ChemComm

RSC Publishing

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2013, **49**, 7325

Received 19th April 2013,
Accepted 22nd June 2013

DOI: 10.1039/c3cc42925c

www.rsc.org/chemcomm

Inverse electron demand Diels–Alder (iEDDA) functionalisation of macroporous poly(dicyclopentadiene) foams†

Astrid-Caroline Knall,* Sebastijan Kovačič, Manuel Hollauf, David Reishofer, Robert Saf and Christian Slugovc*

Inverse electron demand Diels–Alder reactions performed on the double bonds in open cellular macroporous poly(dicyclopentadiene) monoliths yield a high degree of functionalisation (up to 2 mmol pyridazines per g or 8 mmol N per g) with grafted di(pyridyl)-pyridazines in a single step.

Curing of monomers constituting the minority phase of a stabilised High Internal Phase Emulsion (HIPE) is a frequently used method to prepare macroporous polymeric foams characterised by a microcellular structure which is desirably interconnected with smaller pores.[1] Such foams find manifold applications in such diverse fields as tissue engineering,[2] water purification[3] or as separator membranes in lithium-ion batteries.[4] Common prerequisites for most applications are good mechanical properties and easy methods to post-functionalise the foams.[5]

A particularly promising class of HIPE templated foam is made of dicyclopentadiene (DCPD) *via* Ring-Opening Metathesis Polymerisation (ROMP).[6] These self-crosslinked poly-(dicyclopentadiene) (pDCPD) foams combine an interconnected microcellular open porous structure with the highest mechanical resilience reported amongst HIPE templated materials.[6,7] Furthermore, pDCPD bears a high degree of unsaturation (as a consequence of the metathesis polymerisation) offering ways for further functionalisation (*e.g.* epoxidation[8] or bromination[9] followed by conversion with nucleophiles or radical initiated thiol–ene chemistry[10]). Accordingly, pDCPD foams ideally fulfil the prerequisites for the preparation of highly functionalised porous materials.

Herein we disclose a straightforward and versatile single-step method for the post-functionalisation of pDCPD foams *via* the inverse electron demand Diels–Alder (iEDDA) reaction of tetrazines with the residual double bonds in the foam skeleton, which is one of the first reports on using this promising conjugation scheme in materials science.[11] The iEDDA reaction of tetrazines and olefins has emerged as a high potential click chemistry scheme in life- and materials sciences in the last few years.[12] In these applications mostly highly strained olefins such as *trans*-cyclooctenes or norbornenes and hydrolytically stable, yet less reactive, tetrazine species are used for conjugation purposes.[13] However, using more reactive dienes or applying higher reaction temperatures[14] allows conversion of less reactive dienophiles[15] such as double bonds with a large degree of steric hindrance. For example, the iEDDA reaction has been used for the synthesis of pyridazine-based ligands[16] which were used, amongst other applications in organometallic chemistry, as building blocks in metal–organic frameworks.[17]

A pDCPD monolith with 80% porosity was prepared according to a previously developed procedure.[10] To ensure that no oligomeric DCPD units or surfactant molecules remain entrapped in the pDCPD framework, the foams were purified using sequential Soxleth extractions in dichloromethane, THF and acetone (24 h each) and dried *in vacuo*. For the immobilisation of pyridazines using iEDDA chemistry, pieces of this monolith were immersed in scintillation vials containing 0.5 and 0.1 equiv. (with respect to repeating units) of **pyTz** (3,6-di(pyridin-2-yl)-1,2,4,5-tetrazine, Fig. 1) in THF or MeOH, respectively, for 48 h. The monoliths, which were initially white, exhibited a yellow colour while the supernatant remained virtually colourless.

