Supramolecular hydrogels with tunable swelling by host-complexation with cyclobis(paraquat-p-phenylene)

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KEYWORDS: hydrogels, supramolecular chemistry, host-guest complexation, tunable swelling

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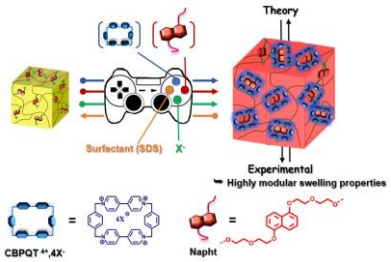

ABSTRACT: Controlling the swelling properties of hydrogels is of primary importance for many applications ranging from actuators and valves to tissue engineering and drug delivery. Herein, we report the use of cyclobis(paraquat-p-phenylene) ($CBPQT^{4+}$, $4X^-$) as a versatile host

to finely tune the swelling behavior of 1,5-dialkyloxynaphthalene guest containing poly(*N*,*N*-dimethylacrylamide) hydrogels (**NaphtGel$_z$**) through supramolecular host-guest complexation. While the equilibrium swelling of **NaphtGel$_z$** in water decreases with increasing amount of hydrophobic naphthalene groups, the opposite behavior is observed with superabsorbing behavior (up to 180 times their initial dry mass) upon immersion in aqueous solutions containing the macrocyclic $CBPQT^{4+}$,$4X^-$ due to formation of tetracationic host-guest complexes. In this case, the swelling amplitude could be conveniently programmed either by variation of the naphthalene content of the hydrogels or by controlling the stoichiometry of the host-guest binding events. Furthermore, by modifying the nature of the counter-ions ($X = Cl^-$, Br^-, I^-) of the tetracationic $CBPQT^{4+}$ macrocyclic host, the swelling of the hydrogels could be tuned in line with Pearson's absolute hardness scale of X^-. The swelling behavior of these supramolecular hydrogels could be successfully described by a theoretical model taken into account the hydrophobic association of the naphthalene groups and their screening by host-guest complexation. Finally, addition of SDS (Sodium Dodecyl Sulfate) as surfactant to the supramolecularly swollen hydrogels led to a large decrease in hydrogel size due to dissociation of the host-guest complexes and the formation of $CBPQT^{4+}$,$4DS^-$ within the hydrogel.

Introduction

Hydrogels constitute a unique class of hydrophilic three-dimensional cross-linked polymeric networks that have been extensively studied because of their outstanding characteristics and wide applications in bioscience and material science.[1–3] Importantly, hydrogels can absorb and retain a large amount of water within their structures, leading to shape and volume changes of materials.[4] Controlling the swelling properties is, thus, of primary importance for a wide range of applications including drug delivery systems and tissue engineering.[5] It is well-established that

water uptake capabilities of such hydrophilic materials are strongly related to their cross-linking density and the chemical structure of the polymer. Especially interesting are smart hydrogels whose swelling properties can be tuned in response to external stimuli.[6,7] Among such materials, those displaying macroscopic swelling changes upon exposure to temperature,[8,9] pH,[10,11] light,[12] and electric fields[13] have shown a great potential for applications in controlled drug delivery systems[14] and actuators[15].

Non-covalent interactions occupy a pivotal role in living systems by determining the structure and function of a plethora of biomolecules such as DNA, RNA and proteins.[16,17] They also enable specifical, transient recognition and binding of (macro)molecules, rendering adaptive supramolecular assemblies.[18–20] In particular, in the last past two decades, the marriage of supramolecular host-guest chemistry and hydrogel science has led to the development of materials featuring fascinating swelling, adhesive, shape-memory and self-healing properties.[21,22] A large majority of these studies deal with supramolecular hydrogels in which host-guest interactions act as cross-link junctions to create single or double-networks while their stimuli-controlled dissociation results in a gel-sol transition.[23,24,25,26] Recently, host-guest interactions have also been exploited to tune the swelling-shrinking properties of covalently cross-linked hydrogels. For example, methylated β-cyclodextrin was used as host entity to trigger the swelling of chemically cross-linked poly(*N*,*N*-ethylacrylamide) hydrogels bearing complementary hydrophobic adamantyl modules.[27] By forming adamantyl-cyclodextrin complexes, an hydrophobic-to-hydrophilic transition took place with an associated increase of equilibrium swelling (Q_{eq} = volume of the swollen gel over the volume of the dried gel) from 1 to 6 compared to pure water for hydrogels containing up to 10 mol % of adamantyl units. However, for higher adamantyl contents, the hydrogels became too hydrophobic and did not

swell upon addition of host molecules. Moderate degrees of swelling-shrinking transition were also reported for covalent polymeric networks containing cyclodextrins (α-, β-CD) or pillar[n]arenes and complementary stimuli-responsive guests (diazo, viologens, ferrocene) as pendant groups.[28–31]

More recently, thanks to its strong hydrophilicity and capability of binding electron-poor hydrophobic guest subunits, such as ferrocene in its cavity, the percarboxylated pillar[6]arene, which bears twelve negatively charged carboxylates, has emerged as an efficient host to endow ferrocene functionalized polyacrylamide hydrogels with large swelling and shrinking abilities upon complexation and decomplexation, respectively.[32] Remarkably, a hydrogel containing 10 mol% of ferrocene units was able to swell with an increase in equilibrium swelling of approximatively 40 upon exposure to the pillar[6]arene host. Furthermore, the complexed hydrogel was shown to shrink upon applying various external stimuli that induce decomplexation of the ferrocene pillar[6]arene host-guest complexes, including temperature, pH, redox and competitive guests. This large swelling upon complexation with the percarboxylated pillar[6]arene was ascribed to the formation of percarboxylated pillar[6]arene −ferrocene inclusion complexes that both masks the hydrophobic character of the ferrocene and leads to electrostatic repulsion between the polymer chains inside the hydrogel. However, a sharp decrease of the swelling upon complexation was observed when the molar ratio of ferrocene moieties was higher than 10% due to the strong electrostatic repulsion between the negatively charged host units, thereby preventing full complexation of all the hydrophobic ferrocene guests.

