1*b***. Vinylbenzylchloride/styrene = 0.15/0.83. Yield: 80%. Loading: 1.95 mmol Cl/g.

2.3.3. Synthesis of catalysts SP-TBD 2*a-c*

2.3.3.1. SP-TBD 2*a*. In a round bottomed flask equipped with a nitrogen inlet, a condenser and a magnetic stirrer, TBD (0.2 g, 1.44 mol) was dissolved in dry THF (2 mL) and SP-Cl **1*a*** (0. 245 g, 4.86 mmol Cl/g, 1.2 mmol) was added. The mixture was left under stirring at 70°C for 24 h, then allowed to cool at room temperature. The polymer beads were isolated by filtration, washed with THF and then dried under vacuum for 15 h at room temperature. The degree of functionalization was determined to be 3.28 mmol TBD/g by elemental analysis: C 68.13, H 8.34, N 13.80.

2.3.3.2. SP-TBD 2*b*. Prepared by following the procedure described above for **2*a***, starting from SP-Cl **1*b***. The degree of functionalization was determined to be 2.38 mmol TBD/g by elemental analysis: C 70.33, H 8.28, N 10.00.

2.3.3.3. SP-TBD 2*c*. Prepared by following the procedure described above for **2*a***, starting from SP-Cl **1*c***. The degree of functionalization was determined to be 0.68 mmol TBD/g by elemental analysis: C 81.92, H 7.82, N 2.96.

2.3.4. Synthesis of catalysts SP-TEA 3*a-c*

2.3.4.1. SP-TEA 3*a*. In a round bottomed flask equipped with a nitrogen inlet, a condenser and a magnetic stirrer, diethylamine (0.263 g, 3.6 mmol) was dissolved in dry DMF (2 mL) and SP-Cl **1*a*** (0. 245 g, 4.86 mmol Cl/g, 1.2 mmol) was added. The mixture was left under stirring at 85°C for 24 h, then allowed to cool at room temperature. The polymer beads were isolated by filtration, washed with DMF and extracted by using methanol (100 mL), dichloromethane (100 mL), and acetone (100 mL) in a Soxhlet apparatus. Subsequently, the resin was dried under vacuum for 15 h at room temperature. The degree of functionalization was determined to be 2.74 mmol TEA/g by elemental analysis: C 69.33, H 8.51, N 4.03.

2.3.4.2. SP-TEA 3*b*. Prepared by following the procedure described above for **3*a***, starting from SP-Cl **1*b***. The degree of functionalization was determined to be 1.74 mmol TEA/g by elemental analysis: C 71.86, H 8.50, N 2.37.

2.3.4.3. SP-TEA 3*c*. Prepared by following the procedure described above for **3*a***, starting from SP-Cl **1*c***. The degree of functionalization was determined to be 0.90 mmol TEA/g by elemental analysis: C 80.29, H 8.25, N 1.20.

2.3.5. Representative experimental procedure for phenolysis of epoxide 5

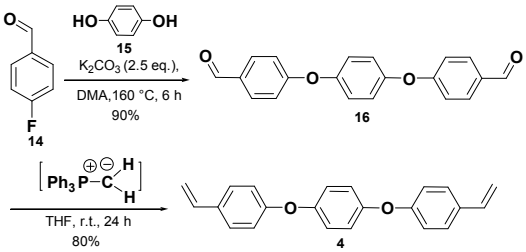
In a screw-capped vial equipped with a magnetic stirrer SP-TBD (2b, 0,021 g, 0.05 mmol, 2.38 mmol/g), phenol (**6**) (0.094 g, 1.0 mmol) and phenyl glycidyl ether (**5**) (0.150 g, 1.0 mmol) were consecutively added and the resulting mixture was left under stirring at 60°C. After 20 h EtOAc (0,5 mL) was added and the reaction mixture filtered. The catalyst was washed using additional 0,5x2 mL of EtOAc. Organic layers were collected and solvent was removed under vacuum to give 0.237 g (97% yield) of 1,3-diphenoxypropan-2-ol (**17**) as a white solid.

3.Results and discussion

3.1. SP-supported catalysts synthesis and characterization

3.1.1. Synthesis of 1,4-bis(4-vinylphenoxy)benzene (4)

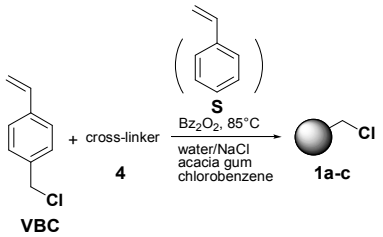
1,4-Bis(4-vinylphenoxy)benzene cross-linker **4** was synthesized as outlined in Scheme 2. The synthesis begins by reacting 4-fluorobenzaldehyde **14** with hydroquinone **15** in the presence of K_2CO_3.[9] The resulting ether-linked dialdehyde 4,4'-[1,4-phenylenebis(oxy)]dibenzaldehyde **16** is subjected to subsequent reaction with methyltriphenyl phosphonium bromide under Wittig conditions to afford the target product in good overall yield (72%).