While the experiments in THF were completed after this time (as indicated by the discolouration of the initially pink tetrazine solution), the reactions in MeOH could not be brought to completion, even after 9 d, which is due to the more pronounced swelling of pDCPD[18] in THF in comparison to MeOH. This facilitates diffusion of **pyTz** into the swollen pDCPD scaffold making more double bonds accessible in THF in spite of a higher reaction rate expected for MeOH.[12,19]

Then, the samples were purified by immersion in acetone and, after drying *in vacuo*, subsequently subjected to elemental analysis to determine the nitrogen content of the modified samples. Due to the high degree of unsaturation and their large surface area, pDCPD foams are known to be rapidly oxidised when stored under ambient conditions.[8] Fully oxidised pDCPD

Institute for Chemistry and Technology of Materials, Stremayrgasse 9/5, A-8010 Graz, Austria. E-mail: a.knall@TUGraz.at, slugovc@TUGraz.at; Fax: +43 316 873 1032284; Tel: +43 316 873 32284

† Electronic supplementary information (ESI) available: Experimental procedures, NMR spectra of conversion products of **pyTz** and norbornadiene, cyclopentene or hexene, respectively, FTIR, elemental analysis data, additional SEM micrographs, EDX, porosity and synthesis of the europium reference compound. See DOI: 10.1039/c3cc42925c

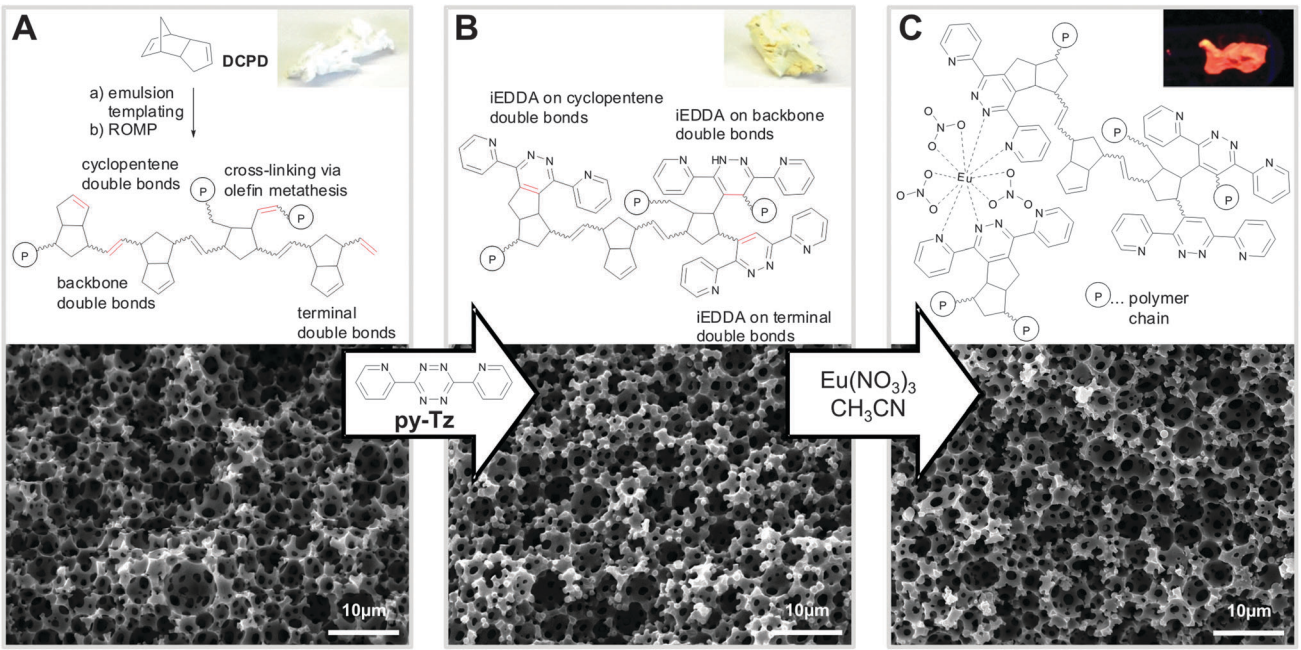

Fig. 1 Representative chemical structures, SEM micrographs and photographs of (A) pDCPD foam, (B) after modification with 0.5 equiv. of **pyTz** (3,6-di(pyridin-2-yl)-1,2,4,5-tetrazine) and (C) after impregnation with $Eu(NO_3)_3$ (photograph taken under UV light (λ = 365 nm)).

has an oxygen content of about 36%.[10] This was also inevitable during the purification procedure and the time allowed between sample preparation and elemental analysis. Therefore, varying oxygen contents were observed for our samples (ESI†). In Fig. 2, the pyridazine contents of reactively modified foams (calculated from elemental analysis) are compared with the respective theoretically expected ones. For samples immersed in THF, values close to the theoretical compositions (2.2 mmol grafted pyridazines per g monolith *vs.* 2.1 calculated) were observed which correspond to a value of 8.8 mmol g^{-1} nitrogen. Raising the reaction temperature to 60 °C resulted in shorter conversion times (3 h) while the same composition was obtained. In methanol, only a fraction of the applied tetrazine amount (0.37 mmol g^{-1} *vs.* 2.1 calculated) was grafted.