Recently, we designed and synthesized a covalently crosslinked poly(*N*,*N*-dimethylacrylamide)(PDMAc) hydrogel using free radical copolymerization of *N*,*N*-dimethylacrylamide (DMAc) with *N*,*N*'-methylenebisacrylamide (MBA) in presence of 3 mol%

of a dialkoxynaphthalene guest functionalized monomer (**Figure 1**). This hydrogel swelled upon complexation with the tetracationic cyclophane cyclobis(paraquat-p-phenylene) ($CBPQT^{4+}$,$4Cl^-$).[33] Remarkably, despite the rather low content of electron-rich naphthalene guest molecules in the hydrogel, the complexation with $CBPQT^{4+}$,$4Cl^-$ induced an important increase of Q_{eq} from 20 in the non-complexed state to 90 in the complexed state.

Inspired by this remarkable host-guest complexation induced hydrogel swelling results of this naphthalene based hydrogel containing only a low molar fraction of guest modules, we further investigated the swelling-shrinking capabilities of such naphthalene containing PDMAc hydrogels (**Figure 1**). In the present work, NaphtPDMAc polymer networks (**$NaphtGel_z$**), functionalized with various molar ratios ($1 < z < 12$ mol%) of dialkoxynaphthalene units, were prepared and their complexation with $CBPQT^{4+}$,$4X^-$ as well as the accompanied hydrogel swelling were investigated. Complexation of **$NaphtGel_z$** with the tetracationic $CBPQT^{4+}$,$4Cl^-$ host induced hydrogel swelling from $Q_{eq} = 47$ to $Q_{eq} = 182$. Remarkably, the Q_{eq} could be finely controlled by the naphthalene content of the hydrogels, the nature of the $CBPQT^{4+}$ counter-anions ($X=Cl^-$, Br^-, I^-) as well as by controlling the stoichiometry of the host-guest complexation. Moreover, the addition of an anionic surfactant (Sodium Dodecyl Sulfate), which promotes the dissociation of the host-guest complexes within the network, is demonstrated to induce abrupt deswelling of the **$NaphtGel_z$** hydrogels.

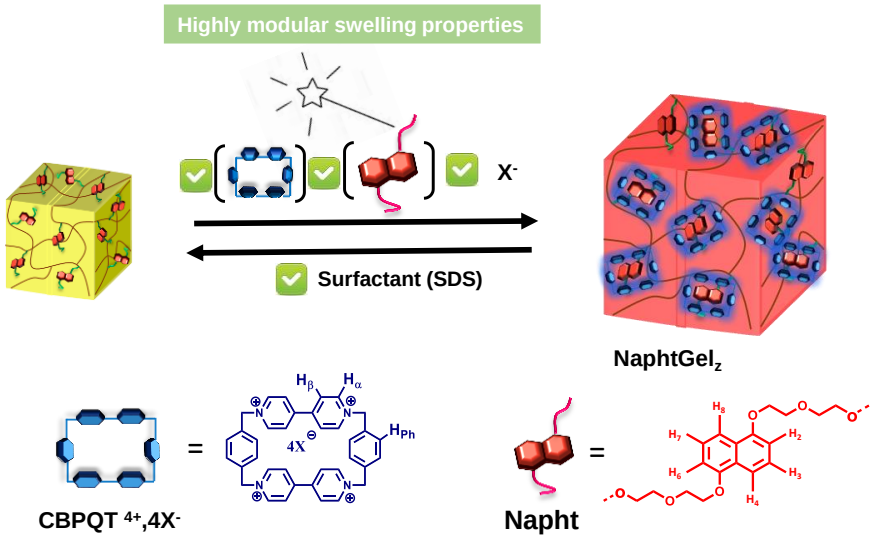

Figure 1. Schematic representation of the CBPQT^{4+},4X^{-}-Naphthalene host-guest complexation induced swelling of **NaphtGel$_z$**.

Results and discussion

The **NaphtGel$_z$** hydrogels with different amounts of dialkoxynaphthalene were prepared following our previously reported procedure (**Figure 2a**).[33] Briefly, naphthalene functionalized acrylamide (Napht-Am) was incorporated as comonomer in poly(*N*,*N*-dimethylacrylamide) based networks *via* conventional radical copolymerization initiated by 2,2'-azobisisobutyronitrile (AIBN) in dimethylformamide (DMF) and in the presence of 0.8 mol% of *N*,*N*'-methylenebisacrylamide (MBA) as cross-linker, which was previously determined to be optimal for supramolecular hydrogel swelling.[33] The parameters y and z represent the amount (mol%) of *N*,*N*-dimethylacrylamide (DMAc) and Napht-Am monomers in the polymer networks, respectively. Cross-linked **NaphtGel$_{0\text{-}12}$** polymer networks containing 0 to 12 mol% of Napht-Am were prepared to investigate the effect of the guest content on the swelling properties, both in absence and presence of the CBPQT^{4+},4X^{-} supramolecular host. Attempts to prepare hydrogels with higher naphthalene content were unsuccessful, which is hypothesized to be due to

quenching of the radicals by the naphthalene units albeit further research is needed to confirm this. Due to water-insolubility of the Napth-AM, the crosslinked polymer networks were prepared in *N*,*N*-dimethylformamide leading to organogels that were, subsequently, washed with acetone to remove the unreacted compounds, dried and swelled in water to afford the **NaphtGel$_{0\text{-}12}$** hydrogels.

The incorporation of Napht-Am in the cross-linked polymer networks was confirmed by ^{1}H NMR spectroscopy as shown for **NaphGel$_{12}$** in **Figure 2b** (see Supplementary Information for the ^{1}H NMR spectra of the other hydrogels). The ^{1}H NMR spectra clearly exhibit the three characteristic resonances of the aromatic protons belonging to the naphthalene units ($H_{2/6}$, $H_{3/7}$, $H_{4/8}$) between 6.5 and 8 ppm, and the signals corresponding to the protons of the polymer backbone between 1 and 3 ppm. Based on the relative integration of the aromatic protons and the methylene fragments belonging to the polymer backbone, the composition of the prepared **NaphGel$_{z}$** were estimated, which was found to be in line with the monomer feed ratios (Supporting information, Table S1).

