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Communication

Fabrication of Nanopatterned Polymeric Microparticles using a Diatom as a Sacrificial Template

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Natural structures with complex hierarchical architecture are employed as biotemplates to fabricate constructs with both nano- and micro-scale features. Diatoms have served as templates for the preparation of inorganic constructs, but are under-explored for the preparation of organic constructs. Herein, we report a method to fabricate nanopatterned polymeric microparticles using the diatom as a sacrificial template.

Introduction

Material scientists have derived inspiration from nature in the design of hierarchical structures. Indeed, several distinct disciplines of bio-inspired research have emerged including biomimetics and bio-replication.^{1,2} The former exploits principles found in nature for the design of materials. The latter involves the use of a biological system as a template for replication. The diatom, a unicellular algae with a hallmark intricate siliceous cell wall, has provided motivation in both these themes of bio-inspired research. The sophisticated architecture of the cell walls, termed frustules, has drawn attention from many disciplines with a range of proposed applications including; catalysis³, separation science⁴, optics⁵, and drug delivery⁶. The identification of key proteins involved in the biomineralization processes underlying the formation of the elaborate diatom cell walls⁷⁻¹⁰ opened the door to exploration of biomimetic *in vitro* preparation of silica

structures¹¹⁻¹³ and more recently titania structures^{14,15}. Harnessing the full potential of the frustule architecture has led to exploration of replication strategies either through chemical conversion of the siliceous frustule into an alternative inorganic material¹⁶⁻¹⁹, or through bio-replication to inorganic replicas using the core material as a template.²⁰⁻²² Only a few studies have reported on the preparation of polymeric constructs employing the diatom as a biotemplate²³⁻²⁵. Gaddis *et al.* described the generation of epoxy replicas of the pennate diatom *Aulacoseira*.²³ In order to retain the features in the replica at the mesoscale, dilute epoxy solutions were used in the solution coating process. The work of Holmes *et al.* yielded negative replicas of diatomaceous earth composed of carbon without retention of the gross morphological features that are the hallmark of the diatom.²⁴ Attempts to replicate the structure employed immersion of the diatom in a polymer solution with subsequent polymerization or cross-linking and final dissolution of the silica core. Layer-by-layer (LbL) strategies to coat the diatom surface have been reported^{26,27}, but this approach has not been employed to create a free-standing structure. We report the preparation of a polyacrylic acid/polyallylamine hydrochloride (PAA/PAH) microparticle *via* LbL assembly using the diatom *Thalassiosira weissflogii* as a biotemplate. Figure 1 illustrates schematically the preparation of the PAA/PAH 3-bilayer system.

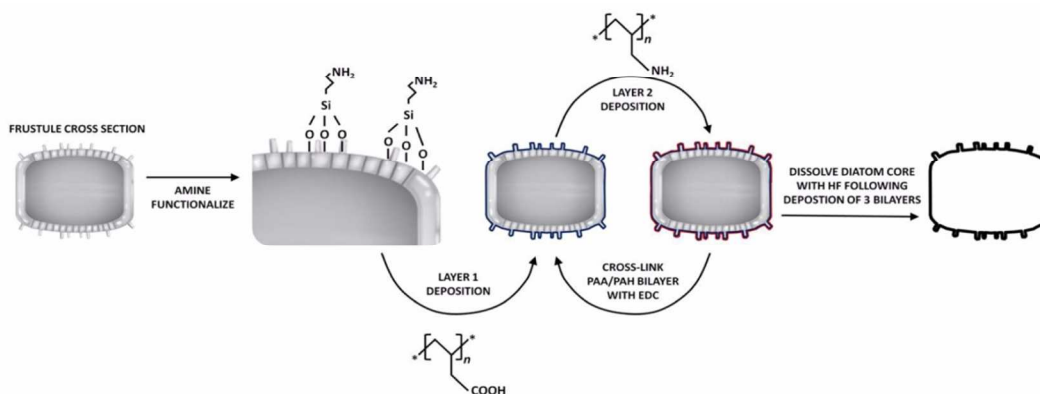


Fig. 1 – Amine groups are introduced on to the surface of the diatom *via* silanization with 3-aminopropyltriethoxysilane. Sequential deposition of polyacrylic acid and polyallylamine hydrochloride layers is performed to yield a three bilayer system. Hydrofluoric acid (HF) dissolution of the diatom core yields a free-standing nanopatterned polymeric microparticle.

