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Non-aqueous Isorefractive Pickering Emulsions

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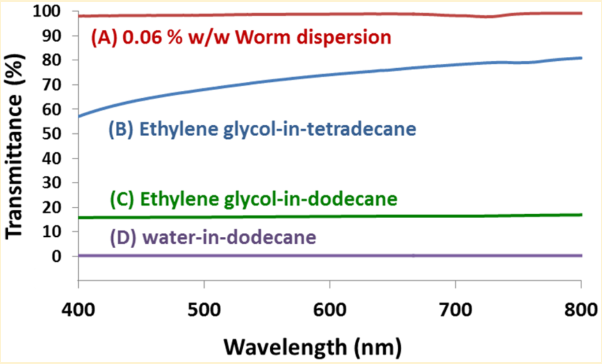
Supporting Information

ABSTRACT: Non-aqueous Pickering emulsions of 16–240 μm diameter have been prepared using diblock copolymer worms with ethylene glycol as the droplet phase and an *n*-alkane as the continuous phase. Initial studies using *n*-dodecane resulted in stable emulsions that were significantly less turbid than conventional water-in-oil emulsions. This is attributed to the rather similar refractive indices of the latter two phases. By utilizing *n*-tetradecane as an alternative oil that almost precisely matches the refractive index of ethylene glycol, almost isorefractive ethylene glycol-in-*n*-tetradecane Pickering emulsions can be prepared. The droplet diameter and transparency of such emulsions can be systematically varied by adjusting the worm copolymer concentration.



INTRODUCTION

Emulsions are droplets of one immiscible liquid suspended within another, with long-term stability toward droplet coalescence being achieved by the adsorption of surfactant, polymer, or particles. In the vast majority of literature examples, the two phases comprise water and a hydrophobic oil (e.g., *n*-alkanes, sunflower oil, paraffin oil, etc.).[1] Reports of so-called "non-aqueous emulsions", sometimes referred to as oil-in-oil or anhydrous emulsions, are much less common. Nevertheless, such emulsions may offer important advantages where the presence of water is detrimental, e.g. in the biomedical and cosmetic sectors for the handling and controlled release of hydrolytically unstable or barely soluble drugs or other actives.[2,3] Another potential application of non-aqueous emulsions is for the synthesis of bespoke latex particles. In this case, a conventional water-in-oil (or oil-in-water) emulsion would limit the polymerization formulation to hydrolytically stable monomers/initiators/catalysts. In principle, switching to a non-aqueous emulsion polymerization formulation should enable a wider range of polymeric particles to be prepared within the droplet phase.[4−10] Literature examples of so-called Pickering[11] non-aqueous emulsions are rather rare.[12−14] However, adsorbed particles may offer an important advantage over surfactants in this context because the much higher adsorption energies of the former should lead to significantly more stable non-aqueous emulsions.[1]

Refractive index-matched emulsions have been designed to enable the detailed study of adsorbed proteins at oil/water interfaces, where the scattered light arising from the emulsion droplets is otherwise problematic.[15] Contrast-matched emulsions have also been studied by confocal laser scanning microscopy in order to image the droplet interior.[16] However, it is emphasized that each of these emulsion formulations contains water. In this work, we describe Pickering emulsions that are both wholly non-aqueous and almost isorefractive in nature. More specifically, we use diblock copolymer worms prepared by polymerization-induced self-assembly[17,18] to stabilize ethylene-glycol-in-*n*-alkane Pickering emulsions. The worm concentration and *n*-alkane type are systematically varied to examine the effect on the emulsion droplet size and turbidity.

RESULTS AND DISCUSSION

Poly(lauryl methacrylate)-poly(benzyl methacrylate) (L-B) diblock copolymer worms were prepared in the form of a free-standing, relatively transparent pink gel at 20% w/w solids in *n*-dodecane, as reported previously.[18,19] GPC (see Figure S1) and ^{1}H NMR spectroscopy indicated a mean diblock composition of L_{16}-B_{37}, while TEM studies confirmed the distinctive highly anisotropic particle morphology (Figure 1). Such worms are relatively well-defined in terms of their mean width but are rather polydisperse in terms of their mean length, with a minor population of spheres also present. Previous work has shown that similarly anisotropic worms prepared in aqueous media are more effective Pickering emulsifiers than diblock copolymer spheres.[20]