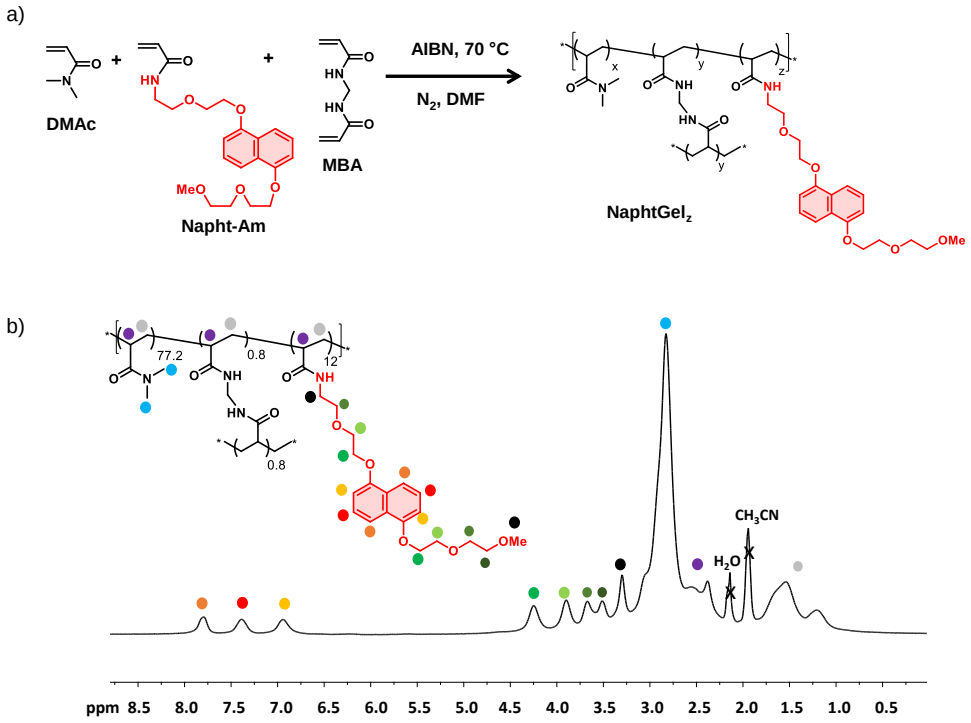

Figure 2. a) Synthesis of **NaphtGelz**; b) ^{1}H NMR spectrum of NaphtGel12 recorded in CD_3CN at 25°C

After the successful preparation of the **NaphtGel$_z$**, we investigated their ability to form host-guest complexes between the incorporated electron-rich naphthalene moieties with the electron-poor macrocyclic CBPQT^{4+},4Cl^{-} host in aqueous media. Upon addition of CBPQT^{4+},4Cl^{-} to the **NaphtGel$_z$** hydrogels a visual color change from light yellow to purple was observed, consistent with the formation of donor–acceptor host-guest complexes between the π-electron rich naphthalene moieties and the π-electron deficient CBPQT^{4+},4Cl^{-} hosts (**Figure 3a**). The formation of host-guest complexes was also confirmed by UV/vis spectroscopy displaying the existence of a charge-transfer absorption band centered at 530 nm.[34] Furthermore, the host-guest complexation of **NaphtGel$_z$** with CBPQT^{4+},4Cl^{-} could be demonstrated by ^{1}H NMR spectroscopy.

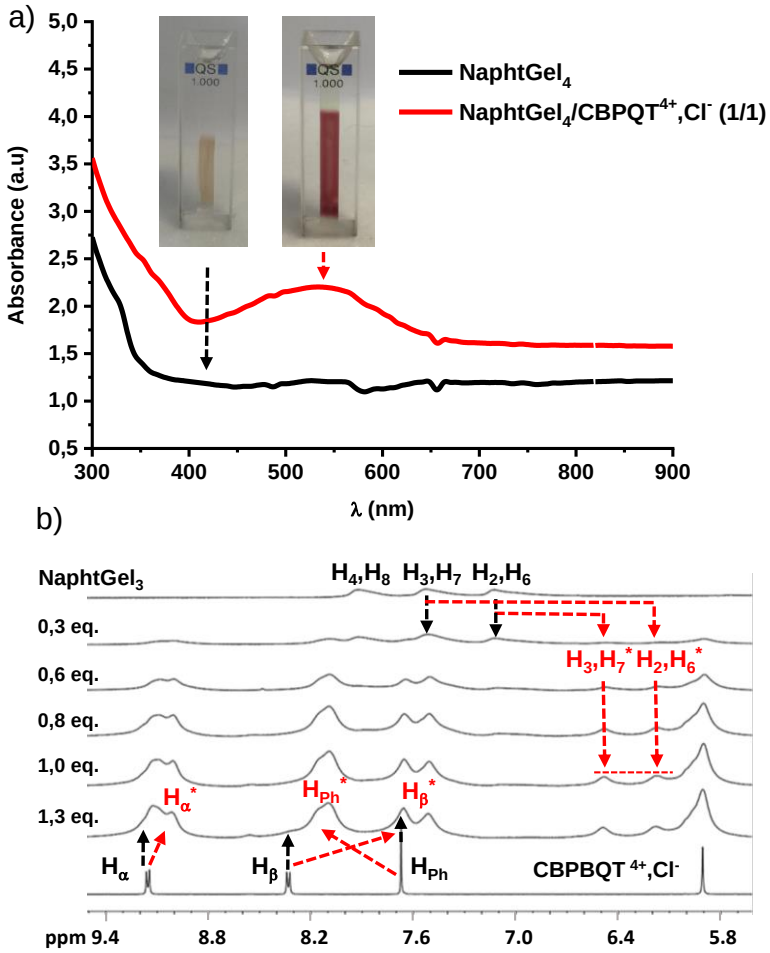

Figure 3: a) UV–vis spectra of **NaphtGel$_3$** and **NaphtGel$_3$**/CBPQT^{4+},4Cl$^-$ complexes recorded in water at 25°C; b) Partial ^{1}H NMR spectra of CBPQT^{4+},4Cl$^-$ and **NaphtGel$_3$** upon the addition of 0.3, 0.6, 0.8, 1 and 1.3 equiv. of CBPQT^{4+},4Cl$^-$; recorded in D_2O at 25°C.