About 1–2 mmol of functional units per gram of the polymeric scaffold are typical for similar, commercially available systems,[20,21] such as (bipyridyl)-functionalised polystyrene, which is obtained from polystyrene in a three-step postmodification approach (with approximately every 8th or 9th repeating unit being derivatised).[22] Following our post-modification approach, we were able to derivatise every second repeating unit in the pDCPD network, or, in other words, every 4th double bond in a single step under mild conditions.

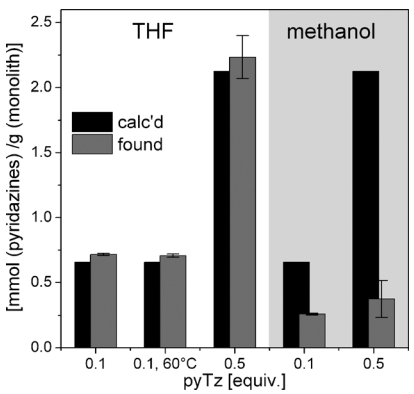

Fig. 2 Di(pyridyl)pyridazine content of modified monoliths.

The morphology of the pDCPD foam before and after functionalisation was found to be broadly similar according to evaluation of the scanning electron micrographs of representative samples (*cf.* Fig. 1). Mercury porosimetry and helium pycnometry revealed a somewhat higher porosity for the monolith functionalised in THF (85 ± 1%) compared to the unmodified specimens (80 ± 1%) and the sample functionalised in methanol (70 ± 1%). An increase in skeletal density from 1.20 g cm^{-3} (initial sample) to 1.52 g cm^{-3} (MeOH) and 1.75 g cm^{-3} (THF) reflected the increasing loading with pyridazines.

To confirm the presence of pyridazine moieties in the foams a model reaction was elaborated. Soluble low molecular weight oligo-DCPD (n = about 10) was prepared using a 1st generation Grubbs initiator at 0 °C and subsequently reacted with **pyTz**. The reaction was followed by ^{1}H NMR spectroscopy (Fig. 3) which revealed complete consumption of **pyTz** after 24 h at room temperature. Furthermore, no characteristic dihydropyridazine signals (which should appear at 9–9.5 ppm) were found, and characteristic signals of the respective polymer-grafted pyridazine products peaking up at 7.1, 7.4, 7.5 and 8.5 ppm confirmed conversion of **pyTz**. Indeed, in a model experiment using **pyTz** and cyclopentene we also observed fast oxidation of the intermediate dihydropyridazine product without additional oxidants and found similar chemical shifts for the corresponding pyridazine (ESI†). The sharp peaks found in the NMR spectrum of fully converted oligo-DCPD (Fig. 3C) can be attributed to terminal vinyl groups transformed in an iEDDA reaction, which was confirmed by comparison with the iEDDA

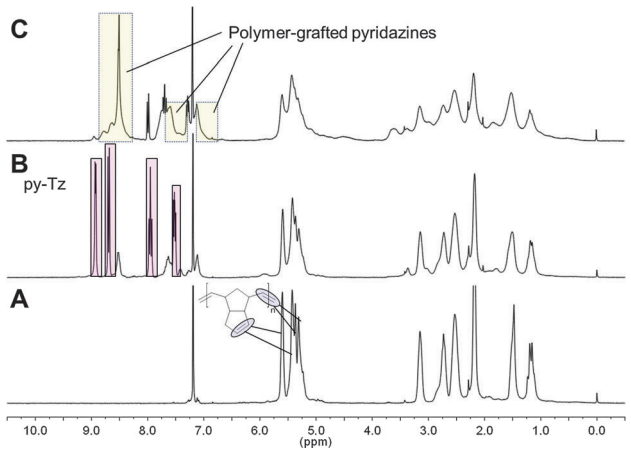

Fig. 3 ^{1}H-NMR spectra of oligo-DCPD in $CDCl_3$ (A) before, (B) 1 h and (C) 24 h after addition of **pyTz** (0.5 equiv., rt).

pyridazine product of **pyTz** and 1-hexene (ESI†). This ''self-oxidation'' of dihydropyridazines has been reported for terminal olefins,[15] styrene[19] and cyclopentene.[23] No pronounced preference for any type of olefinic double bond (internal, strained or terminal) was observed.

FT-IR spectra of oligo-DCPD treated with **pyTz** (ESI†) showed new signals in the range of 1400 to 1600 cm^{-1} (ring stretching vibrations of 2-monosubstituted pyridines) while the absence of N–H stretching vibration of dihydropyridazines at about 3400 cm^{-1} confirmed that the grafted heterocycles were present in their oxidised (pyridazine) form.

Finally, to visualise the grafted dipyridyl(pyridazine) units and to show their principal accessibility, we selected europium(III) nitrate due to the bright red long-lived emission of Eu^{3+} which can be sensitised by so-called ''antenna ligands''. This has also been demonstrated for pyridyl(triazine) europium(III) coordination compounds[24] and similar reactions were performed on an ORMOSIL monolith bearing β-diketonates and malonamides.[25] Therefore, we impregnated a piece of our pyridazinyl-bearing monolith in acetonitrile containing $Eu(NO_3)_3(H_2O)_5$ (1.2 equiv. with respect to grafted **pyTz** groups). A colour change of the monolith to a darker shade was noticed only after a few seconds and after 10 minutes, characteristic red europium emission was observed under UV light (λ = 365 nm, Fig. 1C). 3,6-Di(pyridin-2-yl)-pyridazine was reacted with $Eu(NO_3)_3$ (1 equiv.) in acetonitrile to give a red-emitting model compound which was identified as bis(3,6-di(pyridin-2-yl)pyridazine)europium(III) nitrate by MALDI-TOF-MS (ESI†) suggesting a similar stoichiometry when polymer-grafted pyridazines are used as ligands. EDX measurements of a cross-section (ESI†) proved an even distribution of Eu^{3+} over the surface of monoliths with an Eu content of 0.3 atom%, which can be translated into every 10th pyridazine (or every 5th pyridazine if two ligands are forming the complex) coordinating to europium while the characteristic open porous morphology is still maintained.

In conclusion, pDCPD was shown, because of its high degree of unsaturation, to have inherent reactivity in iEDDA reactions which allows facile functionalisation in a single reaction step (with nitrogen being released as the only byproduct) while involving mild reaction conditions and maintaining the characteristic open-porous morphology of emulsion-templated pDCPD foams. A high loading of up to 2 mmol g^{-1} of di(pyridyl)pyridazines (8 mmol g^{-1} of nitrogen) could be achieved. Thereby, a modular way of introducing functionalities on porous materials with a high degree of functionalisation (50% with respect to repeating units) has been disclosed and can be further exploited using other tetrazine derivatives.

Financial support from the Austrian Science Fund (FWF): [T 578-N19] is gratefully acknowledged. Karel Jerabek is thanked for mercury and helium porosimetry measurements.

Notes and references

1 (*a*) I. Pulko and P. Krajnc, *Macromol. Rapid Commun.*, 2012, **33**, 1731; (*b*) N. R. Cameron, P. Krajnc and M. S. Silverstein, Colloidal Templating, in *Porous Polymers*, ed. M. S. Silverstein, N. R. Cameron and M. A. Hillmyer, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2011.
2 (*a*) W. Busby, N. R. Cameron and C. A. B. Jahoda, *Biomacromolecules*, 2001, **2**, 154; (*b*) M. W. Hayman, K. H. Smith, N. R. Cameron and S. A. Przyborski, *J. Biochem. Biophys. Methods*, 2005, **62**, 231; (*c*) M. De Colli, M. Massimi, A. Barbetta, B. L. Di Rosario, S. Nardecchia, L. Conti Devirgiliis and M. Dentini, *Biomed. Mater.*, 2012, **7**, 055005; (*d*) P. Viswanathan, S. Chirasatitsin, K. Ngamkham, A. J. Engler and G. Battaglia, *J. Am. Chem. Soc.*, 2012, **134**, 20103.
3 I. Pulko, M. Kolar and P. Krajnc, *Sci. Total Environ.*, 2007, **386**, 114.
4 S. Kovačič, H. Kren, P. Krajnc, S. Koller and C. Slugovc, *Macromol. Rapid Commun.*, 2013, **34**, 581.
5 (*a*) L. Kircher, P. Theato and N. R. Cameron, *Polymer*, 2013, **54**, 1755; (*b*) L. Kircher, P. Theato and N. R. Cameron, Functionalisation of porous polymers from high-internal-phase emulsions and their applications, in *Functional polymers by post-polymerisation modification: concepts, practical guidelines and applications*, ed. P. Theato and H.-A. Klok, Wiley-VCH, Weinheim, D, 2012; (*c*) L. Moine, H. Deleuze and B. Maillard, *Tetrahedron Lett.*, 2003, **44**, 7813.
6 S. Kovačič, K. Jeřabek, P. Krajnc and C. Slugovc, *Polym. Chem.*, 2012, **3**, 325.
7 S. Kovačič, N. B. Matsko, K. Jeřabek, P. Krajnc and C. Slugovc, *J. Mater. Chem. A*, 2013, **1**, 487.
8 M. Perring, T. R. Long and N. B. Bowden, *J. Mater. Chem.*, 2010, **20**, 8679.
9 M. Perring and N. B. Bowden, *Langmuir*, 2008, **24**, 10480.
10 S. Kovačič, P. Krajnc and C. Slugovc, *Chem. Commun.*, 2010, **46**, 7504.
11 (*a*) C. Chen, C. A. Allen and S. M. Cohen, *Inorg. Chem.*, 2011, **50**, 10534; (*b*) H. Hayden, Y. K. Gun'ko and T. S. Perova, *Chem. Phys. Lett.*, 2007, **435**, 84.
12 A.-C. Knall and C. Slugovc, *Chem. Soc. Rev.*, 2013, **42**, 5131.
13 N. K. Devaraj and R. Weissleder, *Acc. Chem. Res.*, 2011, **44**, 816.
14 F. Thebault, A. J. Blake, C. Wilson, N. R. Champness and M. Schröder, *New J. Chem.*, 2006, **30**, 1498.
15 A. Niederwieser, A.-K. Späte, L. D. Nguyen, C. Jüngst, W. Reutter and V. Wittmann, *Angew. Chem., Int. Ed.*, 2013, **52**, 4265.
16 G. Cooke, G. M. Ó Máille, R. Quesada, L. Wang, S. Varughese and S. M. Draper, *Dalton Trans.*, 2011, **40**, 8206.
17 R. Hoogenboom, G. Kickelbick and U. S. Schubert, *Eur. J. Org. Chem.*, 2003, 4887.
18 T. R. Long, A. Gupta, A. Lee Miller, D. G. Rethwisch and N. B. Bowden, *J. Mater. Chem.*, 2011, **21**, 14265.
19 J. W. Wijnen, S. Zavarise, J. B. F. N. Engberts and M. Charton, *J. Org. Chem.*, 1996, **61**, 2001.
20 J. Lu and P. H. Toy, *Chem. Rev.*, 2009, **109**, 815.
21 A. Mendonca, *Metal Scavengers*, in *The Power of Functional Resins in Organic Synthesis*, ed. J. Tulla-Puche and F. Albericio, Wiley-VCH, Weinheim, D, 2008, pp. 227–243.
22 R. J. Card and D. C. Neckers, *Inorg. Chem.*, 1978, **17**, 2345.
23 M. Avram, I. G. Dinulescu, E. Marica and C. D. Nenitzescu, *Chem. Ber.*, 1962, **95**, 2248.
24 G. Katsagounos, E. Stathatos, N. B. Arabatzis, A. D. Keramidas and P. Lianos, *J. Lumin.*, 2011, **131**, 1776.
25 N. Brun, B. Julián-López, P. Hesemann, G. Laurent, H. Deleuze, C. Sanchez, M.-F. Achard and R. Backov, *Chem. Mater.*, 2008, **20**, 7117.