Initial experiments were conducted by diluting the initial 20% w/w worm gel in *n*-dodecane to 2.0% w/w solids (or lower, as desired) using *n*-dodecane as a diluent. This is well below the critical gelation concentration of the worm gel, which is estimated to be approximately 11% w/w. The resulting free-flowing worm dispersions were then homogenized using an equal volume of ethylene glycol in each case (Figure 1) and then analyzed by optical microscopy to determine whether a stable Pickering emulsion had been formed. Figure S2A shows

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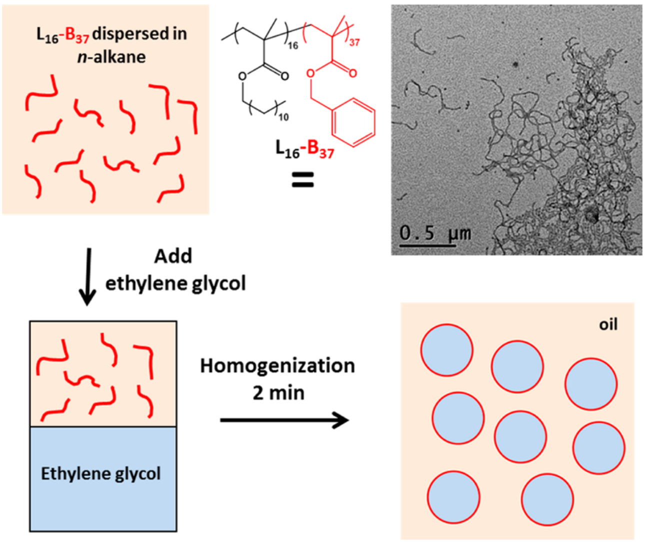

Figure 1. Schematic preparation of ethylene glycol-in-*n*-alkane Pickering emulsions using 0.06 to 2.0% w/w L_{16}-B_{37} worms dispersed in the continuous phase.

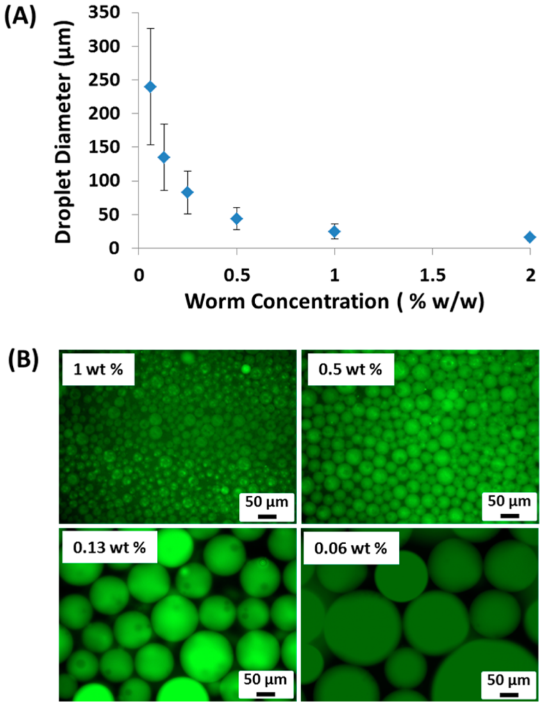

Figure 2. (A) Volume-average droplet diameter (determined via laser diffraction) for ethylene glycol-in-*n*-tetradecane emulsions as a function of the L_{16}-B_{37} worm concentration in the *n*-tetradecane phase. (B) Fluorescence microscopy images of such emulsions with FITC-labeled dextran dissolved in the ethylene glycol phase.