Scheme 2. Synthetic route for 1,4-bis(4-vinylphenoxy)benzene (**4**)

3.1.2. Synthesis and functionalization of resins 1*a-c*.

Resins **1*a-c*** were prepared by suspension (co)polymerization of 4-vinyl-benzylchloride (VBC) and styrene S, in the presence of 2 mol% of cross-linker **4** (Scheme 3).



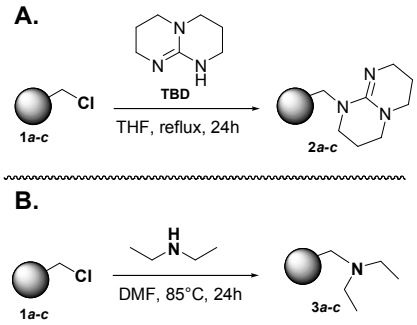
Scheme 3. Synthesis of chloromethylated resins **1*a-c***

The polymerization reactions were performed according to Experimental section. Note that by varying co-monomers' ratio resins with different chlorine loading capacities (L) can be achieved (see Experimental section). In all cases, the polymerization yields were good (~80%, Table 1).

Table 1. Polymers **1*a-c***. Syntheses data

Polymer	VBC (mol%)	S (mol%)	cross-linker (mol%)	yield (%)
1*a*	98	0	2	79
1*b*	54	44	2	78
1*c*	15	83	2	80

Nucleophilic substitution of the chlorine atoms by TBD in THF at reflux temperature (Scheme 3A) successfully furnished base catalysts **2*a-c***. Similarly, SP-TEA catalysts **3*a-c*** were easily prepared by reacting the corresponding SP-Cl resins **1*a-c*** with diethylamine in DMF at 85°C for 24 h (Scheme 3B). Longer reaction times (up to 48 h) did not influence the loading values of SP-TEA catalysts. The microanalytical data (C, H, N) obtained from elemental analysis were used to find out the degree of substitution of **2*a-c***, **3*a-c*** (see Table 2 and Experimental section). The analysis of base content by acid-base tritration[10] confirmed such values, thereby anticipating a good accessibility of the catalytic sites.



Scheme 3. Synthesis of catalysts **2*a-c*** (A.) and **3*a-c*** (B.)

Table 2. Nitrogen content and loading (L) of catalysts **2*a-c*** and **3*a-c***

Catalyst	N (%)	L[a]
2*a*	13.80	3.28 mmol TBD/g
2*b*	10.00	2.38 mmol TBD/g
2*c*	2.96	0.68 mmol TBD/g
3*a*	4.03	2.74 mmol TEA/g
3*b*	2.37	1.74 mmol TEA/g
3*c*	1.20	0.90 mmol TEA/g

[a]Loading calculated by elemental analysis

3.1.3. Structural properties of resins 1*a-c* and catalysts 2*a-c* and 3*a-c*

To gain insight into the structure of SP resins **1*a-c*** and polymer-bound base catalysts **2*a-c*** and **3*a-c***, characterization by physicochemical methods was performed.

3.1.3.1. FTIR spectroscopy. FTIR spectroscopy (Figures 2-3, and Figure S1-S2 in Supplementary Information) demonstrates the successful synthesis of SP-Cl supports **1*a-c*** and their derivatives. As the monomer feeds of styrene in the polymerization reaction progressively increases from SP-Cl **1*b***

This journal is © The Royal Society of Chemistry 20xx

to SP-Cl **1*c***, the intensity of the characteristic peaks of polystyrene at 1493, 1452 and 700 cm^{-1} gradually increases as observed in Figure 2. The TEA and TBD derivatives of SP-Cl **1*a-c*** were successfully obtained and easily characterized by the IR absorption at 1470 cm^{-1} and 1615 cm^{-1} for TEA and TBD derivatives respectively, as exemplified in Figure 3.