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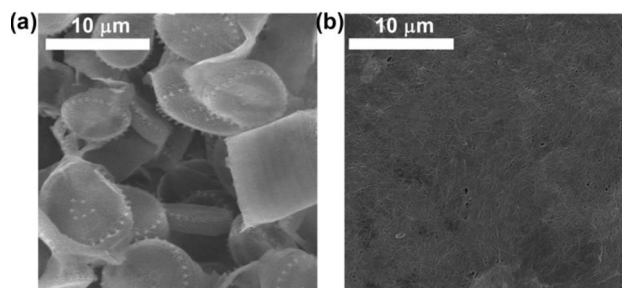


Fig. 2 – (a) SEM micrograph of *Thalassiosira weissflogii*, a centric diatom with a characteristic ring of horns decorating both the centre and periphery of the diatom face. (b) SEM micrograph of *T. weissflogii* following hydrofluoric acid dissolution of the siliceous cell wall revealing fibres embedded within the frustule.

Experimental

T. weissflogii culture maintenance and harvest protocol

T. weissflogii cultures were grown in enriched artificial seawater for 192 hours at a 14 hour:10 hour light:dark cycle, light intensity of 3000 lux, and temperature range of 16–22°C. Cultures were supplemented with sodium metasilicate nonhydrate at a final concentration of 200 µM at time of inoculation and at 48 hour intervals until cultures were harvested. The organic casing of the diatom was removed by successive washes with 50:50 HCl:de-ionised water, de-ionised water, and methanol. Briefly, diatoms were suspended in 50:50 HCl:de-ionised water for 20 minutes. Samples were then centrifuged at 2500 g for 20 minutes. The pellet was resuspended in 50:50 HCl:de-ionised water. Three HCl wash cycles were performed. This was followed by three washes in de-ionised water. The final cleaning step involved a minimum of three washes in methanol until the pellet appeared white in colour. The dry weight of cleaned frustules was measured following heating at 60°C for 48 hours.

Amine-functionalization of *T. weissflogii*

Cleaned *T. weissflogii* frustules were washed three times with 50 mM phosphate buffer containing 0.5% (w/v) sodium azide. Chitinase was added to the cleaned frustules at a ratio of 3.75 x 10⁻³ units enzyme:1 mg dry weight *T. weissflogii*, and incubated at 37°C for 72 hours. Samples were washed three times in de-ionised water to remove excess chitinase and degraded chitin. Silanization of cleaned *T. weissflogii* post chitinase treatment was performed by incubation with aminopropyltriethoxysilane (APTES) at a ratio of 1:7.5 in an ethanolic solution containing 1% ammonium hydroxide for 24 hours at room temperature. The solution was washed three times with ethanol and centrifuged at 2500 g for 20 minutes. Amine-functionalization was confirmed by fourier transform infra-red spectroscopy (FTIR), and by measurement of the zeta potential pre- and post-functionalization.

Fabrication of PAA/PAH microparticle via layer-by-layer assembly on amine-functionalized *T. weissflogii*

Amine-functionalized *T. weissflogii* was washed three times with 0.7 M NaCl and re-suspended in PAA in 0.7 M NaCl at a weight ratio of 1:1. The solution was mixed for six hours at room temperature. Excess PAA was removed by three washes in 0.7 M NaCl. PAA-coated *T. weissflogii* was re-suspended in PAH (MW 17000) in 0.7 M NaCl at a weight ratio of 1:1. The solution was mixed for six hours at room temperature. Excess PAH was removed by three washes in 0.7 M NaCl. Cross-linking of the PAA/PAH bilayer was achieved by 12 hour incubation with 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC) in de-ionised water at a weight ratio of 5:1. Excess EDC was removed by three washes in de-ionised water. This process was repeated to build up a three-bilayer system. PAA and PAH deposition was monitored by measuring zeta potential after the deposition of each layer. Dissolution of *T. weissflogii* was achieved by treatment with 1 M HF for 20 minutes. The pellet was washed six times with de-ionised water. Samples were examined both pre- and post-dissolution by energy-dispersive x-ray spectroscopy coupled to a scanning electron microscope (EDX-SEM). EDX-SEM analysis was performed using Hitachi S-4700 SEM with INCA[®] software. TEM images of frustules were collected using Hitachi H-7500 TEM with AMT image capture software. FTIR spectra were collected using a Shimadzu FTIR-8300 in transmittance mode at a resolution of 4cm⁻¹. Twenty scans were collected per sample and data processed using Shimadzu IR[™] solution software. The zeta potential was collected from a minimum of ten runs per sample, suspended in water, using Malvern Instruments Zetasizer NanoZS90 (software ver.6.34).