digital images of such emulsions after standing undisturbed at 20 °C for several hours. Emulsion droplets could be readily dispersed into *n*-dodecane, confirming that this solvent was the continuous phase. This is consistent with the observation of sedimentation of the droplet phase upon standing because ethylene glycol has a significantly higher density (1.11 g cm^{-3}) than *n*-dodecane (0.75 g cm^{-3}). Optical microscopy studies of the spherical ethylene glycol droplets (Figure S2B) confirmed that their mean diameter increased from 19 to 220 μm on lowering the L_{16}-B_{37} worm concentration. These observations are consistent with the preparation of worm-stabilized non-aqueous Pickering emulsions.[21] The turbidity of these ethylene glycol-in-*n*-dodecane emulsions is appreciably lower than that of a conventional water-in-oil emulsion, which is typically very opaque. Upon further investigation, this was attributed to the rather similar refractive indices of the two components. (Literature values are 1.43[22] and 1.42[23] for ethylene glycol and *n*-dodecane, respectively.) To examine whether the turbidity of these new non-aqueous emulsions could be reduced further, *n*-tetradecane (refractive index = 1.43)[23] was selected instead of *n*-dodecane so that the ethylene glycol droplets would become essentially isorefractive with the continuous phase (see Figure S3A). However, preparing the L_{16}-B_{37} worms directly in *n*-tetradecane was considered to be problematic because the worm phase is relatively narrow and the diblock copolymer phase diagram is known to be sensitive to relatively modest changes in the solvent.[18] Instead, the 20% w/w worm gel prepared directly in *n*-dodecane was diluted to 2.0% w/w solids (or below, as required) using *n*-tetradecane. Using this protocol, the continuous phase comprises at least 92% w/w *n*-tetradecane. Figure 2A shows the characteristic monotonic increase in droplet diameter (from 16 to 240 μm, as determined by laser diffraction) observed on systematically lowering the worm concentration, as expected for a Pickering emulsion.[21] The ~16 μm droplets produced using 2.0% w/w worms are significantly smaller than the ~50 μm droplets reported for *n*-dodecane-in-water emulsions[20] but are comparable to the smallest (~19 μm) droplets prepared with *n*-dodecane (see above). This is most likely to be the result of the significantly lower interfacial tensions for the ethylene glycol/*n*-tetradecane (17.8 mN m^{-1}) or ethylene glycol/*n*-dodecane (18.0 mN m^{-1}) formulations used herein, compared to that of water/*n*-dodecane (54.5 mN m^{-1}).[24] In addition, it is worth emphasizing that very high emulsification efficiencies are achieved, with essentially all of the ethylene glycol being converted to droplets during homogenization.

The relatively high contrast match between the ethylene glycol droplets and the *n*-tetradecane continuous phase made it rather difficult to obtain high-quality optical microscopy images for these emulsions (Figure S3B). In view of this problem, fluorescence microscopy studies were undertaken using FITC-labeled dextran dissolved in the droplet phase (Figure 2B). Spherical ethylene glycol droplets that are comparable in size to those indicated by laser diffraction are observed. Given that FITC-dextran is soluble in ethylene glycol but insoluble in *n*-tetradecane, this provides further experimental evidence for the ethylene glycol-in-*n*-tetradecane nature of this non-aqueous Pickering emulsion.

The Pickering emulsion efficiency was estimated by using a turbidimetry assay previously utilized by Thompson and co-workers to quantify the fraction of nonadsorbed diblock copolymer nanoparticles remaining in the continuous phase after the removal of the droplets (Figure S4).[25] Table S1 shows relatively high adsorption efficiencies of 81 to 96%, which are significantly higher than those previously reported for diblock copolymer vesicles[25] and are comparable to those found for Pickering emulsions stabilized using aqueous diblock copolymer worms (up to 90% adsorption efficiency).[20] Digital images of the ethylene glycol-in-*n*-tetradecane Pickering emulsions recorded after standing are shown in Figure S3A. The emulsion turbidity is clearly reduced on lowering the worm concentration. For example, the most transparent emulsion is observed at the lowest particle concentration of 0.06% w/w. This unexpected observation suggests that the rather low emulsion turbidity is actually dominated by light scattering from the L_{16}-B_{37} worms, rather than the ethylene glycol droplets. With the benefit of hindsight, this is understandable because the refractive index of the poly(benzyl methacrylate) block is 1.57,[26] which is significantly higher than that of ethylene glycol or *n*-tetradecane.

Figure S5 illustrates how varying the refractive indices of the droplet and continuous phases affects the emulsion turbidity. Figure S5A shows a digital photograph of the visual appearance of a conventional water-in-*n*-dodecane emulsion prepared using 50 vol % *n*-dodecane containing 0.06% w/w L_{16}-B_{37} worms. The sedimented droplet phase has the typical milky appearance associated with water-in-oil emulsions; the relatively large water droplets possess a significantly lower refractive index compared to that of the continuous phase, which leads to intense light scattering. In contrast, Figures S5B and S5C illustrate the physical appearance of non-aqueous Pickering emulsions prepared at the same worm concentration and oil volume fraction using either *n*-dodecane or *n*-tetradecane, respectively. Both emulsions are much less turbid than the water-in-*n*-dodecane emulsion because the refractive index of ethylene glycol is much closer to that of the continuous phase, with ethylene glycol-in-*n*-tetradecane proving to be particularly transparent.