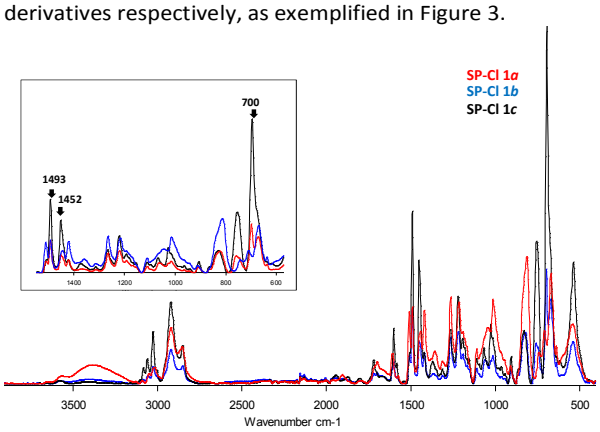


Figure 2. Full FTIR spectra of SP-Cl supports **1*a-c***. The inset shows the expanded spectral region between 600 cm^{-1} and 1500 cm^{-1}.

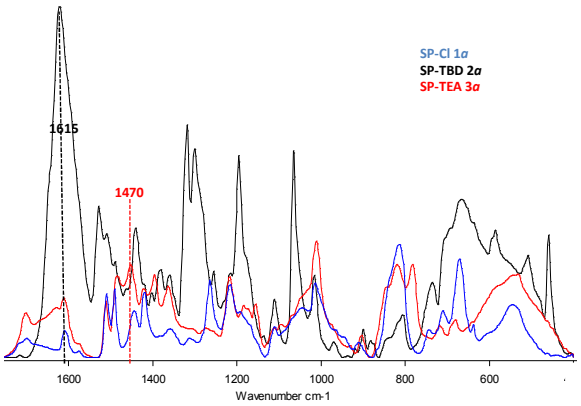


Figure 3. Partial FTIR spectra of SP-Cl **1*a***, SP-TBD **2*a*** and SP-TEA **3*a***

However, with increased mole percentage of styrene in SP-Cl **1*c***, the corresponding 1470 cm^{-1} peak for the TEA derivative was masked by strong absorption at 1452 and 1493 cm^{-1} from polystyrene as shown in Figure S2. In that case, the SP-bound TEA **3*c*** was identified by the absorption peak at 1277 cm^{-1} (Figure S2) relative to the benzyl type C-N stretching.

3.1.3.2. ^{13}C-CP/MAS NMR characterization. Figure 4 presents ^{13}C-CP/MAS NMR spectra of SP-Cl (**1*a-c***). The spectrum of **1*a*** displays three signals in the aromatic region (146, 135 and 128 ppm) as well as five signals in the aliphatic region (72, 68, 64, 46 and 40 ppm). While the resonance at 146 ppm arises from C-9 of VBC and C-10, C-13 and C-14 of the 1,4(4-vinylphenoxy)benzene cross linker, the signals at 135 ppm and 128 ppm can be assigned to C-6 of VBC and all non-substituted aromatic carbons (C-7, C-8, C-11, C-12, C15), respectively.

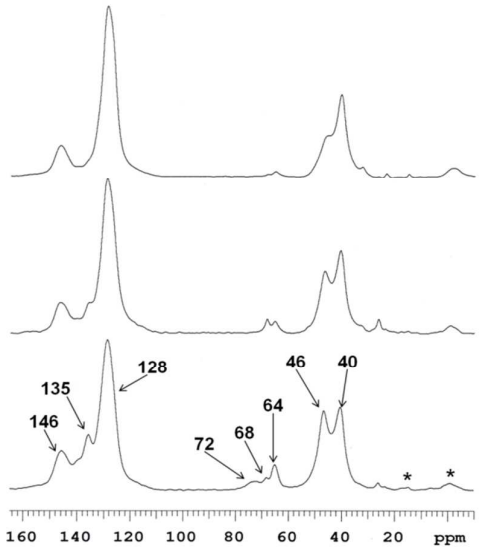


Figure 4. Chemical structure and carbon-numbering scheme (left) and 13C-CP/MAS NMR spectra of SP-Cl **1*a-c*** (right). * indicates spinning side bands.

Table 3. Signal assignment of the ^{13}C resonance signals of SP-Cl

Resonance signal (ppm)	Assignment
40	C-2, C-4
46	C-1, C-3, C-5
128	C-7, C-8, C-11, C-12, C-15
135	C-6
146	C-9, C-10, C-13, C-14

The three resonances at 72, 68 and 64 ppm can be attributed to -CH2-OH methylol groups, originating from the partial hydrolysis of the chloromethylene groups during polymerization. Indeed, since the suspension polymerizations are carried out at elevated temperatures in the presence of an excess of water, it is not surprising that this side reaction occurs[11]. The signal at 46 ppm arises from C-1 of VBC as well as from the C-3 and C-5 tertiary methine carbons of the polymer backbone while the resonance at 40 ppm can be attributed to the backbone C2 and C4 secondary methylene carbons. As compared to the spectrum of **1*a***, the spectra of **1*b*** and **1*c*** show decreasing intensities for the signals at 135 and 46 ppm as well as for the total intensity of the 75-64 ppm region, due to the increasing amount of styrene co-monomer used in the synthesis.