Results and Discussion

A critical step for the success of LbL assembly is the deposition of the first PAA layer, which in turn is dependent on the success of cleaning the *T. weissflogii* frustule for subsequent amine functionalization. Contaminants such as extraneous proteins or polysaccharides on the frustule compromise successful coating of the surface and ultimately affect the fidelity of retention of the characteristic architectural features. The organic casing of the diatom was removed from the frustule by successive washes in HCl (50% v/v in de-ionized water), de-ionized water, and methanol. Residual organic matter was enzymatically degraded by treatment with chitinase. SEM images of chitinase-treated cleaned *T. weissflogii* reveal the characteristic protrusions, known as fuloportulae, on the valve face (Fig. 2a). The external valve face is also decorated with openings and rib-like structures. The cleaned frustule is composed of SiO₂ that is dissolved by HF treatment to reveal fibres that are embedded in the frustule (Fig.2b). These fibres were considered to be chitin, as the chitin synthase gene has been identified in *T. weissflogii* and it is known to produce chitin²⁸.

Irrespective of the chemical composition of the fibres embedded within the frustule, it was important to recognise the presence of such structures so as to avoid confusing these fibres with polymeric material following dissolution of the diatom core.

Surface modification of cleaned frustules was achieved by silanization with APTES. This approach has been reported previously for the modification of cleaned diatoms^{26,30,31}, and is a strategy routinely employed to functionalise silica particles for assembly of a polyelectrolyte bilayer³²⁻³⁴. Surface Si-OH groups present in *T. weissflogii* show an FTIR absorption peak between 3400-3200 cm⁻¹ (Fig. 3a). Primary amines have two characteristic FTIR bands between 3600-3100 cm⁻¹ as observed in amine-functionalized *T. weissflogii*. Silanization of *T. weissflogii* with APTES was also confirmed by a net change of 10.2 ± 0.9 mV in zeta potential (Fig. 3b).

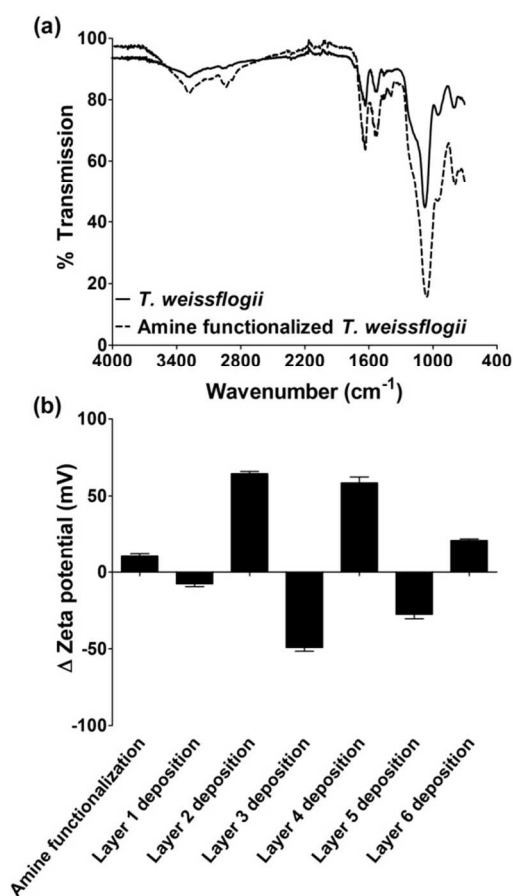


Fig. 3 - (a) FTIR spectra of *T. weissflogii* and amine-functionalized *T. weissflogii*. (b) Δ Zeta potential following amine-functionalization of *T. weissflogii* and sequential deposition of alternating PAA and PAH layers on the surface of amine-functionalized *T. weissflogii*.

Sequential deposition of three PAA/PAH bilayers was monitored by the change in zeta potential following the deposition of each layer (Fig. 3b). Deposition of the initial PAA layer generated a net change in zeta potential of -7.8 ± 0.6 mV. Deposition of PAH led to a net change of 64.7 ± 0.6 mV. Subsequent layers showed a similar profile of a more negative charge following PAA and less negative following PAH. LbL build-up has typically been reported on planar and spherical systems. Surfaces with hierarchical features pose a challenge to the success of individual

layer coating. The absence of complete charge reversal following deposition of layer five and layer six in this study, is indicative that complete surface coating was not achieved, or that preferential coating of certain regions on the frustule surface may have occurred. The deposition of three PAA/PAH bilayers resulted in a coating on the valve face visible by SEM analysis (Fig. 4a). The characteristic fultoportulae were visible at the centre of the valve, as were the rib-like features. The valleys interspersed between the ribs were coated concealing the pore openings on the valve face. Alteration to the morphology of a particle surface following deposition of polyelectrolyte layers has been observed previously and has been attributed to the stacking of the oppositely charged components³⁴. It is possible that during the deposition of the layers the pores became filled with the polyelectrolyte and were concealed. The flattened appearance of the ribs on the surface of the frustule following deposition of the three PAA/PAH bilayers is suggestive of the polyelectrolytes coating the surface. However, a comparison of the rib width pre- and post-layer build up did not show statistical significance (Fig. 4b). It is possible that the thickness of the coating is less than that which is quantifiable by analysis of SEM micrographs.

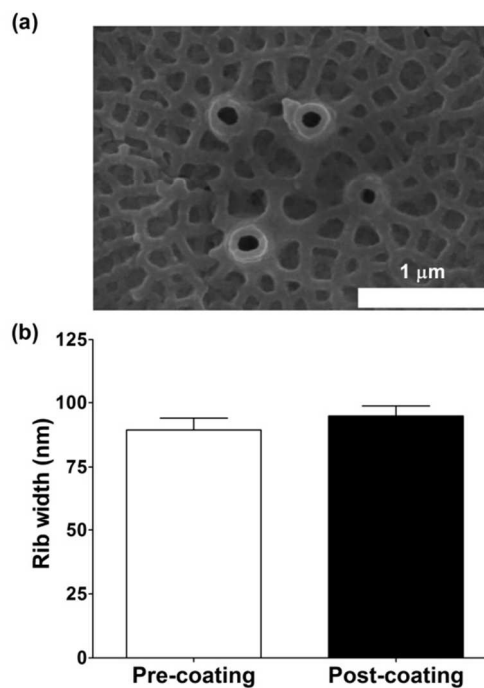


Fig. 4 - (a) SEM micrographs illustrating the valve face of amine-functionalized *T. weissflogii* following deposition of three PAA/PAH bilayers. (b) The rib width of PAA/PAH coated *T. weissflogii* is similar to uncoated *T. weissflogii*. Data are shown as mean ± sem (n =10-12). No statistical difference between groups was seen by *t*-test.

EDX analysis confirmed a silica signal in the amine-functionalized *T. weissflogii* (Fig. 5a). HF treatment resulted in the complete removal of the *T. weissflogii* core confirmed by the absence of silica signal in the EDX-SEM spectrum (Fig. 5b). The characteristic rib-like features on the valve face (Fig. 5c) and the protrusions on the periphery of the valve face (Fig. 5d) are retained. The polymeric microparticle is a hollow structure as revealed by both SEM and TEM analysis where the internal void space is visible (Fig. 5e-f). Interestingly, fibres akin to those embedded in the frustule were present post HF treatment,

confirming dissolution of siliceous frustule (Fig. 5e).

Conclusions

A free-standing polyelectrolyte microstructure that retains the characteristic nanoscale architectural features was successfully
5 fabricated using a siliceous diatom as a core material. The broad

range of both PEs and diatoms available allows for tailoring of both the chemistry and architecture of such microstructures. These microstructures have potential uses in the field of drug delivery and biosensing.