Figure 3 shows the visible spectra (displayed in transmittance mode) recorded for the 0.06% w/w L_{16}-B_{37} worms in *n*-dodecane alone and also for the three emulsions shown in Figure S5. As expected, the water-in-*n*-dodecane emulsion is essentially opaque, displaying less than 0.2% transmittance from 400 to 800 nm. The ethylene glycol-in-*n*-dodecane emulsion is somewhat less turbid at around 16% transmittance. Finally, the almost contrast-matched ethylene glycol-in-*n*-tetradecane emulsion is relatively transparent (up to 81% transmittance at higher wavelengths), as suggested by visual inspection.

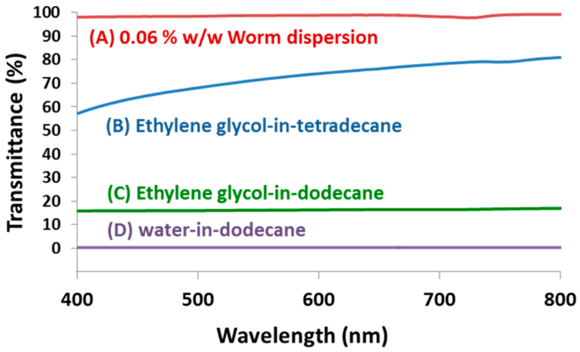

Figure 3. Visible spectra (recorded in transmittance mode) for (A) a 0.06% w/w dispersion of L_{16}-B_{37} diblock copolymer worms in *n*-dodecane, (B) an ethylene glycol-in-*n*-tetradecane emulsion, (C) an ethylene glycol-in-*n*-dodecane emulsion, and (D) a conventional water-in-*n*-dodecane emulsion. Each emulsion was prepared via homogenization of ethylene glycol (or water) with an equal volume of 0.06% w/w L_{16}-B_{37} worms dispersed in the relevant *n*-alkane.

CONCLUSIONS

Approximately isorefractive non-aqueous Pickering emulsions can be prepared by tuning the refractive index of the continuous phase to match that of the droplet phase. More specifically, ethylene glycol-in-*n*-dodecane emulsions are significantly less turbid than a conventional water-in-*n*-dodecane emulsion. This turbidity can be further reduced on switching from *n*-dodecane to *n*-tetradecane in order to provide a closer match between the refractive index of the droplets and that of the continuous phase. These Pickering emulsions are stabilized using highly anisotropic diblock copolymer worms dispersed in the *n*-alkane continuous phase. For the ethylene glycol-in-*n*-tetradecane emulsions, up to 81% transmittance can be achieved at longer wavelengths when using relatively low worm copolymer concentrations.

ASSOCIATED CONTENT

Ⓢ Supporting Information

Full experimental details, additional digital photographs, and further optical microscopy images of the emulsions and visible absorption spectroscopy calibration. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Binks, B. P. Particles as surfactants - similarities and differences. *Curr. Opin. Colloid Interface Sci.* **2002**, *7*, 21.

(2) Crespy, D.; Landfester, K. Making dry fertile: a practical tour of non-aqueous emulsions and miniemulsions, their preparation and some applications. *Soft Matter* **2011**, *7*, 11054.

(3) Atanase, L. I.; Riess, G. Block copolymer stabilized nonaqueous biocompatible sub-micron emulsions for topical applications. *Int. J. Pharm.* **2013**, *448*, 339.

(4) Dorresteijn, R.; Ragg, R.; Rago, G.; Billecke, N.; Bonn, M.; Parekh, S. H.; Battagliarin, G.; Peneva, K.; Wagner, M.; Klapper, M.; Muellen, K. Biocompatible Polylactide-block-Polypeptide-block-Polylactide Nanocarrier. *Biomacromolecules* **2013**, *14*, 1572.

(5) Dorresteijn, R.; Haschick, R.; Klapper, M.; Muellen, K. Poly(L-lactide) Nanoparticles via Ring-Opening Polymerization in Non-aqueous Emulsion. *Macromol. Chem. Phys.* **2012**, *213*, 1996.

(6) Antonietti, M.; Landfester, K. Polyreactions in miniemulsions. *Prog. Polym. Sci.* **2002**, *27*, 689.

(7) Klapper, M.; Nenov, S.; Haschick, R.; Müller, K.; Müllen, K. Oil-in-Oil Emulsions: A Unique Tool for the Formation of Polymer Nanoparticles. *Acc. Chem. Res.* **2008**, *41*, 1190.

(8) Mueller, K.; Klapper, M.; Muellen, K. Preparation of high molecular weight polyurethane particles by nonaqueous emulsion polyaddition. *Colloid Polym. Sci.* **2007**, *285*, 1157.

(9) Mueller, K.; Klapper, M.; Muellen, K. Polyester nanoparticles by non-aqueous emulsion polycondensation. *J. Polym. Sci. Part A: Polym. Chem.* **2007**, *45*, 1101.

(10) Dorresteijn, R.; Billecke, N.; Parekh, S. H.; Klapper, M.; Muellen, K. Polarity Reversal of Nanoparticle Surfaces by the Use of Light-Sensitive Polymeric Emulsifiers. *J. Polym. Sci. Part A: Polym. Chem.* **2015**, *53*, 200.

(11) Pickering, S. U. Emulsions. *J. Chem. Soc.* **1907**, *91*, 2001.

(12) Dimitrova, T. D.; Cauvin, S.; Lecomte, J.-P.; Colson, A. Non-aqueous, surfactant-free antifoam emulsions: Properties and triggered release. *Can. J. Chem. Eng.* **2014**, *92*, 330.

(13) Binks, B. P.; Fletcher, P. D. I.; Thompson, M. A.; Elliott, R. P. Influence of Propylene Glycol on Aqueous Silica Dispersions and Particle-Stabilized Emulsions. *Langmuir* **2013**, *29*, 5723.

(14) Cai, D.; Thijssen, J. H. T.; Clegg, P. S. Making Non-aqueous High Internal Phase Pickering Emulsions: Influence of Added Polymer and Selective Drying. *ACS Appl. Mater. Interfaces* **2014**, *6*, 9214.

(15) Husband, F. A.; Garrood, M. J.; Mackie, A. R.; Burnett, G. R.; Wilde, P. J. Adsorbed Protein Secondary and Tertiary Structures by Circular Dichroism and Infrared Spectroscopy with Refractive Index Matched Emulsions. *J. Agric. Food Chem.* **2001**, *49*, 859.

(16) Hibberd, D. J.; Mackie, A. R.; Moates, G. K.; Penfold, R.; Watson, A. D.; Barker, G. C. Preparation and characterisation of a novel buoyancy and refractive index matched oil-in-water emulsion. *Colloids Surf., A* **2007**, *301*, 453.

(17) Warren, N. J.; Armes, S. P. Polymerization-Induced Self-Assembly of Block Copolymer Nano-objects via RAFT Aqueous Dispersion Polymerization. *J. Am. Chem. Soc.* **2014**, *136*, 10174.

(18) Fielding, L. A.; Lane, J. A.; Derry, M. J.; Mykhaylyk, O. O.; Armes, S. P. Thermo-responsive Diblock Copolymer Worm Gels in Non-polar Solvents. *J. Am. Chem. Soc.* **2014**, *136*, 5790.

(19) Fielding, L. A.; Derry, M. J.; Ladmiral, V.; Rosselgong, J.; Rodrigues, A. M.; Ratcliffe, L. P. D.; Sugihara, S.; Armes, S. P. RAFT dispersion polymerization in non-polar solvents: facile production of block copolymer spheres, worms and vesicles in n-alkanes. *Chem. Sci.* **2013**, *4*, 2081.

(20) Thompson, K. L.; Mable, C. J.; Cockram, A.; Warren, N. J.; Cunningham, V. J.; Jones, E. R.; Verber, R.; Armes, S. P. Are block copolymer worms more effective Pickering emulsifiers than block copolymer spheres? *Soft Matter* **2014**, *10*, 8615.

(21) Binks, B. P.; Whitby, C. P. Silica Particle-Stabilized Emulsions of Silicone Oil and Water: Aspects of Emulsification. *Langmuir* **2004**, *20*, 1130.

(22) Sprung, M. M.; Guenther, F. O. Some cyclic acetals of glyoxal. *J. Am. Chem. Soc.* **1951**, *73*, 1884.

(23) Vogel, A. I. Physical properties and chemical constitution. IX. Aliphatic hydrocarbons. *J. Chem. Soc.* **1946**, 133.

(24) Jańczuk, B.; Wójcik, W.; Zdziennicka, A. Determination of the Components of the Surface Tension of Some Liquids from Interfacial Liquid-Liquid Tension Measurements. *J. Colloid Interface Sci.* **1993**, *157*, 384.

(25) Thompson, K. L.; Chambon, P.; Verber, R.; Armes, S. P. Can Polymersomes Form Colloidosomes? *J. Am. Chem. Soc.* **2012**, *134*, 12450.

(26) Holder, A. J.; Ye, L.; Eick, J. D.; Chappelow, C. C. A quantum-mechanical QSAR model to predict the refractive index of polymer matrices. *QSAR Comb. Sci.* **2006**, *25*, 905.