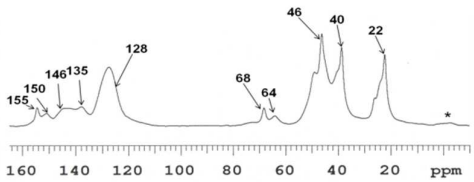


Figure 5. Chemical structure and carbon numbering scheme (left) and ^{13}C-CP/MAS NMR spectrum (right) of TBD functionalized resin **2a**

Table 4. Signal assignment of the ^{13}C resonance signals of SP-TBD

Resonance signal (ppm)	Assignment
22	C-18, C-21
40	C-2, C-4
46	C-1, C-3, C-5, C-17, C-19, C-20, C22
68	C-1^{I}
128	C-7, C-8, C-11, C-12, C-15
135	C-6
146	C-9, C-10, C-13, C-14
150 + 155	C-16

The ^{13}C-CP/MAS NMR spectrum of SP-TBD **2*a*** is shown in Figure 5. The region between 120 and 160 ppm displays five resonances at 155, 150, 146, 135 and 128 ppm (Figure 5 and Table 4). The resonances at 155 and 150 ppm are assigned to the quaternary C16 carbon of the TBD substituent for which the origin of splitting is probably caused by regio-regularity and stereo-regularity (tacticity). The other aromatic signals can be assigned as for compound **1*a***. The aliphatic region shows signals at 68, 64, 48, 46, 40 and 22 ppm. The signal at 68 ppm can be attributed to the methylene C-1^{I} carbon that links the TBD moiety to the resin as well as to the methylol groups of the resin as for **1*a*-*c***. Also the signal at 64 ppm arises from methylol groups as for **1*a*-*c***. The resonances in the 48-46 ppm region are assigned to the secondary carbons bonded to a nitrogen atom of the bicyclic TBD moiety (C-17, C-19, C-20 and C-22) and to the C-1, C-3 and C-5 carbons as described for the supports **1*a*-*c***. The signal at 40 ppm represents the C-2 and C-4 carbons of the backbone as discussed for the supports **1*a*-*c***. Finally, the signals around 24-22 ppm can be attributed to the C-18 and C-21 secondary carbons of the TBD moiety. As compared to the spectrum of **2*a***, the spectra of **2*b*** and **2*c*** (Figure S3) show decreasing intensities for the signals related to the TBD substituent due to the increasing amount of styrene co-monomer (less VBC) used in the synthesis.

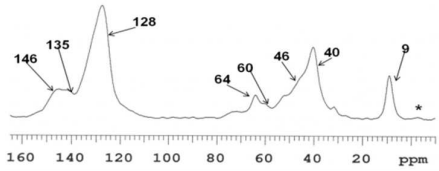


Figure 6. Chemical structure and carbon-numbering scheme (left) and ^{13}C-CP/MAS NMR spectrum (right) of TEA functionalized resin **3a**

Table 5. Signal assignment of the ^{13}C resonance signals of SP-TEA

Resonance signal (ppm)	Assignment
9	C-24
40	C-2, C-4
46	C-1, C-3, C-5, C-23
60	C-1^{II}
128	C-7, C-8, C-11, C-12, C-15
135	C-6
146	C-9, C-10, C-13, C-14

Figure 6 illustrates the ^{13}C-CP/MAS NMR spectrum of SP-TEA **3*a***. The aromatic region shows resonances at 146, 135 and 128 ppm (Figure 6 and Table 5) which can be assigned as for the SP-Cl compounds **1*a*-*c***. In the aliphatic region, the resonances between 72-64 ppm can be attributed to -CH_2-OH methylol groups as also already described for **1*a*-*c***. The resonances of the TEA functional groups appear at 60 ppm for the C-1^{II} methylene carbon that links the TEA moiety to the resin, 46 ppm for the C-23 secondary carbons of the ethyl groups (overlaps with the C-1, C-3 and C-5 carbons) and 9 ppm for the methyl carbons. Finally, the signal at 40 ppm represents the C-2 and C-4 methylene backbone carbons as discussed for the supports **1*a*-*c***. As compared to the spectrum of **3*a***, the spectra of **3*b*** and **3*c*** (Figure S4) show decreasing intensities for the signals related to the TEA substituent due to the increasing amount of styrene co-monomer (less VBC) used in the synthesis.