Figure 3b displays the ^{1}H NMR spectra of **NaphtGel$_3$** upon addition of aliquots of CBPQT^{4+},4Cl$^-$ in D_2O. In essence, upon addition of the host to the **NaphtGel$_3$**, the protons of naphthalene guest underwent significant upfield shifts ($\Delta > 0.6$ ppm), while the H_α/H_β and H_{Ph} protons of CBPQT^{4+},4Cl$^-$ were substantial broadened and shifted to higher and lower fields, respectively. An interesting feature of these ^{1}H NMR spectra is that they showed a concomitant increase and decrease of both the integrals of the complexed and uncomplexed $H_{2/6}$, $H_{3/7}$

aromatic naphthalene protons, respectively, up to the addition of one equivalent of $CBPQT^{4+}$,$4Cl^-$. The coexistence of the signals of both the free and complexed naphthalene guests in the ^1H NMR spectra indicate a slow exchange between the complexed and the non-complexed species on the ^1H NMR time scale (10 ms range), and also demonstrate the opportunity to fine-tune the extent of host-guest complexation within the hydrogels by the addition of sub-stoichiometric quantities of $CBPQT^{4+}$,$4Cl^-$.[20]

After having demonstrated the binding capability of **NaphtGel$_z$** with $CBPQT^{4+}$,$4Cl^-$, we investigated the effect of host-guest complexation on the swelling behavior. First, the impact of the molar ratio of naphthalene subunits inside the non-complexed **NaphtGel$_z$** hydrogels on the swelling was evaluated. As expected based on the hydrophobic character of the naphthalene groups, the Q_{eq} of the **NaphtGel$_z$** decreased from 33 to 14 as the naphthalene content increased from 0 mol% to 12 mol% (**Figure 4a**). This decrease in Q_{eq} is proposed to be induced by aggregation of the hydrophobic naphthalene units, which can theoretically be described using the model of Rubinstein and Semenov[35] with pairwise associations between naphthalene groups (see Supporting Information). Under these conditions, the equilibrium swelling can be calculated using the following equation, taking into account the different contributions to the pressure inside the gel and their equalization with the pressure outside the gel, in the external medium (Π_{ext}) :

$$\Pi_{gel} = \Pi_m + \Pi_{el} + \Pi_{ion} + \Pi_{st} = \Pi_{ext} \qquad \{1\}$$

with Π_m, Π_{el}, Π_{ion} and Π_{st} the mixing, elastic, ionic and solvophobic contributions to the osmotic pressure of the gel (Π_{gel} ; see supporting information).

In the present case where there is no ionic contribution ($\Pi_{ion} = 0$) and equilibrium in pure water ($\Pi_{ext} = 0$), the swelling behavior is only controlled by the mixing term (Π_m : quality of solvent),

the elastic term (Π_{el} : level of crosslinking) and the interaction term (Π_{st}) taking into account the pairwise associations between the naphthalene groups.[36] Following this description, a good fit of the experimental data was obtained using $\chi_{12} \cong 0.35$ for the Flory-Huggins interaction parameter of the binary system PDMAC/water (good solvent conditions) and $\varepsilon = 20$ kT for the interaction energy between the naphthalene units. Interestingly, when the naphthalene decorated hydrogels are immersed in an aqueous solution of $CBPQT^{4+}$,$4Cl^-$, the variation of the Q_{eq} (red bars and symbols in **Figure 4**) strongly increases with increasing naphthalene content, reaching a Q_{eq} up to 180 for the sample with the highest naphthalene content (**NaphtGel$_{12}$**). As the swelling of the reference **NaphtGel$_0$** hydrogel, that does not contain naphthalene moieties, did not significantly change in the presence of $CBPQT^{4+}$,$4Cl^-$, the large expansion observed for the naphthalene modified hydrogels can be ascribed to the formation of host-guest complexes between the naphthalene guest units and the $CBPQT^{4+}$,$4Cl^-$ hosts. This supramolecular host-guest association both masks the hydrophobic nature of the naphthalene units, thereby disrupting the hydrophobic associations, and introduces the charged $CBPQT^{4+}$ molecules and their Cl^- counter-ions inside the gels. Assuming the above mentioned contributions of $CBPQT^{4+}$,$4Cl^-$ host molecules, i.e. cancellation of hydrophobic interactions ($\Pi_{st} = 0$) and that the osmotic contribution of chloride counterions dominate the electrostatic interactions ($\Pi_{ion} > 0$), it is possible to fit the experimental equilibrium swelling data in pure water ($\Pi_{ext} = 0$) using the same procedure. In this case, the large contribution of the Cl^- counterions to the osmotic pressure of the gels needs to be lowered taking into account the osmotic coefficient (Φ_p). This latter takes into account the non-ideality of the Cl^- counterions as well as their condensation with the cationic charges of the tetracationic $CBPQT^{4+}$. Even if we consider this data treatment as semi-quantitative, the small values of Φ_p reported in **Table 1**, highlight the low degree of freedom of the counterions. This can be

attributed 1) to the low polar environment around the naphthalene/CBPQT^{4+} complex (lower dielectric constant, higher Bjerrum length and stronger electrostatic interactions between CBPQT^{4+} and its counterions) and 2) to the charge multivalency of CBPQT^{4+} which induces a high local electrostatic potential.