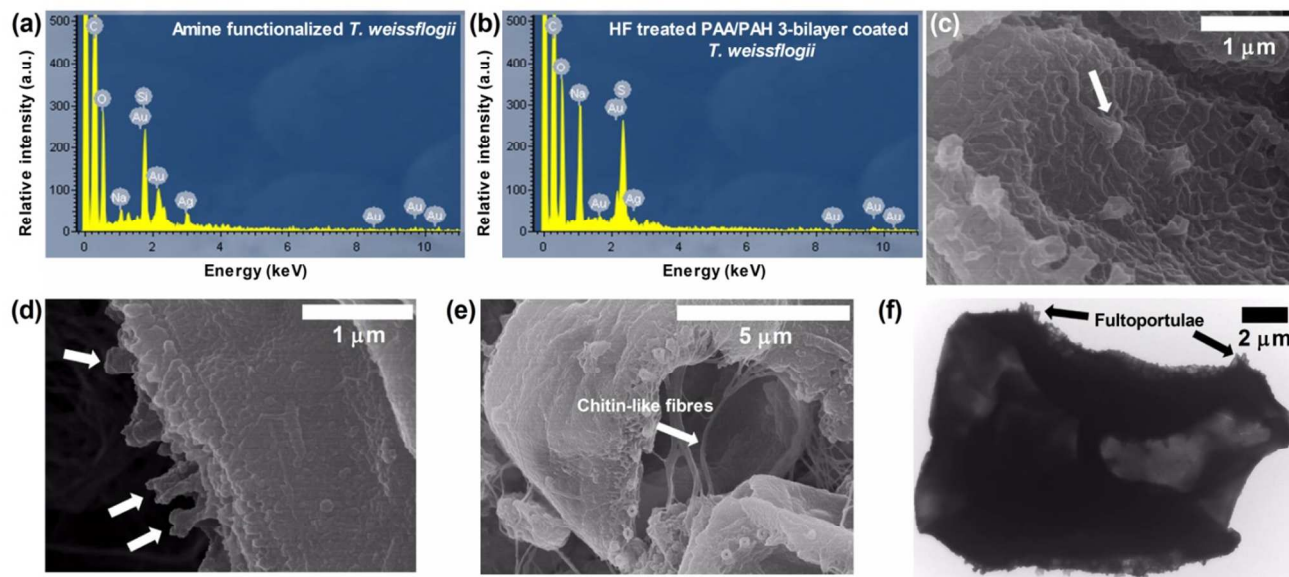


Fig. 5 - EDX spectra of (a) amine functionalized *T. weissflogii* (b) HF treated PAA/PAH bilayer coated *T. weissflogii* revealing the absence of a silica signal post-HF treatment. (c-e) SEM micrographs of PAA/PAH bilayer coated *T. weissflogii* post HF treatment illustrating the rib-like features on the valve face, and the protrusions on the periphery of the valve. (f) TEM micrograph of PAA/PAH bilayer coated *T. weissflogii* post HF treatment

Notes

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References

- S. Sotiropoulou, Y. Sierra-Sastre, S.S. Mark, and C.A. Batt, *Chem Mater*, 2008, **20**, 821.
- D.P. Pulsifer and A. Lakhtakial, *Bioinsp. Biomim.*, 2011, **6**, 031001.
- A. Jantschke, A-K. Herrmann, V. Lesnyak, A. Eychmüller, and E. Brunner, *Chem. Asian J.*, 2012, **7**, 85.
- Y. Yu, J. Addai-Mensah, and D. Losic, *J. Nanosci. Nanotech.*, 2011, **11**, 10349.
- S. De Luca, R. Ivo, S. De Mario, and B. Alfredo, *Appl. Phys. Lett.*, 2005, **87**, 233902.
- D. Losic, Y. Yu, M.S. Aw, S. Simovic, B. Thierry, and J. Addai-Mensah, *Chem. Commun.*, 2010, **46**, 6323.
- N. Kröger, R. Deutzmann, and M. Sumper, *Science*, 1999, **286**, 1129.
- N. Kröger, S. Lorenz, E. Brunner, and M. Sumper, *Science*, 2002, **298**, 584.
- N. Kröger, R. Deutzmann, C. Bergsdorf, and M. Sumper, *Proc. Natl. Acad. Sci. U.S.A.*, 2000, **97**, 14133.
- N. Kröger, R. Deutzmann, and M. Sumper, *J. Biol. Chem.*, 2001, **276**, 26066.
- M. Sumper, S. Lorenz, and E. Brunner, *Angew. Chem., Int. Ed.*, 2003, **42**, 5192.
- W.D. Marner II, A.S. Shaikh, S.J. Muller, and J.D. Keasling, *Biomacromolecules*, 2008, **9**, 1.
- A. Bernecker, R. Wieneke, R. Riedel, M. Seibt, A. Geyer, and C. Steinem, *JACS*, 2010, **132**, 1023.
- E. Kharlampieva, C.M. Jung, V. Kozlovskaya, and V.V.J. Tsukruk, *Mater. Chem.*, 2010, **20**, 5242.
- N. Kröger, M.B. Dickerson, G. Ahmad, Y. Cai, M.S. Haluska, K.H. Sandhage, N. Poulsen, and V.C. Sheppard, *Angew. Chem., Int. Ed.*, 2006, **45**, 7239.
- K.H. Sandhage, M.B. Dickerson, P.M. Huseman, M.A. Caranna, J.D. Clifton, T.A. Bull, T.J. Heibel, W.R. Overton, and M.E.A. Schoenwaelder, *Adv. Mater.*, 2002, **14**, 429.
- Y. Cai, S.M. Allan, K.H. Sandhage, and F.M. Zalar, *J. Am. Ceram. Soc.*, 2005, **88**, 2005.
- S. Shian, Y. Cai, M.R. Weatherspoon, S.M. Allan, and K.H. Sandhage, *J. Am. Ceram. Soc.*, 2006, **89**, 694.
- R.R. Unocic, F.M. Zalar, P.M. Sarosi, Y. Cai, and K.H. Sandhage, *Chem. Commun.*, 2004, **7**, 796.
- E.K. Payne, N.L. Rosi, C. Xue, and C.A. Mirkin, *Angew. Chem., Int. Ed.*, 2005, **44**, 5064.
- Y. Fang, V.W. Chen, Y. Cai, J.D. Berrigan, S.R. Marder, J.W. Perry, and K.H. Sandhage, *Adv. Funct. Mater.*, 2012, **22**, 2550.
- U. Kusari, Z. Bao, Y. Cai, G. Ahmad, K.H. Sandhage, and L.G. Sneddon, *Chem. Commun.*, 2007, **11**, 1177.
- C.S. Gaddis, and K.H. Sandhage, *J. Mater. Res.*, 2004, **19**, 2541.

- 24 S.M. Holmes, B.E. Graniel-Garcia, P. Foran, P. Hill, E.P.L. Roberts, B.H. Sakakini, J.M. Newton, *Chem. Commun.*, 2006, **25**, 2662.
- 25 D. Liu, P. Yuan, D. Tan, H. Liu, T. Wang, M. Fan, J. Zhu, and H. He, *J. Colloid. Interf. Sci.*, 2012, **388**, 176.
- 26 M.R. Weatherspoon, M.B. Dickerson, G. Wang, Y. Cai, S. Shian, S.C. Jones, S.R. Marder, and K.H. Sandhage, *Angew. Chem., Int. Ed.*, 2007, **46**, 5724.
- 27 Y. Fang, J.D. Berrigan, Y. Cai, S.R. Marder, and K.H. Sandhage, *J. Mater. Chem.*, 2012, **22**, 1305.
- 28 C.A. Durkin, T. Mock, and E.V. Armbrust, *Eukaryot. Cell*, 2009, **8**, 1038.
- 29 De Stefano, L., Lamberti, A., Rotiroti, L., De Stefano, M. *Acta Biomaterialia*, 2008, **4**, 126.
- 30 M.S. Aw, S. Simovic, Y. Yu, J. Addai-Mensah, and D. Losic, *Powder Technol.*, 2012, **223**, 52.
- 31 Y. Wang, and F. Caruso, *Chem. Mater.*, 2006, **18**, 4089.
- 32 Y. Wang, A. Yu, and F. Caruso, *Angew. Chem., Int. Ed.*, 2005, **44**, 2888.
- 33 J.W. Goodwin, R.S. Harbron, and P.A. Reynolds, *Colloid. Polym. Sci.*, 1990, **268**, 766.
- 34 S. Ye, C. Wang, X. Liu, and Z. Tong, *J. Biomater. Sci. Polym. Ed.*, 2005, **16**, 909.