3.1.4. Surface morphology. Scanning and transmission electron microscopy reveal that SP resins **1*a*-*c*** and their derivatives **2*a*-*c*** and **3*a*-*c*** are spheres with high porosity (Figure 7, Figure S5-S9). Scanning electron microscopy (SEM) images in Figure 7 and Figure S5 show representative surface morphology of the resultant spheres, while additional higher magnification SEM images are available in Figure S6.

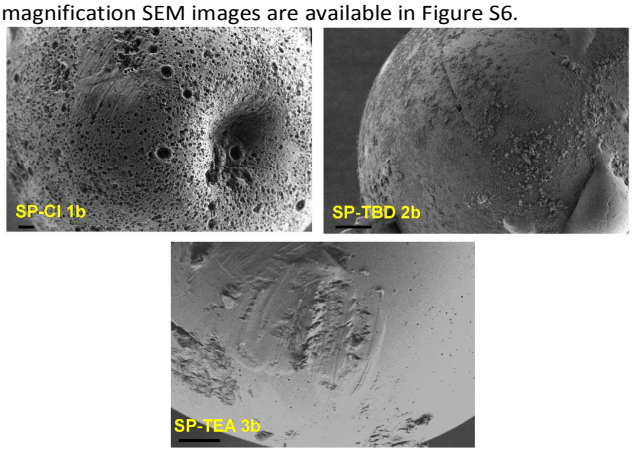


Figure 7. SEM Images of SP-Cl **1b**, SP-TBD **2b**, and SP-TEA **3b** (all scale bars are 20 micron).

Detailed microstructures of the copolymers are made available by examining embedded and microtomed sample thin films with transmission electron microscopy (TEM). Representative lower magnification TEM images are presented in Figure S7 and S8. Higher magnification TEM images in Figure S9 demonstrate that SP-Cl **1*a*** has alternating layered structures with spacing values of about 30-70 nm. Since TEM images reflect the local electron density variations of the corresponding components, this observed ordered structure may be attributed to the different packing density of spacer component and polymer backbone. With increased styrene mole percentage in the matrix (SP-Cl **1*b*** and SP-Cl **1*c***), this alternating layered structure between spacer and backbone becomes significantly swelled. TBD functionalization largely obscures such alternating structures, while this ordered

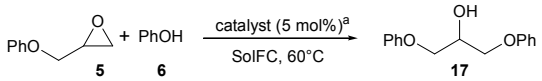
This journal is © The Royal Society of Chemistry 20xx

structure is essentially diminished in copolymer systems after TEA functionalization.

3.2. Catalytic activity

In a model study, the efficiency of catalytic systems **2*a*-*c*** and **3*a*-*c*** was evaluated and compared also to PS-TBD, commercially available, and PS-TEA[8] (2% divinylbenzene cross-linked) in the reaction of phenyl glycidyl ether **5** and phenol **6** (Table 6). We found that SP polymers were highly promising when used under solvent-free conditions (SolFC), thereby pointing out that the spacing between the linear polymeric chains is large enough to enable the reactants to access the active sites easily, without the help of a swelling medium. Indeed, in such conditions, SP-supported TBD catalytic activity rivaled or exceeded that of the PS-supported counterpart, with **2*b*** giving the best results (Table 6, entries 1, 2 and 5 *vs*. 9). The reduction of the efficiency of the highly loaded **2*a*** compared to **2*b*** (Table 6, entries 1 *vs* 2) might be likely due to crowding of the catalytic sites. By using 5 mol% of catalyst **2*b*** in the presence of an organic medium, i.e. acetonitrile and dichloromethane, a significant drop of the catalytic efficiency was observed (Table 6, entries 3 and 4, respectively). Lower catalytic activity of a heterogeneous system it is expected in the presence of a reaction medium (swelling medium) as it has been observed in several other processes.[2] This effect is ascribable to the higher reactivity of both catalyst and reactants under highly concentrated or solvent-free conditions. It is well known[2] that the presence of a medium lowers the reactivity of both catalyst and reagents, in fact for this reason we have been developing catalytic systems for being used under highly concentrated conditions or SolFC.

Table 6. Phenolysis of phenyl glycidyl ether **5** and phenol **6**.