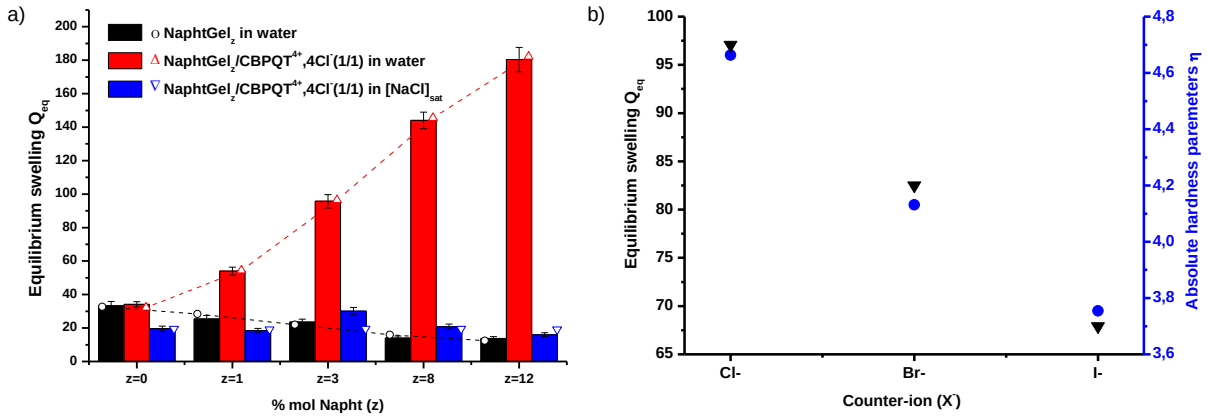

Figure 4. a) Experimental (Bar) and theoretical (symbols) swelling at equilibrium of **NaphtGel$_z$** after 24h immersion in water (■ and ○) and after addition of CBPQT^{4+},4Cl$^-$ in stoichiometric conditions either in pure water (■ and △) or in saturated NaCl (350 g/L: ■ and ▽). b) Influence of the hardness of X$^-$ (●) on the swelling ratios of **NaphtGel$_3$** / CBPQT^{4+},X$^-$(▼) in pure water.

To evaluate the electrostatic contribution of the complexed CBPQT^{4+} host molecules and their chloride counter-ions on the swelling behavior of the NaphtGel$_z$ hydrogels complexed with CBPQT^{4+},4Cl$^-$, these water-swollen complexed hydrogels were immersed in a saturated NaCl solution revealing a significant decrease of the equilibrium swelling (**Figure 4**; blue bars and symbols). The final shrunken hydrogels remained colored and reached similar equilibrium swelling as the uncomplexed reference **NaphtGel$_0$**. Hence, in these conditions where the ionic concentration within the gel is almost the same as in the external medium ($\Pi_{ion} = \Pi_{ext}$) and the

hydrophobic interactions do not take place as the naphthalene groups are shielded by complexation with $CBPQT^{4+}$ ($\Pi_{st} = 0$), the swelling at equilibrium only depends on the elastic contribution and the quality of solvent ($\Pi_{gel} = \Pi_m + \Pi_{el} = 0$). As these contributions are the same for all the hydrogels, the same equilibrium swelling is expected with a lower value compared to pure water as the quality of PDMAc solvation decreases in salty media (increase of the Flory parameter from 0.35 in pure water to 0.45 in saturated NaCl).

Table 1 Fitting parameters for the ionic contribution of the Cl^- counter-ions to the swelling pressure, with z the naphthalene content, α the theoretical degree of ionization assuming the stoichiometry of the complex Napht/$CBPQT^{4+}$, Φ_p the osmotic coefficient and $\alpha\Phi_p$ the effective degree of ionization

z	0	0.01	0.03	0.08	0.12
α=4*z	0	0.04	0.12	0.32	0.49
Φ_p	0	0.50	0.38	0.21	0.16
$\Phi_p\alpha$	0	0.02	0.05	0.07	0.08

To further evidence the key role of the counter-ions of the $CBPQT^{4+}$ host, the swelling of **NaphtGel$_3$** was evaluated in the presence of $CBPQT^{4+}$,$4X^-$ featuring different counter-ions (X^- = Cl^-, Br^- and I^-) (**Figure 4b**). Interestingly, the equilibrium swelling of **NaphtGel$_3$** complexed with $CBPQT^{4+}$,$4X^-$ was found to be dependent on the nature of the counter-ions in line with their Pearson's absolute hardness parameter (η).[37] Indeed, the results indicate that the softer the X^- is ($\eta_{I^-} < \eta_{Br^-} < \eta_{Cl^-}$), the lower the equilibrium swelling of the **NaphtGel$_3$** complexed with $CBPQT^{4+}$,$4X^-$, indicating that the soft iodide anions might interact more efficiently with the

$CBPQT^{4+}$ host, which can also be considered as a soft cation due to the delocalization of the charges over the whole polyaromatic cycle. Hence, these results demonstrate the opportunity to tune the swelling degree of complexed **NaphtGel$_z$** hydrogels simply by changing the hardness of the halide counterions.

As we have shown by ^{1}H NMR spectroscopy, *vide supra*, that the extent of host-guest complexation of **NapthGel$_z$** could be conveniently tuned by controlling the equivalents of $CBPQT^{4+}$,$4Cl^-$, we investigated the impact of the extent of host-guest complexation the **NaphtGel$_3$** swelling behavior. The results are depicted in **Figure 5** revealing a gradual increase of the equilibrium swelling with the extent of complexation until full complexation was reached. The equilibrium swelling of the complexed **NaphtGel$_3$** remained constant when adding more than one equivalent of $CBPQT^{4+}$,$4Cl^-$ as all electron-rich binding sites were already complexed. Photographs recorded on the **NaphtGel$_3$** hydrogels complexed with different ratios of $CBPQT^{4+}$,$4Cl^-$ tend to confirm these findings visually with an increase in size and the purple color of complexes until one equivalent of host was added.

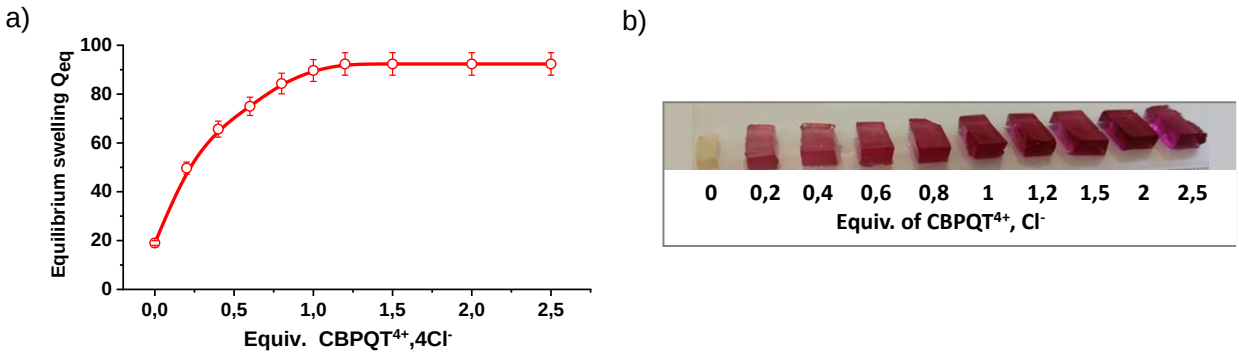

Figure 5: Swelling behavior (a) and photographs of **NaphtGel$_3$** (b) after being immersed in different [$CBPQT^{4+}$, $4Cl^-$] for 2h and then swelled into deionized water at 25°C for 24h.

The development of supramolecular hydrogels that exhibit a large mascroscopic swelling – shrinking transition in response to stimuli is still a great challenge. We have previously shown that $CBPQT^{4+}$-naphthalene based pseudorotaxane assemblies can be dethreaded in aqueous media by adding a strong binding competitive guest, such as tetrathiafulvalene or an anionic surfactant, such as sodium dodecyl sulfate (SDS).[38] In essence, the addition of SDS to a solution containing the naphthalene-$CBPQT^{4+}$,$4Cl^-$ complex induced an anion exchange reaction between Cl^- and DS^-, leading to precipitation of the $CBPQT^{4+}$,$4DS^-$ complex and a complete dissociation of the naphthalane-$CBPQT^{4+}$ host-guest interactions. In this work, we explored whether this strategy could also be used to promote the dissociation of the host-guest complexes inside the **NaphtGel$_z$** complexed with $CBPQT^{4+}$,$4Cl^-$ and, more importantly, to induce their macroscopic shrinking. **Figure 6** depicts a gradual decrease of the swelling of the **NaphtGel$_3$** complexed with $CBPQT^{4+}$,$4Cl^-$ with time after addition of an aqueous SDS solution (3.6 M). Even though the thermodynamic equilibrium has not been reached within the 10 hours of this experiment, it may be expected that the gel will, eventually, reach an equilibrium swelling degree that is comparable to the one observed in pure water, in absence of $CBPQT^{4+}$,$4Cl^-$ ($Q_{eq} \approx 14$). The photographs in Figure 6 confirm that large shrinking of the hydrogel, accompanied by its complete discoloration confirming efficient surfactant-induced decomplexation that promotes the large macroscopic shrinking of the **NaphtGel$_3$** complexed with $CBPQT^{4+}$,$4Cl^-$.

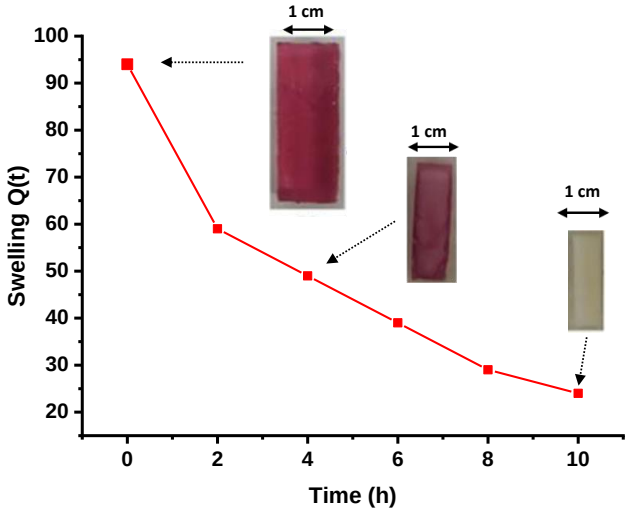

Figure 6: Evolution of the swelling degree, color and size of **NaphtGel$_3$** complexed with CBPQT^{4+},4Cl$^-$ in time after being immersed in an aqueous solution of SDS (3.6 M) at 25°C.

Conclusion

Hydrogels with superabsorbing properties (Q_{eq} > 180) resulting from CBPQT^{4+}-naphthalene host-guest complexation have been described. The swelling degree of the poly(*N*,*N*-dimethylacrylamide) hydrogels can be conveniently tuned by introducing hydrophobic naphthalene guests into the network which can be switched to highly hydrophilic moieties by complexation with CBPQT^{4+}, 4X$^-$ macrocyclic hosts. This host-guest complexation leads to a significant increase in hydrogel swelling, especially for those containing high contents of hydrophobic naphthalene subunits. Furthermore, the equilibrium swelling degree of the naphthalene-functionalized hydrogels could be easily adjusted by the amount of incorporated naphthalene guest moieties, the extent of complexation with CBPQT^{4+},4Cl$^-$, as well as by changing the hardness of the halide counter-anions. Furthermore, we have demonstrated successful surfactant-assisted dissociation of CBPQT^{4+},4Cl$^-$-naphthalene based pseudorotaxanes

inside the hydrogels by addition of a surfactant solution, which led to host-guest decomplexation, accompanied by a large macroscopic shrinking and decoloration of the hydrogels. Future work will focus on the exploitation of these smart hydrogels and related systems to create actuators and artificial muscles showing macroscopic swelling transitions.

ASSOCIATED CONTENT

Supporting Information.

Materials, Instrumentation, Synthesis and characterization of $NaphtGel_Z$ (z= 1, 3, 8, 12); Swelling studies and complexation of $NaphtGel_z$, effect of [NaCl] on the swelling of $NaphtGel_z$, $NaphtGel_z/CBPQT^{4+}$, references.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. ‡These authors contributed equally.

Notes

The authors declare no competing financial interest

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REFERENCES

(1) Mishra, S.; Rani, P.; Sen, G.; Dey, K. P. Preparation, Properties and Application of Hydrogels: A Review. In *Hydrogels: Recent Advances*; Thakur, V. K., Thakur, M. K., Eds.; Springer Singapore: Singapore, 2018; pp 145–173. https://doi.org/10.1007/978-981-10-6077-9_6.

(2) Varaprasad, K.; Raghavendra, G. M.; Jayaramudu, T.; Yallapu, M. M.; Sadiku, R. A Mini Review on Hydrogels Classification and Recent Developments in Miscellaneous Applications. *Materials Science and Engineering: C* **2017**, *79*, 958–971. https://doi.org/10.1016/j.msec.2017.05.096.

(3) Zhang, Y. S.; Khademhosseini, A. Advances in Engineering Hydrogels. *Science* **2017**, *356* (6337), 1–10. https://doi.org/10.1126/science.aaf3627.

(4) Shang, J.; Le, X.; Zhang, J.; Chen, T.; Theato, P. Trends in Polymeric Shape Memory Hydrogels and Hydrogel Actuators. *Polym. Chem.* **2019**, *10* (9), 1036–1055. https://doi.org/10.1039/C8PY01286E.

(5) Mahinroosta, M.; Jomeh Farsangi, Z.; Allahverdi, A.; Shakoori, Z. Hydrogels as Intelligent Materials: A Brief Review of Synthesis, Properties and Applications. *Materials*

Today Chemistry **2018**, *8*, 42–55. https://doi.org/10.1016/j.mtchem.2018.02.004.

(6) Erol, O.; Pantula, A.; Liu, W.; Gracias, D. H. Transformer Hydrogels: A Review. *Advanced Materials Technologies* **2019**, *4* (4), 19000436–19000470. https://doi.org/10.1002/admt.201900043.

(7) Guo, Y.; Bae, J.; Fang, Z.; Li, P.; Zhao, F.; Yu, G. Hydrogels and Hydrogel-Derived Materials for Energy and Water Sustainability. *Chem. Rev.* **2020**, *120* (15), 7642–7707. https://doi.org/10.1021/acs.chemrev.0c00345.

(8) Jiang, Y.; Wu, Y.; Huo, Y. Thermo-Responsive Hydrogels with N-Isopropylacrylamide/Acrylamide Interpenetrating Networks for Controlled Drug Release. *Journal of Biomaterials Science, Polymer Edition* **2015**, *26* (14), 917–930. https://doi.org/10.1080/09205063.2015.1068532.

(9) Sun, H.; Chen, J.; Han, X.; Liu, H. Multi-Responsive Hydrogels with UCST- and LCST-Induced Shrinking and Controlled Release Behaviors of Rhodamine B. *Materials Science and Engineering: C* **2018**, *82*, 284–290. https://doi.org/10.1016/j.msec.2017.08.067.

(10) Tanaka, M.; Nakahata, M.; Linke, P.; Kaufmann, S. Stimuli-Responsive Hydrogels as a Model of the Dynamic Cellular Microenvironment. *Polymer Journal* **2020**, *52*, 861–870. https://doi.org/10.1038/s41428-020-0353-6.

(11) Traitel, T.; Kost, J. PH-Responsive Hydrogels: Swelling Model. In *Biomaterials*; Hasirci, N., Hasirci, V., Eds.; Springer US: Boston, MA, 2004; pp 29–43.

(12) Li, L.; Scheiger, J. M.; Levkin, P. A. Design and Applications of Photoresponsive Hydrogels. *Advanced Materials* **2019**, *31* (26), 1807333–1807350. https://doi.org/10.1002/adma.201807333.

(13) Yang, C.; Liu, Z.; Chen, C.; Shi, K.; Zhang, L.; Ju, X.-J.; Wang, W.; Xie, R.; Chu, L.-Y. Reduced Graphene Oxide-Containing Smart Hydrogels with Excellent Electro-Response and Mechanical Properties for Soft Actuators. *ACS Appl. Mater. Interfaces* **2017**, *9* (18), 15758–15767. https://doi.org/10.1021/acsami.7b01710.

(14) Qureshi, D.; Nayak, S. K.; Maji, S.; Anis, A.; Kim, D.; Pal, K. Environment Sensitive Hydrogels for Drug Delivery Applications. *European Polymer Journal* **2019**, *120*, 109220–109259. https://doi.org/10.1016/j.eurpolymj.2019.109220.

(15) Han, D.; Farino, C.; Yang, C.; Scott, T.; Browe, D.; Choi, W.; Freeman, J. W.; Lee, H. Soft Robotic Manipulation and Locomotion with a 3D Printed Electroactive Hydrogel. *ACS Appl. Mater. Interfaces* **2018**, *10* (21), 17512–17518. https://doi.org/10.1021/acsami.8b04250.

(16) Raghunathan, S.; Jaganade, T.; Priyakumar, U. D. Urea-Aromatic Interactions in Biology. *Biophys Rev* **2020**, *12* (1), 65–84. https://doi.org/10.1007/s12551-020-00620-9.

(17) Frieden, E. Non-Covalent Interactions: Key to Biological Flexibility and Specificity. *J. Chem. Educ.* **1975**, *52* (12), 754–761. https://doi.org/10.1021/ed052p754.

(18) Liu, K.; Kang, Y.; Wang, Z.; Zhang, X. 25th Anniversary Article: Reversible and Adaptive Functional Supramolecular Materials: "Noncovalent Interaction" Matters. *Advanced Materials* **2013**, *25* (39), 5530–5548. https://doi.org/10.1002/adma201302015.

(19) Sambe, L.; Stoffelbach, F.; Lyskawa, J.; Delattre, F.; Fournier, D.; Bouteiller, L.; Charleux, B.; Cooke, G.; Woisel, P. Host–Guest Modulation of the Micellization of a Tetrathiafulvalene-Functionalized Poly(N-Isopropylacrylamide). *Macromolecules* **2011**, *44* (16), 6532–6538. https://doi.org/10.1021/ma2009854.

(20) Sambe, L.; de La Rosa, V. R.; Belal, K.; Stoffelbach, F.; Lyskawa, J.; Delattre, F.; Bria, M.; Cooke, G.; Hoogenboom, R.; Woisel, P. Programmable Polymer-Based Supramolecular Temperature Sensor with a Memory Function. *Angewandte Chemie International Edition* **2014**, 5044–5048. https://doi.org/10.1002/anie.201402108.

(21) Mantooth, S. M.; Munoz-Robles, B. G.; Webber, M. J. Dynamic Hydrogels from Host–Guest Supramolecular Interactions. *Macromolecular Bioscience* **2019**, *19* (1), 1800281–1800293. https://doi.org/10.1002/mabi.201800281.

(22) Xia, D.; Wang, P.; Ji, X.; Khashab, N. M.; Sessler, J. L.; Huang, F. Functional Supramolecular Polymeric Networks: The Marriage of Covalent Polymers and Macrocycle-Based Host–Guest Interactions. *Chem. Rev.* **2020**, *120* (13), 6070–6123. https://doi.org/10.1021/acs.chemrev.9b00839.

(23) Tamesue, S.; Noguchi, S.; Kimura, Y.; Endo, T. Reversing Redox Responsiveness of Hydrogels Due to Supramolecular Interactions by Utilizing Double-Network Structures. *ACS Appl. Mater. Interfaces* **2018**, *10* (32), 27381–27390. https://doi.org/10.1021/acsami.8b10001.

(24) Xiao, T.; Xu, L.; Zhou, L.; Sun, X.-Q.; Lin, C.; Wang, L. Dynamic Hydrogels Mediated by Macrocyclic Host–Guest Interactions. *J. Mater. Chem. B* **2019**, *7* (10), 1526–1540. https://doi.org/10.1039/C8TB02339E.

(25) Kashiwagi, Y.; Katashima, T.; Takashima, Y.; Harada, A.; Inoue, T. Effect of Host-Guest Interaction on Swelling Behavior and Equilibrium Swollen State of Host-Guest Gel. *Nihon Reoroji Gakkaishi* **2019**, *47* (3), 99–104. https://doi.org/10.1678/rheology.47.99.

(26) Royes Mir, J.; Coudret, C.; Roux, C.; Benoit-Marquié, F.; Cazalès, M.; Séverac, C.; Lorenzo, C.; Mingotaud, A.-F. Rational Hydrogel Formulation Leads to Reversible and Enhanced Photocontrolled Rigidity. *ChemPhotoChem* **2017**, *1* (7), 311–316. https://doi.org/10.1002/cptc.201700038.

(27) Peters, O.; Ritter, H. Supramolecular Controlled Water Uptake of Macroscopic Materials by a Cyclodextrin-Induced Hydrophobic-to-Hydrophilic Transition. *Angewandte Chemie International Edition* **2013**, *52* (34), 8961–8963. https://doi.org/10.1002/anie.201301286.

(28) Nakahata, M.; Takashima, Y.; Hashidzume, A.; Harada, A. Redox-Generated Mechanical Motion of a Supramolecular Polymeric Actuator Based on Host–Guest Interactions. *Angewandte Chemie International Edition* **2013**, *52* (22), 5731–5735. https://doi.org/10.1002/anie.201300862.

(29) Takashima, Y.; Hatanaka, S.; Otsubo, M.; Nakahata, M.; Kakuta, T.; Hashidzume, A.; Yamaguchi, H.; Harada, A. Expansion–Contraction of Photoresponsive Artificial Muscle Regulated by Host–Guest Interactions. *Nature Communications* **2012**, *3* (1), 1270–1278. https://doi.org/10.1038/ncomms2280.

(30) Takashima, Y.; Otani, K.; Kobayashi, Y.; Aramoto, H.; Nakahata, M.; Yamaguchi, H.; Harada, A. Mechanical Properties of Supramolecular Polymeric Materials Formed by

Cyclodextrins as Host Molecules and Cationic Alkyl Guest Molecules on the Polymer Side Chain. *Macromolecules* **2018**, *51* (16), 6318–6326. https://doi.org/10.1021/acs.macromol.8b01410.

(31) Xu, X.; Jerca, F. A.; Van Hecke, K.; Jerca, V. V.; Hoogenboom, R. High Compression Strength Single Network Hydrogels with Pillar[5]Arene Junction Points. *Mater. Horiz.* **2020**, *7* (2), 566–573. https://doi.org/10.1039/C9MH01401B.

(32) Ni, M.; Zhang, N.; Xia, W.; Wu, X.; Yao, C.; Liu, X.; Hu, X.-Y.; Lin, C.; Wang, L. Dramatically Promoted Swelling of a Hydrogel by Pillar[6]Arene–Ferrocene Complexation with Multistimuli Responsiveness. *J. Am. Chem. Soc.* **2016**, *138* (20), 6643–6649. https://doi.org/10.1021/jacs.6b03296.

(33) Belal, K.; Stoffelbach, F.; Lyskawa, J.; Fumagalli, M.; Hourdet, D.; Marcellan, A.; Smet, L. D.; de la Rosa, V. R.; Cooke, G.; Hoogenboom, R.; Woisel, P. Recognition-Mediated Hydrogel Swelling Controlled by Interaction with a Negative Thermoresponsive LCST Polymer. *Angewandte Chemie International Edition* **2016**, *55* (45), 13974–13978. https://doi.org/10.1002/anie.201605630.

(34) Bigot, J.; Bria, M.; Caldwell, S. T.; Cazaux, F.; Cooper, A.; Charleux, B.; Cooke, G.; Fitzpatrick, B.; Fournier, D.; Lyskawa, J.; Nutley, M.; Stoffelbach, F.; Woisel, P. LCST: A Powerful Tool to Control Complexation between a Dialkoxynaphthalene-Functionalised Poly(N-Isopropylacrylamide) and CBPQT4+ in Water. *Chem. Commun.* **2009**, No. 35, 5266–5268. https://doi.org/10.1039/B910856D.

(35) Rubinstein, M.; Semenov, A. N. Thermoreversible Gelation in Solutions of Associating Polymers. 2. Linear Dynamics. *Macromolecules* **1998**, *31* (4), 1386–1397. https://doi.org/10.1021/ma970617+.

(36) Hourdet, D.; Ducouret, G.; Varghese, S.; Badiger, M. V.; Wadgaonkar, P. P. Thermodynamic Behavior of Hydrophobically Modified Polyacrylamide Containing Random Distribution of Hydrophobes: Experimental and Theoretical Investigations. *Polymer* **2013**, *54* (11), 2676–2689. https://doi.org/10.1016/j.polymer.2013.03.039.

(37) Parr, R. G.; Pearson, R. G. Absolute Hardness: Companion Parameter to Absolute Electronegativity. *J. Am. Chem. Soc.* **1983**, *105* (26), 7512–7516. https://doi.org/10.1021/ja00364a005.

(38) Louisy, J.; Delattre, F.; Lyskawa, J.; Malfait, A.; Maclean, C. E.; Sambe, L.; Zhu, N.; Cooke, G.; Woisel, P. Surfactant-Mediated Control of CBPQT4+–Dialkoxynaphthalene Complexation. *Chem. Commun.* **2011**, *47* (24), 6819–6821. https://doi.org/10.1039/C1CC10571J.