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# Synthesis and Properties of Amphiphilic Photoresponsive Gelators for Aromatic Solvents

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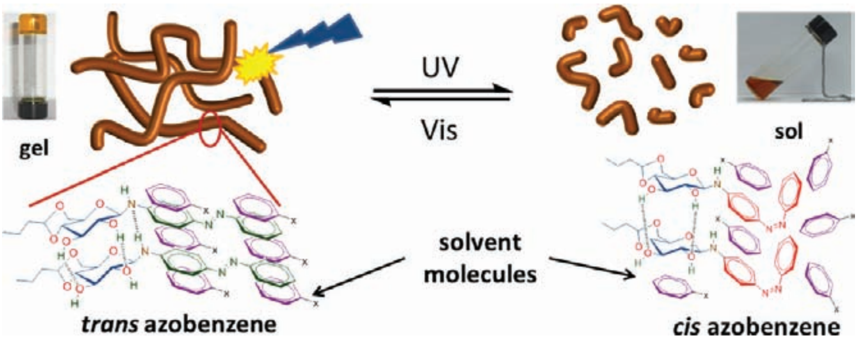
## ABSTRACT



**A sugar-based photoresponsive supergelator, *N*-glycosylazobenzene that shows selective gelation of aromatic solvents is described. The partial *trans*–*cis* isomerization of the azobenzene moiety allows photoinduced chopping of the entangled gel fibers to short fibers, resulting in controlled fiber length and gel–sol transition. The gelator is useful for the selective removal of toxic aromatic solvents from water.**

Organogelators have wide-ranging applications as scaffolds for energy transfer, as drug delivery agents, cosmetic additives, and enzyme-immobilization matrices, and for oil recovery and tissue engineering.[1−4] Sugar-based gelators have a significant role in many of the above applications.[5] For applications such as drug delivery or preparation of smart materials, it is necessary to have reversible control on the gelation and the morphological properties.[6] Reversible light-induced control of molecular aggregation and gelation can be achieved by incorporating photochromic

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(1) (a) Terech, P.; Weiss, R. G. *Chem. Rev.* **1997**, *97*, 3133. (b) Sangeetha, N. M.; Maitra, U. *Chem. Soc. Rev.* **2005**, *34*, 821. (c) Ajayaghosh, A.; Praveen, V. K. *Acc. Chem. Res.* **2007**, *40*, 644. (d) Ajayaghosh, A.; Praveen, V. K.; Vijayakumar, C. *Chem. Soc. Rev.* **2008**, *37*, 109. (e) Jung, J. H.; Park, M.; Shinkai, S. *Chem. Soc.Rev.* **2010**, *39*, 4286–4302. (f) Babu, S. S.; Kartha, K. K.; Ajayaghosh, A. *J. Phys. Chem. Lett.* **2010**, *1*, 3413. (g) Dawn, A.; Shiraki, T.; Haraguchi, S.; Tamaru, S.; Shinkai, S. *Chem. Asian J.* **2011**, *6*, 266.

(2) (a) Lee, K. Y.; Mooney, D. J. *Chem. Rev.* **2001**, *101*, 1869. (b) Dastidar, P. *Chem. Soc. Rev.* **2008**, *37*, 2699. (c) Mukhopadhyay, P.; Fujita, N.; Takada, A.; Kishida, T.; Shirakawa, M.; Shinkai, S. *Angew. Chem., Int. Ed.* **2010**, *49*, 6338.

(3) (a) Zhao, F.; Ma, M. L.; Xu, B. *Chem. Soc. Rev.* **2009**, *38*, 883. (b) John, G.; Shankar, B. V.; Jadhav, S. R.; Vemula, P. K. *Langmuir* **2010**, *26*, 17843. (c) Hirst, A. R.; Escuder, B.; Miravet, J. F.; Smith, D. K. *Angew. Chem., Int. Ed.* **2008**, *47*, 8002.