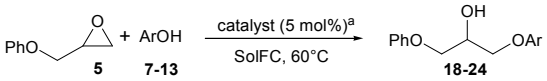


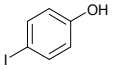
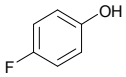
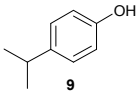
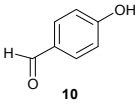
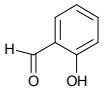
Entry	catalyst	Time (h)	C (%)[b]
1	**2*a***	20	86
2	**2*b***	20	>99[c]
3	**2*b***[d]	20	18
4	**2*b***[e]	20	-
5	**2*c***	20	95
6	**3*a***	20	76
7	**3*b***	20	93[f]
8	**3*c***	20	90
9	PS-TBD	20	88
10	PS-TEA	20	74
11	TBD	20	97
12	TEA	20	96

[a]Referred to the amount of immobilized base moieties. [b]Conversion (C) to 17 determined by GC analyses using 1,4-dimethoxy benzene as internal standard; the remaining material was the equimolar unreacted mixture of 5 and 6. [c]98% of isolated yield of the pure product 17. [d]Reaction conducted in CH3CN (2 mL). [e]Reaction conducted in CH2Cl2 (2 mL). [f]Complete conversion of 5 to 17 was achieved in 30 h.

Not unexpectedly, the reaction mediated by SP-supported TBD **2*a*-*c*** was faster compared to SP-TEA **3*a*-*c*** (Table 6, entries 1, 2 and 5 *vs* 6-8), the active sites of these latter featuring a lower basic strength. However, under SolFC **3*a*-*c*** gave better results than the PS-supported counterpart (Table 6, entries 6-8 *vs* 10).

Table 7. Phenolysis of phenyl glycidyl ether (**5**) catalyzed by 5% mol of SP-catalyst at 60°C under SolFC

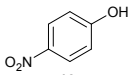
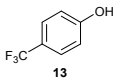


Entry	Phenol	catalyst	Time (h)	C (%)[b]
1	 **7**	**2a**	34	96
2		**2b**	34	>99%
3		**2c**	34	95
4		**3a**	34	90
5		**3b**	34	92
6		**3c**	34	90
7		PS-TBD	34	92
8		PS-TEA	34	80
9	 **8**	**2a**	30	91
10		**2b**	30	>99
11		**2c**	30	96
12		**3a**	30	76
13		**3b**	30	86
14		**3c**	30	86
15		PS-TBD	30	87
16		PS-TEA	30	75
17	 **9**	**2a**	18	86
18		**2b**	18	>99
19		**2c**	18	95
20		**3a**	18	80
21		**3b**	18	93
22		**3c**	18	92
23		PS-TBD	18	91
24		PS-TEA	18	79
25	 **10**	**2a**	80	89
26		**2b**	80	>99
27		**2c**	80	88
28		**3a**	80	78
29		**3b**	80	84
30		**3c**	80	84
31		PS-TBD	80	93
32		PS-TEA	80	81
33	 **11**	**2a**	55	79
34		**2b**	55	96
35		**2c**	55	84
36		**3a**	55	68
37		**3b**	55	81
38		**3b**	55	80
39		PS-TBD	55	18
40		PS-TEA	55	9

(Continued)

Table 7. Phenolysis of phenyl glycidyl ether (**5**) catalyzed by 5% mol of SP-catalyst at 60°C under SolFC

(*Continued*)

Entry	Phenol	catalyst	Time (h)	C (%)[b]
41	 **12**	**2a**	70	72
42		**2b**	70	90
43		**2c**	70	68
44		**3a**	70	76
45		**3b**	70	82
46		**3c**	70	79
47		PS-TBD	70	77
48		PS-TEA	70	61
49	 **13**	**2a**	216	48
50		**2b**	216	52
51		**2b**[c]	216	70
52		**2c**	216	51
53		**3a**	216	35
54		**3b**	216	51
55		**3c**	216	43
56		PS-TBD	216	39
57		PS-TEA	216	32

[a]Referred to the amount of immobilized base moieties. [b]Conversion to **18**-**24** determined by GC analyses, using 1,4-dimethoxy benzene as internal standard; the remaining material was the equimolar unreacted mixture of **5** and **7**-**13**. [c]8mol%

In all cases, no trace of the regioisomer coming from the α-attack of **6** to the epoxide **5** was observed. The results obtained by employing homogeneous TBD and TEA (Table 6, entries 11 and 12) demonstrated that the SP support did not influence either the rate or the selectivity of the reaction.

To broaden the catalysts' scope, other substrates were considered. The most significant data for the reactions of epoxide **5** and phenols bearing electron-donating or electron-withdrawing groups **7-13** are reported in Table 7 and Figures 8-9. At 60°C and by using 5% mol of **2a-c** under SolFC, very good conversions could be achieved and the reactions proceeded giving only the β-products starting from equimolar mixtures of **5** and **7-13**. These results confirmed that SP-supported TBD ***2a-c*** gave better results than SP-TEA ***3a-c***, for which longer reaction times are needed. Further, a similar trend to the model reaction is observed for SP-TBD, with ***2b*** revealing a higher activity. Finally, systems ***2a-c*** and ***3a-c*** again ensured a catalytic efficiency which rivaled or overcame that of the corresponding PS-supported counterparts.

This journal is © The Royal Society of Chemistry 20xx

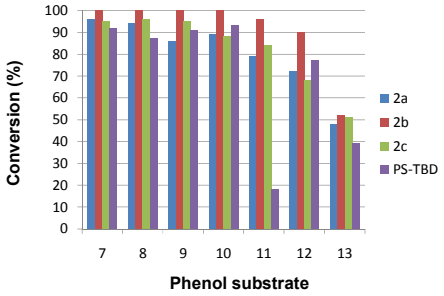


Figure 8. Comparison of the catalytic behavior of **2*a-c*** *versus* PS-TBD in the reaction of **5** with phenols **7-13**

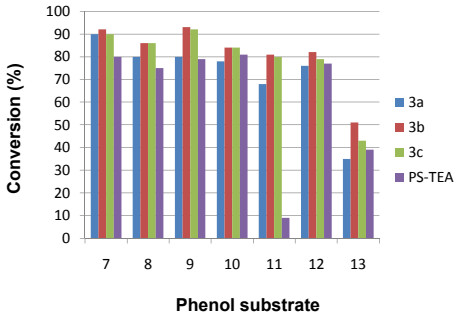


Figure 9. Comparison of the catalytic behavior of **3*a-c*** *versus* PS-TEA in the reaction of **5** with phenols **7-13**

When polymer supported catalysts are employed, an important issue is the decrease of their activity after being recovered.[1] The recovery and reuse of the catalytic systems has been investigated and the results reported for the reaction of epoxide **5** and phenol **6** carried out in the best conditions (Table 6, entry 2). After the reaction was completed, the catalyst used was recovered by filtration. The recovered catalyst **2*b*** was then washed, dried and subsequently re-used. It demonstrated to substantially retain its catalytic activity after three consecutive runs (Table S1, Supplementary Information). Reduced catalytic efficiency is observed after additional reuse in agreement to similar results obtained when commercially available catalyst have been used.[2b-2d]

Conclusions

In conclusion, the synthesis and characterization of a new family of base catalysts immobilized on polystyrene gel-type resins (SPACeR, SP) containing the 1,4-bis(4-vinylphenoxy)benzene cross-linker has been reported. All the systems gave optimal to excellent results in catalyzing the reaction of phenyl glycidyl ether and a range of phenols under solvent free conditions, both in terms of conversion into target products and regioselectivity. These findings point out that the spacing between the linear polymeric chains is large enough to enable the reactants to access the active sites easily, without the help of a swelling medium. Particularly, the catalytic efficiency of SP-supported TBDs generally overcome that of commercially available PS-TBD, thereby revealing themselves highly promising tools.

Acknowledgements

This research has been developed and partially financed within the National project “BIT3G“ – Italian Green Chemistry Cluster. We gratefully acknowledge the Università degli Studi di Perugia for financial support.

Notes and references

1 (a) J.R.H. Ross (Ed), *Heterogeneous Catalysis: Fundamentals and Applications*, Elsevier, Amsterdam, 2012; (b) N. Madhavan, C.W.Jones and M. Weck, *Acc. Chem. Res*. 2008, **41**, 1153-1165; (c) S. Takizawa, M. L. Patil, K. Marubayashi and H. Sasai, *Tetrahedron* 2007, **63**, 6512-6528; (d) C. Baleizao and H. Garcia, *Chem. Rev.* 2006, **106**, 3987-4043; (e) P. Barbaro, *Chem. Eur. J.* 2006, **12**, 5666- 5675; (f) J. M. Notestein and A. Katz, *Chem. Eur. J.* 2006, **12**, 3954-3965.

2 (a) G. Strappaveccia, D. Lanari, D. Gelman, F. Pizzo, O. Rosati, M. Curini and L. Vaccaro, *Green Chem*. 2013, **15**, 199-204; (b) S. Bonollo, D. Lanari, J. M. Longo and L. Vaccaro, *Green Chem.* 2012, **14**, 164-169; (c) D. Lanari, R. Ballini, S. Bonollo, A. Palmieri, F. Pizzo and L. Vaccaro, *Green Chem*. 2011, **13**, 3181–3186. (d) F. Fringuelli, F. Pizzo, C. Vittoriani and L. Vaccaro, *Chem. Commun*. 2004, 2756-2757.