(4) (a) Bhattacharya, S.; Ghosh, Y. K. *Chem. Commun.* **2001**, 185. (b) Peng, J.; Liu, K.; Liu, X.; Xia, H.; Liu, J.; Fang, Y. *New J. Chem.* **2008**, *32*, 2218. (c) Kar, T.; Debnath, S.; Das, D.; Shome, A.; Das, P. K. *Langmuir* **2009**, *25*, 8639.

(5) (a) Kobayashi, H.; Friggeri, A.; Koumoto, K.; Amaike, M.; Shinkai, S.; Reinhoudt, D. N. *Org. Lett.* **2002**, *4*, 1423. (b) Vemula, P. K.; John, G. *Acc. Chem. Res.* **2008**, *41*, 769. (c) Jadhav, S. R.; Vemula, P. K.; Kumar, R.; Raghavan, S. R.; John, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 7695.

(6) (a) Miyata, T.; Uragami, T.; Nakamae, K. *Adv. Drug Delivery Rev.* **2002**, *54*, 79. (b) Tamesue, S.; Takashima, Y.; Yamaguchi, H.; Shinkai, S.; Harada, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 7461.

(7) (a) Mamiya, J. I.; Kanie, K.; Hiyama, T.; Ikeda, T.; Kato, T. *Chem. Commun.* **2002**, 1870. (b) Yagai, S.; Kitamura, A. *Chem. Soc. Rev.* **2008**, *37*, 1520.

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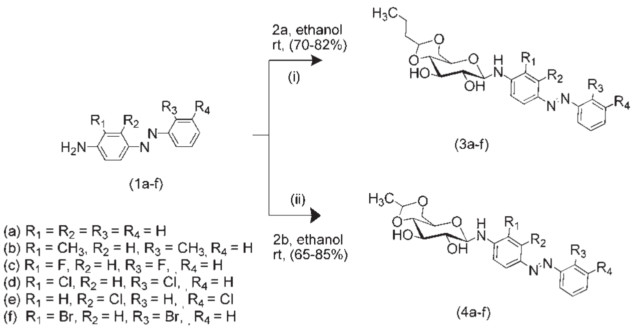
azobenzene moieties into gel-forming molecules.[7,8] Herein, we report the design, synthesis, and self-assembly of a photoswitchable sugar hybrid that undergoes phase-selective removal of aromatic solvent from water.

**Scheme 1.** Synthesis of *N*-Glycosylamines (**3a**–**f**, **4a**–**f**)



Synthesis of *p*-aminoarylazobenzenes (**1a**–**f**)[9] was accomplished in two steps: synthesis of diazoaminobenzenes followed by conversion of these derivatives to *p*-aminoarylazobenzenes from the corresponding aniline derivatives (see Supporting Information for more details). *N*-Glycosylamine based azobenzene derivatives **3a**–**f** and **4a**–**f** were synthesized from *p*-aminoazobenzene derivatives (**1a**–**f**) and 4,6-*O*-butylidene-D-glucopyranose[10] (**2a**) and 4,6-*O*-ethylidene-D-glucopyranose[11] (**2b**) (Scheme 1). The reactants were chosen to have a desired functional group, such as the primary amine in the aromatic moiety and active hydroxyl group in the 4,6-*O*-protected-D-glucose moieties. All of the new *N*-glycosylamine compounds (**3a**–**f**, **4a**–**f**) were characterized through spectral techniques. $^1$H NMR spectra of *N*-glycosylamines showed signals at around 5.40 (J = 4.5 Hz) and 7.00 (J = 8.1 Hz) ppm corresponding to Ano-H and Gly-NH, respectively, which supports the product formation.

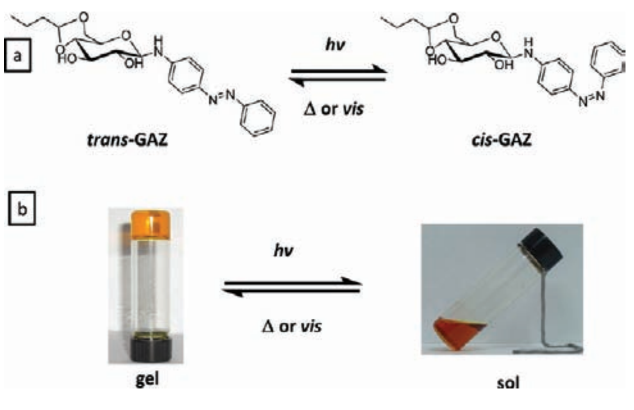


**Figure 1.** (a) Photoisomerization of *trans*-**GAZ** to *cis*-**GAZ**. (b) Gel–sol transition photograph of **GAZ** in toluene ($1 \times 10^{-3}$ M).

Among compounds **3a**–**f**, **4a**–**f**, with the exception of **3b** and **4b** all other molecules are able to form gels from aromatic solvents. Gelation ability of a representative compound, **3a** (**GAZ**), in a number of different organic solvents has been carried out by using the “test tube inversion method”.[12] Stable transparent gels were obtained from different organic aromatic solvents at low critical gelation concentration (see Supporting Information for more details). The lowest concentration was observed to be 0.05% (w/v) in toluene. Since gelation occurs with less than 0.1% (w/v), this molecule falls under the category of a photoresponsive super gelators.[13] Thermodynamic parameters for **GAZ** in 1,2-dichlorobenzene was evaluated using DSC. The higher enthalpy [$\Delta H$ = 287.6 J/g] of the gel reflects the greater stability of the self-assembly (see Supporting Information for more details).

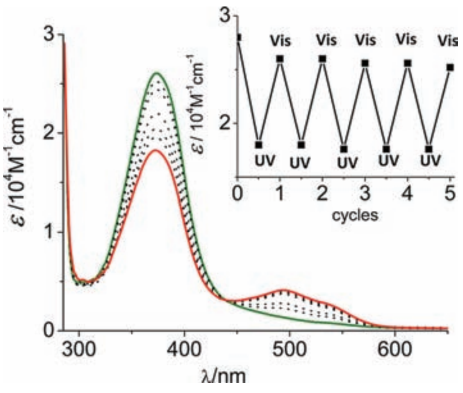


**Figure 2.** Absorption spectral change of **GAZ** in toluene ($2.5 \times 10^{-4}$ M) with respect to UV irradiation. Inset shows the reversibility in the photoisomerization by alternate irradiation of UV and visible light.

It is well-known that the azobenzene chromophore undergoes *trans* to *cis* isomerization by irradiation (Figure 1) with UV light and the reversal by visible light irradiation.[14] The *trans* form of the molecule which favors the long-range self-assembly leads to an entangled network structure that can form a gel in aromatic solvents. The selectivity of

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(8) (a) Komura, N.; Kudo, M.; Tamaoki, N. *Langmuir* **2004**, *20*, 9897. (b) Uchida, K.; Yamaguchi, S.; Yamada, H.; Akazawa, M.; Katayama, T.; Ishibashi, Y.; Miyasaka, H. *Chem. Commun.* **2009**, 4420. (c) Zhao, Y. L.; Stoddart, J. F. *Langmuir* **2009**, *25*, 8442. (d) Stoll, R. S.; Hecht, S. *Org. Lett.* **2009**, *11*, 4790. (e) Wang, C.; Chen, Q.; Sun, F.; Zhang, D.; Zhang, G.; Huang, Y.; Zhao, R.; Zhu, D. *J. Am. Chem. Soc.* **2010**, *132*, 3092.

(9) Sharma, P.; Kumar, A.; Upadhyay, S.; Sahu, V.; Singh, J. *Eur. J. Med. Chem.* **2009**, *44*, 251.

(10) Mellies, P. L.; Mehltretter, C. L.; Rist, E. C. *J. Am. Chem. Soc.* **1951**, *73*, 294.

(11) Baker, R.; Mac Donald, D. L. *J. Am. Chem. Soc.* **1960**, *82*, 294.

(12) (a) Vemula, P. K.; Li, J.; John, G. *J. Am. Chem. Soc.* **2006**, *128*, 8932. (b) Zhou, Y.; Xu, M.; Wu, J.; Yi, T.; Han, J.; Xiao, S.; Li, F.; Huang, C. *J. Phys. Org. Chem.* **2008**, *21*, 338. (c) Somobrata, A.; Sudarshan, K.; Hil, J. P.; Gary, R.; Ariga, K. *Adv. Mater.* **2009**, *21*, 989. (d) Matsuzawa, Y.; Tamaoki, N. *J. Phys. Chem. B* **2010**, *114*, 1586.

(13) Tiefenbacher, K.; Dube, H.; Ajami, D.; Rebek, J., Jr. *Chem. Commun.* **2011**, 7341.

(14) (a) Kumar, G. S.; Neckers, D. C. *Chem. Rev.* **1989**, *89*, 1915. (b) Ichimura, K. *Chem. Rev.* **2000**, *100*, 1847. (c) Eric Wei-Guang, D. *J. Phys. Chem. A* **2004**, *108*, 950.

aromatic solvents may be due to the induced $\pi-\pi$ stacking by the aromatic solvent molecules. The self-assembly will be disturbed by *trans* to *cis* photoisomerization due to the geometrical change that occurs in the structure of azobenzene chromophore.[15] In order to understand the self-assembly and photoresponsive behavior, we chose toluene as the solvent because of its strong gelating ability among the tested aromatic solvents.

The temperature-dependent absorption spectra of **GAZ** in toluene shows (see Supporting Information for more details) a strong aggregation tendency for the molecules. The molecule shows a strong $\pi-\pi^*$ band at 373 nm and a small $n-\pi^*$ band at 495 nm. Upon UV irradiation (370 ± 20 nm) the $\pi-\pi^*$ band decreases and the $n-\pi^*$ band increases, which is the characteristic absorption spectral change for *trans* to *cis* isomerization of azobenzene chromophore (Figure 2). The reverse isomerization was observed by visible light (450–600 nm bandpass) irradiation. On the basis of the absorption spectral change, the percentage of *cis* isomer formed at photostationary state is found to be 31%. Even though the percentage conversion was less, this is enough to make a significant disturbance to the self-assembly of gelator molecules.

The rheological properties of the gelator before and after irradiation are shown in Figure 3. The storage modulus ($G'$) and loss modulus ($G''$) of **GAZ** in toluene gel before and after irradiation are shown as a function of angular frequency ($\omega$) at 0.01% strain ($\gamma$) amplitude. Before and after irradiation the gel showed a plateau region when the angular frequency was varied from 100 to 1 rad $s^{-1}$.

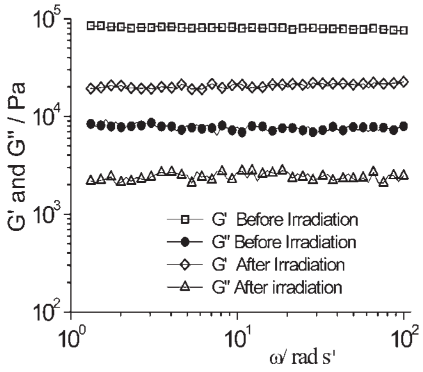

**Figure 3.** Angular frequency sweep ($\omega$) dependencies of dynamic storage ($G'$) and loss modulus ($G''$) of 0.05% w/v **GAZ** gel in toluene.

The $G'$ value showed a substantial elastic response to the gels, which are larger than $G''$ over the entire frequency range. Rheological parameters of the gel before irradiation indicate enhanced solid-like character when compared with the gel after irradiation.

AFM analysis of drop casted **GAZ** ($1 \times 10^{-4}$ M) in toluene on a freshly cleaved mica surface shows a cross-linked fibrillar network-like morphology (Figure 4). However, after UV irradiation (370 ± 20 nm) the self-assembled fibrillar network disintegrates to form short fibers.

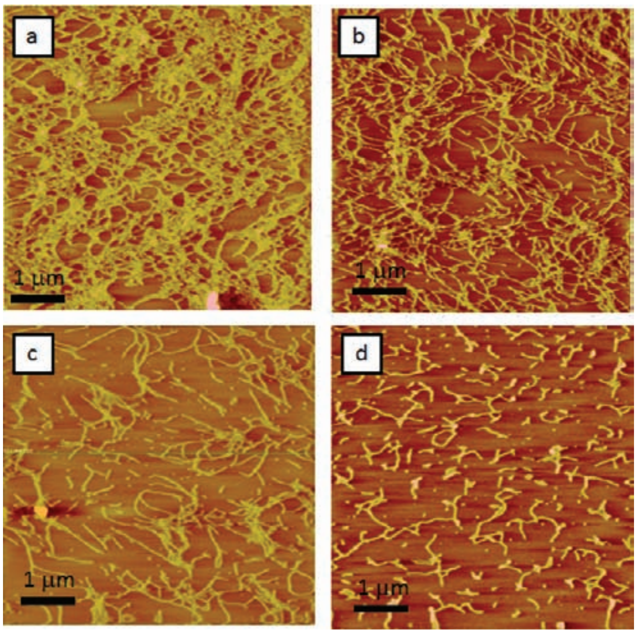

**Figure 4.** AFM images of the **GAZ** molecules in toluene ($1 \times 10^{-4}$ M): (a) before irradiation; (b–d) after 1, 5, and 10 min of UV irradiation, respectivly.

The change in morphology was also investigated by using TEM analysis (see Supporting Information for more details). TEM images of **GAZ** ($1 \times 10^{-4}$ M) in toluene on a carbon coated TEM grid before irradiation showed nanofiber networks of ca. 10–20 nm. After irradiation the population of the fibers has significantly reduced, indicating partial dissolution.

The SEM images obtained from toluene gels of molecules before and after UV irradiation are shown in Figure 5. The SEM analysis clearly reveals that the *trans* form of the gelator facilitates the formation of super bundles of fibers having diameters in the micrometer range. The relatively larger size of the fibers seen in the SEM images indicates that the elementary nanofibers obtained at low concentration as observed in the TEM images have further bundled to form large fibers at higher concentrations required for the gel formation. After UV irradiation the bundles of fibers disintegrates to give short globular aggregates due to the *trans-cis* isomerization of the gelator molecules.

The powder XRD of the toluene xerogel exhibited diffraction peaks corresponding to the *d* spacing of 3.11, 3.23, 9.30, and 26.95 Å. The *d* spacing ratio of 1.0 : 2.99 and 8.65 was consistence with a lamellar structure. After irradiation the xerogel, the XRD pattern showed different diffraction peaks corresponding to 2.97, 4.68, and 27.06 Å. The XRD

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[15] (a) Murata, K.; Aoki, M.; Suzuki, T.; Harada, T.; Kawabata, H.; Komori, T.; Ohseto, F.; Ueda, K.; Shinkai, S. *J. Am. Chem. Soc.* **1994**, *116*, 6664. (b) Yagai, S.; Karatsu, T.; Kitamura, A. *Langmuir* **2005**, *21*, 11048.

data of the toluene xerogels before and after photoirradiation indicate no considerable change in the molecular arrangement (see Supporting Information for more details). From this observation we infer that the partial *trans*-*cis* isomerization which occurs randomly at different parts of the fibers allows chopping into small size. The overall molecular arrangements in the chopped fibers remain more or less the same. Thus, we were able to achieve a morphological state of nonentangled short fibers that is in between large bundles of fibers (gel) and isotropic solution. Such a state is useful for the controlled relase of encapsulated molecules. The partial conversion of *cis*-*trans* isomer (36% at PSS) is responsible for the change of bundled long fibers to short fibers.

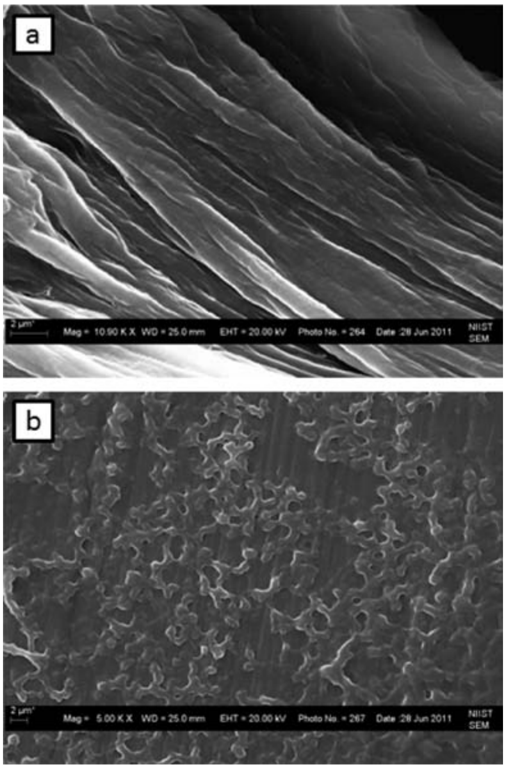

**Figure 5.** SEM images of the self-assembled fibers formed by **GAZ** ($1.3 \times 10^{-2}$ M) in toluene: (a) before UV irradiation, which shows entangled fibers and (b) after UV irradiation, which shows significant morphology change.

Interestingly, irrespective of the amphiphilic nature, the **GAZ** molecule selectively gelates aromatic solvents but does not gelate water and hence is suitable for phase-selective removal of aromatic solvents from water. In a typical procedure, 0.5 mL of a required aromatic solvents and 0.5 mL of water were mixed in a sample tube, to which 0.05 g of the gelator was added and stirred vigorously. The gelation of the aromatic layer was observed, and the water layer remained intact in solution state. The organogel formed can be separated by filtration, and the aromatic solvent trapped by the gelator was recovered by vacuum distillation. The recovered gelator has been used further for phase-selective gelation. The recovery of the aromatic solvents can also be achieved by UV light irradiation. The gel was first separated by simple filtration. Further gel–sol transition could be achieved by photoirradiation, and the aromatic solvents could be separated by filter column using Celite as an adsorbent Figure 6. We also could remove small amounts of aromatic solvents present in water using the gelator. The homogenous phase obtained from use of a small amount of organic solvents resulted in gelation of the organic phase, which ensures the removal of even a small amount of aromatic solvents from the mixture (see Supporting Information for more details).

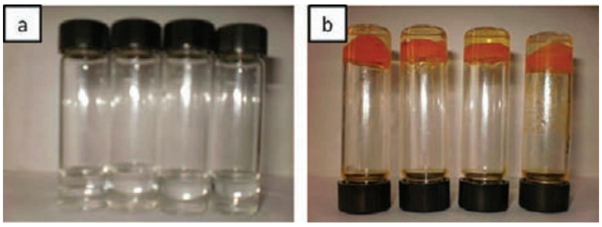

**Figure 6.** Phase-selective gelation of aromatic solvents from two-phase systems: (a) phase-separated mixtures of organic solvents in the presence of water before the addition of the gelator and (b) selective gelation of the organic solvents after the addition of the gelator.

In conclusion, a phase-selective low-molecular weight photoswitchable sugar hybrid has been synthesized, and the selective gelation of aromatic solvents in a mixture has been observed even at micromolar concentrations. The morphological investigation through AFM, TEM, SEM, and XRD analyses implies the formation of self-assembled fibrillar networks that upon irradiation get chopped into short fibers, effecting the gel–sol transition. The gelator is selective for aromatic solvents that allow the removal of such solvents from an aqueous layer. Such phase-selective photoresponsive gelators may be useful for the removal of small amounts of toxic aromatic solvents from contaminated water.

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**Supporting Information Available.** Experimental procedures and spectral, morphological data for all compounds. This material is available free of charge via the Internet at http://pubs.acs.org.