3 R. B. Merrifield, *J. Am. Chem. Soc*. 1963, **85**, 2149-2152.

4 (a) P. H. Toy and K. D. Janda, *Tetrahedron Lett.* 1999, **40**, 6329-6332; (b) P.H. Toy, T. S. Reger, P. Garibay, J. C. Garno, J. A. Malikayil, G. Liu and K. D. Janda, *J. Comb. Chem*. 2001, 3, 117-124.

5 a) I. Vilotijevic and T.F. Jamison, *Angew. Chem*. 2009, **121**, 5352-5385; *Angew. Chem. Int. Ed*. 2009, **48**, 5250-5281; (b) S. C. Bergmeier and D. J. Lapinski, *Progress in Heterocyclic Chemistry* 2009, **21**, 69-93; (c) M. Pineschi, F. Bertolini, V. Di Bussolo and P. Crotti, *Curr. Org. Chem*. 2009, **13**, 290-324.

6 For representative examples see: (a) K. Seth, A. R. Roy, B. V. Pipaliya and A. K. Chakraborti, *Chem. Commun*. 2013, **49**, 5886-5888; (b) A. Zvagulis, S. Bonollo, D. Lanari, F. Pizzo and L. Vaccaro, *Adv. Synth. Catal*. 2010, **352**, 2489-2496; (c) D. Jiang, A. Urakawa, M. Yulikov, M. Mallat, T. Jeschke and A. Baiker, *Chem. Eur. J.* 2009, **15**, 12255-12262; d) J. Barluenga, H. Vazquez-Villa, A. Ballesteros and J. M. Gonzalez, *Org. Lett*. 2002, **4**, 2817-2819.

7 M. Alonzi, M. P. Bracciale, A. Broggi, D. Lanari, A. Marrocchi, M. L. Santarelli and L. Vaccaro, *J. Catal.* 2014, **309**, 260-267.

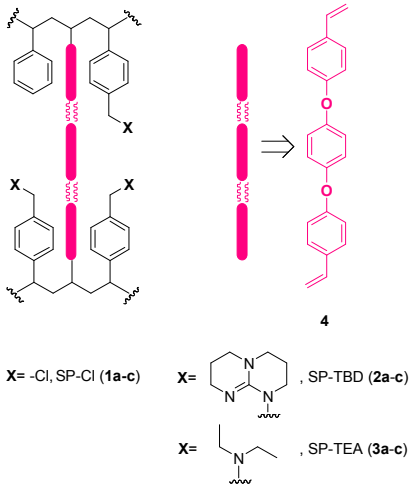
8 C. Petrucci, G. Strappaveccia, F. Giacalone, M. Gruttadauria, F. Pizzo and L. Vaccaro, *ACS Sustainable Chem. Eng*. 2014, **2**, 2813-2819.

9 G.W. Yeager, D. N. Schissel, *Synthesis* 1991, **1**, 63-68

10 K. Iijima, W. Fukuda and M. Tomoi, *J. Macromol. Sci. A*, 1992, **29**, 249-261.

11 (a) U. Wijaya, *IPTEK J. Technol. Sci.* 2007, **18**, 130-136; (b) N. Fontanals, J. Cortés, M. Galià, M.R. Mercè, P.A.G. Cormack, F. Borrull and D.C. Sherrington, *J. Polym. Sci. A Polym. Chem.* 2005, **43**, 1718-1728; (c) S. Subramonian, *React. Funct. Polym*. 1996, **29**, 129-133; (d) R.V. Law, D.C. Sherrington, C.E. Snape, I. Ando and H. Kurosu, *Macromolecules* 1996, **29**, 6284-6293.

Synthesis, characterization and catalytic activity of novel large network polystyrene-immobilized organic bases

Marco Tassi,[1] Elena Bartollini,[2] Peter Adriaensens,*[1] Luca Bianchi,[2] Balaka Barkakati,[3] Robert Carleer,[1] Jihua Chen,[3] Dale K. Hensley,[3] Assunta Marrocchi,*[2] and Luigi Vaccaro*[2]

[1]Hasselt University - Applied and Analytical Chemistry, Agoralaan-Building D, Belgium BE-3590 Diepenbeek
[2]Laboratory of Green Synthetic Organic Chemistry, CEMIN – Dipartimento di Chimica, Biologia e Biotecnologie, Università di Perugia Via Elce di Sotto, 8, 06123 Perugia, Italy
[3]Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA