Electrospinning of 2-hydroxypropyl-β-cyclodextrin aqueous solutions with added salts

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Abstract: It has been proposed that hydrogen bonding plays a role in promoting the electrospinnability of some materials. In this study, the role of non-covalent interactions in the electrospinnability of 2-hydroxypropyl-β-cyclodextrin (2HP-β-CD) was investigated by varying the physical-chemical properties the solvents. The rheological behaviour of a peroxide-aqueous/acetone-ethanol/NaHCO3 solution and an aqueous urea solution, as a function of aqueous 2HP-β-CD concentration, was compared. The rheological behaviour of 2HP-β-CD solutions was characterized by a frequency-independent stress relaxation plateau such as that observed in cross-linked polymer networks and reversible polymer gels with non-linear viscoelasticity. We conclude that the electrospinnability of 2HP-β-CD is, as evidenced by the changes in the morphology of the electrospun 2HP-β-CD materials, in agreement with other related studies on the electrospinning of Cyclodextrins. Also, the electrospinnability of 2HP-β-CD does appear to be related to the physical-chemical properties of the solvent systems.

Keywords: electrospinning, cyclodextrin, hydrogen bonding, nanofibre.

1. Introduction

Electrospinning is a method for the production of continuous polymer fibres with diameters in the sub-micron range [1-3]. During the electrospinning process, a high voltage is applied to a droplet of a polymer solution (or melt), stretching the droplet into a conical shape (known as the Taylor cone) by means of electrostatic repulsion [4]. A jet of polymer solution is emitted from the tip of the Taylor cone if the build-up of internal electrical charge overcomes the surface tension of the droplet. Given an appropriate combination of electro-viscoelastic properties; the polymer jet initially follows a linear trajectory that resists the Plateau-Rayleigh instability. Following stable jet formation, the jet typically undergoes a chaotic instability that leads to extensive jet thinning and solvent loss. A solid polymer fibre is then collected at an earthed electrode if sufficient solvent has been evaporated during the jet flight from tip to collector [1, 3, 5]. The ability of a polymer solution to resist the Plateau-Rayleigh instability during flight is usually attributed to the entanglement of polymeric molecules, and chain entanglement is commonly proposed to be the leading mechanism of fibre formation during electrospinning of polymeric systems [6, 7]. Literature reports that at least 2 entanglements per chain is the level of physical accretion required for uniform electrospun polymeric fibres [8, 9]. However, entanglement conditions may vary with polymer-solvent system and with the polymer chain polydispersity and/or degree of branching [10].

α-, β- and γ-Cyclodextrins (CDs) are toroidal-shaped cyclic oligosaccharides that are composed of 6, 7 and 8 α-D-glucopyranoside units, glycosidically linked *via* the 4-hydroxyl groups of each monosaccharide, respectively [11]. CDs are able to host a wide range of small hydrophobic molecules (or inclusions) within their hydrophobic interior cavity. In contrast, the exterior of the CD molecule is hydrophilic, providing the inclusion-CD complexes with water solubility [11]. Thus, CDs can be used as carriers for solubilizing hormones, vitamins, drugs, and other compounds frequently used in tissue and cell culture and pharmaceutical applications [12-15]. For example, HP-β-CD /Triclosan Inclusion Complexes showed electrospinnability at concentrations of 160% (w/v), except on the case of urea salts addition at concentrations of 20 wt. %. Also, 1:1 host-guest complexation was reported to be ideal to avoid droplet formation within the electrospun nanofibrous mats [14].

Furthermore, Uyar *et al.* demonstrated that α-, β- and γ-CDs and their derivatives may be electrospun into continuous fibres in spite of their low molecular weight (972-1297 g/mol) [16, 17]. Methyl-Beta Cyclodextrin (M-β-CD) in water and DMF showed enhanced electrospinnability at higher solvent concentrations of 160% (w/v) for both cases. Interestingly, amorphous structure on the electrospun material was shown across all samples as confirmed by AFM, XRD, TGA and DSC [16]. Moreover, it was observed that electrospun hydroxypropyl-β-cyclodextrin (HP-β-CD) exhibited uniform fibre (*i.e.* bead-free) formation at concentrations of 160% (w/v), 120% (w/v) and 120% (w/v) in water, DMF and DMAc, respectively [17]. However, at lower concentrations of HP-β-CD in DMF, DMAc and H$_2$O, HP-β-CD solutions could only be electrospun into the form of either beaded structures with little or no fibre formation, 'bead-on-string' structures, or fibres with a ribbon-type morphology [17]. A similar scenario (improved electrospinnability with increased

concentration) was shown for the rest of the (HP-*γ*-CD) and (M-*β*-CD) solutions tested on either water, DMAc and/or DMF [17]. Furthermore, the authors proposed that the formation of molecular aggregates of aqueous CDs, can be attributable to extensive hydrogen bonding; a critical mechanism allowing the formation of *α*-, *β*- and *γ*-CDs fibres during electrospinning [14-17]. Bounded water on CDs aqueous solutions was reported be as high as 100% for solutions over 60% CDs wt. % concentrations, and as suggested by the authors, electrospinnability by depletion flocculation was the driving mechanism for the observed results [18]. Also, Manasco *et al.*, observed that the electrospinnability of HP-*β*-CD is reduced in the presence of urea salts [18]. Urea is known to be a chaotropic agent, disrupting hydrogen bonding between water molecules [19]. Urea can also affect the hydrogen bonding between CD molecules and bound water, reducing the size of the CD aggregates [20]. Similarly, Celebiouglu *et al.*, considered the influence of hydrogen bonding on the electrospinnability of aqueous HP-*β*-CD solutions by adding urea salts to hinder electrospinnability [21].

Nonetheless, arguments regarding the hydrogen bonding "maker or breaker" capacity of urea for disrupting the tetrahedral configuration of the water stereo-chemistry, are still not resolved [22, 23]. Argumentation is bounded around the capacity of urea to slow down the rotational dynamic of water, by geometrically altering hydrogen bonding networks and water stereochemistry [23]. Also, it has been reported that the hydrogen bonding capacity of aqueous HP-*β*-CD solutions is affected (as increased CDs solubility) by using heavy water as solvent and by the addition of Na salts, among others additives [24]. Likewise, ethanol-water mixtures have shown to strengthen the hydrogen bonding between

respective solvent molecules [25]. Moreover, polar solvents like acetone, can also have hydrogen bonding structuring effects on water [26]. Likewise, conductivity surface tension and pH on aqueous CDs solutions can affect CD-water aggregate formation and consequent electrospinnability [22-26]. Moreover, the influence of pH and non-covalent intermolecular bonding on electrospinnability is also acknowledge in polymeric systems [27-30]. For instance, pH and hydrogen bonding are known to influence the electrospinnability of poly (methyl methacrylate) and poly (vinyl alcohol) [29, 30]. For such polymeric systems, rheological studies have shown that pH and hydrogen bonding directly affect the viscoelastic properties of aqueous and non-polar solutions. Likewise, the viscoelasticity of aqueous HP-*β*-CD solutions appears to be dependent on the strength of the hydrogen bonding between CD molecules [18]. For example, aqueous HP-*β*-CD solutions exhibit solid-like behaviour, as indicated by a storage modulus (G′) that exceeds the loss modulus (G″) [18]. However, the relationship between viscoelasticity of CD-aqueous solutions and bounded water-driven aggregation is not fully understood.

In the present validation study, the electrospinnability of 2-hydroxypropyl-*β*-cyclodextrin (2HP-*β*-CD) solutions is further corroborated by investigating the dependence of the electrospinnability of 2HP-*β*-CD on the presence of urea or sodium bicarbonate salts. The electrospinnability of 2HP-*β*-CD was observed to be a sensitive function of the physical- chemical properties of the solvent system. As already reported by others, the formation of a network of non-covalent intermolecular bonding appears to be a key mechanism required for the electrospinning of CDs into continuous fibres.

2. Experimental procedures

2.1 Materials and solution preparation

averaged degree of substitution of 4.5 was purchased from Seebio Biotech, Inc, Shanghai, China -CAS # 128446-35-5; molar mass 1425.38g/mol and molecular substitution per anhydrous glucose unit between 0.57 and 1.29, Figure 1. Urea pellets (> 99.5 %), sodium bicarbonate powder (> 99.7 %) and aqueous hydrogen peroxide solution (50 wt. %) were purchased from Sigma Aldrich, Germany. All materials were used as supplied without further purification.

Aqueous electrospinning solutions were formulated with the intention of either enhancing (Hb-E) or disrupting (Hb-D) the overall hydrogen bonding networks between CD and solvent molecules. Hence two different solutions were made, a saturated urea solution, aimed at disrupting negatively the hydrogen bonding networks between CD and water molecules (Hb-D). On the contrary, a diluted sodium bicarbonate aqueous solution on a (50:50) acetone/ethanol solvent system, aimed at positively enhancing the overall hydrogen bonding network between CD and water molecules; while promoting solvent evaporation during electrospinning (Hb-E).

2.2 Physical properties of the electrospinning solutions

The average values of pH, electrical conductivity and surface tension of the solutions were measured in triplicate at a temperature of 50 °C ± 2°C. The pH of the solutions was measured using a pH meter (SevenEasy, Mettler-Toledo GmbH, Greifensee, Switzerland), with a claimed precision of ± 0.02. The surface tension was measured using an optical goniometer (KSV CAM200, KSV Instruments Ltd., Finland). The electrical conductivity of the solutions

2-hydroxypropyl-*β*-cyclodextrin (2HP-*β*-CD) powder (($C_6H_9O_5$)$_7$(C_3H_7O)$_{4.5}$) with an

The composition of the Hb-E solvent system was 0.5 wt. % sodium bicarbonate in 43.25 wt. % water, with 30 wt. % acetone, 20 wt. % ethanol, and 6.25 wt. % hydrogen peroxide; while Hb-D was prepared as a saturated solution of urea in de-ionised water. The electrospinning solutions were prepared by dispersing 2HP-*β*-CD (55-70 g/cm^{-3}) in the solvents at a temperature of 50 ± 2 °C. Subsequently, all solutions were stored at 50 ± 2 °C to avoid precipitation of 2HP-*β*-CD prior to electrospinning.
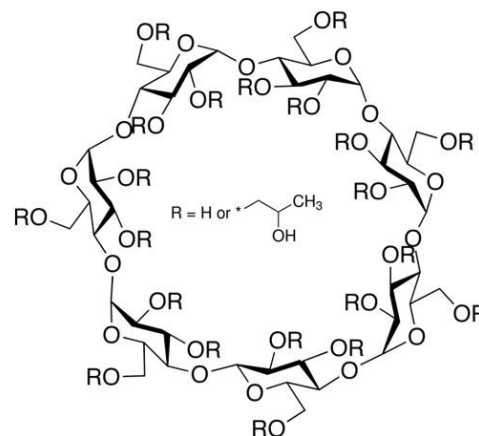

Figure 1. Chemical structure of tested 2-hydroxypropyl-*β*-cyclodextrin (2HP-*β*-CD)

was measured using a conductivity meter (EDT Instruments, RE387TX, Dover, United Kingdom), with a claimed precision of ± 0.5 %.

2.3 Rheological characterization of electrospinning solutions

The rheological behaviour of the 2HP-*β*-CD solutions was measured using an Anton-Paar MCR series rheometer (Anton Paar GmbH, Graz, Austria). All experiments were performed at a temperature of 50 ± 1 °C with a cone and plate configuration having a 50 mm diameter and 2° angle between the

surface of the cone and plate. The rheological properties were measured in rotational mode as a function of the shear rate (0.1-1000 s^{-1}), and in oscillatory mode with a strain of 0.1 % as function of the angular frequency (0.1-1000 s^{-1}). A strain of 0.1 % was determined to be within the linear viscoelastic range of the solutions as

2.4 Electrospinning and characterization of materials

A syringe pump (NE-500, New Era Pump Systems Inc., NY, USA) was used to deliver the electrospinning solution to the spinneret (metal hypodermic syringe needle, internal diameter of 0.3 mm) at a flow rate of 0.3 µl/min. All solutions were supplied to the spinneret at a temperature of 50 ± 2 °C; via a heated glass syringe with a temperature controlled coil, since the solutions were too viscous to be delivered to the spinneret at room temperature (20 °C). The electrospinning apparatus was enclosed in a grounded Faraday cage at a controlled temperature and relative humidity of 35 ± 1 °C and 38 ± 3 %, respectively. Electrospinning of the various solutions was performed using an applied voltage of +15 kV and a spinneret-to-collector distance of

3. Results and discussion

3.1 Physical properties of 2-hydroxypropyl-β-cyclodextrin solutions

As expected, the 2HP-β-CD/Hb-E solutions exhibited both higher pH (Figure 2) and conductivity (Figure 3) compared to those of the 2HP-β-CD/Hb-D or 2HP-β-CD/H$_2$O solutions due to the presence of bicarbonate salts. In contrast, the surface tension of the 2HP-β-CD/Hb-E and 2HP-β-CD/H$_2$O solutions was lower than that of 2HP-β-CD/Hb-D (Figure 4). As expected by the addition of NaHCO$_3$ salts, the pH for all

determined from a strain sweep. Unavoidable least pre-shear calibration forces were automatically exerted by default settings on tested solutions, immediately after the highly viscous CD's solutions were deposited on the rheometer plate, prior testing.

15 cm, resulting in an electric field strength (E) of 1 ± 0.02 kV/cm. The polarity of the applied voltage was not found to influence the electrospinnability of any of the 2HP-β-CD solutions, indicating that tested solutions had a polarity independent charge carrying capability. Electrospun specimens were collected using a grounded aluminium foil substrate and subsequently stored in a temperature-controlled desiccator at low ambient humidity (38% ± 3 %), prior to characterization by clean room microscopy. The microstructures of the electrospun samples were examined with scanning electron microscopy (SEM, JEOL JCM-5000 NeoScope Tokyo, Japan). Specimens were observed by secondary electron imaging without the use of a conductive coating at an accelerating voltage of 10 kV in high vacuum mode.

2HP-β-CD/Hb-E solutions was higher than all tested samples, except for the case of 70 wt. %, where all values converted to a value of 9.5 (Figure 2). Such behaviour could be explained by the concentration dependency of the Hydronium ions (H$_3$O$^+$) mobility while in ethanol-acetone solution, and consequent effects on pH measurements. In contrast, surface tension showed an opposite behaviour, meaning values diverted at increased concentration. In other words, all 55 wt. % solutions showed surface tension values of around 60 to 65 x10^{-1} N/m, while 75 wt.% solutions showed surface tension values from around 60 to almost 75 x10^{-1}

N/m (Figure 4). Likewise, such effects might be attributable to the concentration dependency of water thermodynamic effects (evaporation) with added ionic salts and volatile solvent systems at contact with air. Lower surface tension values have been reported to be favourable to electrospinnability; as acknowledge by visco-elasto capillary theories, showing that an electrospinnable system will tend to minimise its total boundary energy (*i.e.* effectively the surface tension) to form continuous filaments [37,38]. Interestingly, 2HP-*β*-CD/Hb-E showed the lowest surface tension values for all solutions at the same time that good electrospinnability (Figure 4). Furthermore, 2HP-*β*-CD/Hb-E solutions at lower CD concentrations showed a relatively high conductivity (Figure 3) but poor electrospinnability (Figure 5B). Also, none of the 2HP-*β*-CD/Hb-D solutions did electrospin into fibres in spite of a higher conductivity compared to 2HP-*β*-CD/H_2O solutions. In contrast, electrospinnability for polymeric systems is known to be dependent

on the conductivity of the solution [1, 31-36]. In the present work, a consistent correlation between the conductivity of the CD solution (Figure 3) and resulting electrospinnability (Figure 5) was not observed. Therefore, it appears that conductivity of tested solutions cannot be directly linked to the electrospinnability of 2HP-*β*-CD.
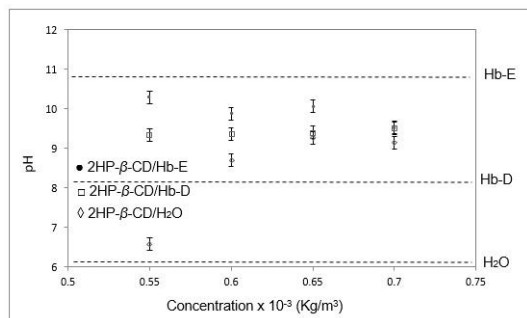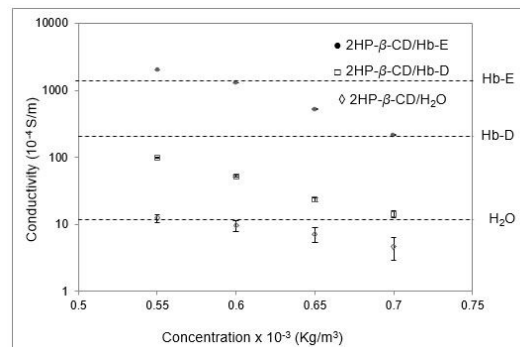

Figure 3. Conductivity of the 2HP-*β*-CD solutions as a function of solution type and concentration of 2HP-*β*-CD (error bars showing an average standard deviation of 0.86).
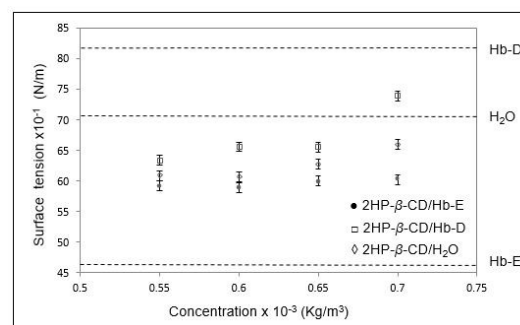

Figure 2. The pH of the 2HP-*β*-CD solutions as a function of solution type and concentration of 2HP-*β*-CD (error bars showing an average standard deviation of 0.16).

3.2. Effect of solution composition on the electrospinnability of 2HP-*β*-CD

Figure 4. Surface tension of the 2HP-*β*-CD solutions as a function of solution type and concentration of 2HP-*β*-CD (error bars showing an average standard deviation of 0.41).

Both stable and chaotic jet formation was observed for all 2HP-*β*-CD/H_2O and 2HP-*β*-CD/Hb-E 60 wt. % solutions. In contrast,

electrospraying of droplets occurred for all 2HP-*β*-CD/Hb-D solutions, with no jet formation observed (Figure 5C, 5F, 5I, 5L). Consequently, no fibre formation was observed during the electrospinning of any 2HP-*β*-CD/Hb-D. The electrospinning of 2HP-*β*-CD/H$_2$O solutions at concentrations of 55 and 60 wt. % resulted in electrospraying of droplets and bead-on-string structures, respectively (Figure 5A, 5D). However, 2HP-*β*-CD/H$_2$O exhibited beaded morphology and stable fibre formation at concentrations greater than 65 wt. % 2HP-*β*-CD. Interestingly, the electrospinning of 2HP-*β*-CD/Hb-E at concentrations of 60 and 65 wt. % resulted in fibres that fractured following deposition onto the collector (Figure 5E, 5F). The presence of fractured fibres may indicate differential shrinkage following deposition, due to a lack of crystallinity within the CD nanofibre, as already reported by Celebioglu A., and Uyar, T. [17, 25].
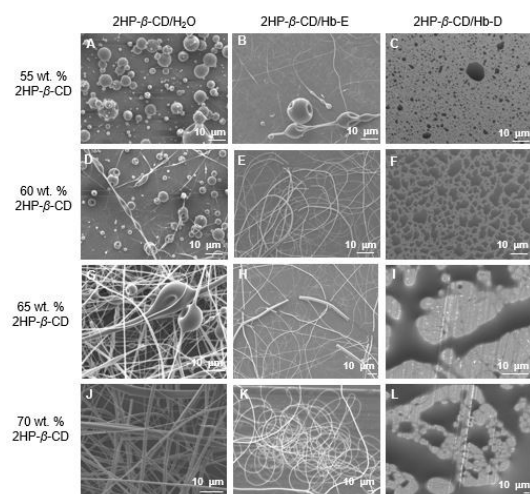

Figure 5. Scanning electron micrographs of as-deposited electrospun 2HP-*β*-CD samples as a function of CD concentration and solvent type.

3.3 Viscoelasticity of 2HP-*β*-CD solutions

Rheological measurements were used to compare the visco-elastic relationships between the electrospinnability of the 2HP-*β*-CD solutions with varying solvent systems. Shear thinning behaviour−−a decrease in the dynamic viscosity ($μ$) with increasing shear rate ($\dot{γ}$), was observed for all solutions during the rotational tests (Figures 6A, 6B and 6C). The frequency response of the 2HP-*β*-CD solutions showed that the solutions exhibit predominantly elastic behaviour over the angular frequency ($ω$) range investigated, as indicated by a storage modulus (G') at least an order of magnitude higher than the loss modulus (G'') (Figures 7A, 7B and 7C).

Reported literature values for the storage and loss modulus of native *β*-CD at 150% (w/v), are in agreement with shown values for 75% wt. % 2HP-*β*-CD ($10^4 – 10^6$ Pa) for both modulus (G' and G''), Figure 7 [25]. In contrast, reported viscosity values for native *β*-CD are between two to three orders of magnitude below the values obtained for 2HP-*β*-CD/H$_2$O and 2HP-*β*-CD/Hb-E solutions. Discrepancies with reported literature values could be attributed to the difference on the molecular weight of the *β*-CD derivative used (2HP-*β*-CD) on this work, with a relatively high molecular substitution per anhydrous glucose unit (0.57 - 1.29). Likewise, the 2-hydroxypropyl-*β*-cyclodextrin (2HP-*β*-CD) used on this work had a lower molecular weight than the 2HP-*β*-CD reported on literature (1460 g/mol) [18]. Such difference on the molecular weight might could also correspond to the variance on the reported viscosity values (Figure 6) [18]. Likewise, storage and loss modulus rheological data is not reported for other than 2HP-*β*-CD with a 0.6 to 0.9 molar averaged substitution. In contrast, 2HP-*β*-CD with a 0.57 to 1.29 anhydrous glucose substitution is reported on this work. Consequently, due to the lack of published *β*-CD density and molecular

weight values elsewhere on the electrospinning literature, further correlations to presented data can't not be made [16-18, 25].

In general, the 2HP-*β*-CD solutions exhibited weakly elastic behaviour above 65 wt. % 2HP-*β*-CD. The observed viscoelastic behaviour agrees in principle with the visco-elasto-capillary thinning theory of complex fluids. According to visco-elasto-capillary thinning theory, non-Newtonian fluids with shear thinning viscosity and $G' > G''$ at higher angular frequencies are able to better resist extensional capillary thinning and filament break-up when compared with Newtonian fluids for which $G' < G''$ at low angular frequencies [37-39].

Interestingly, no electrospinnability was observed for 65 and 70 wt. % 2HP-*β*-CD/Hb-D solutions, even with G' > G''. Also, 65 and 70 wt. % 2HP-*β*-CD/Hb-D corresponded to the highest surface tension values for all solutions at such concentrations, as well showing similar conductivity and pH values in respect to 2HP-*β*-CD/H$_2$O solutions at the same concentration range. Also, the fact that 60 wt. % 2HP-*β*-CD/Hb-E shows electrospinnability ($G' > G''$), in contrast to the 2HP-*β*-CD/H$_2$O solutions at the same concentrations and with $G' > G''$; suggests that the Hb-E solvent system had a positive impact on the density of the intermolecular interactions (hydrogen bonding) and consequent aggregate formation (electrospinnability) in comparison to water systems. This elastic behaviour is in agreement with earlier findings that reported non-linear viscoelasticity or solid-like behaviour of CD solutions due to extensive intermolecular hydrogen bonding [16-18]. Likewise, the above results suggest that the addition of urea salts to the aqueous 2HP-*β*-CD solutions does deters hydrogen bonding within solutions and prevents electrospinnability. Furthermore, viscosities

for 2HP-*β*-CD/H$_2$O at 65 and 70 wt. % were 5 orders of magnitude higher than those for 55 and 60 wt. % 2HP-*β*-CD (Figure 6A); suggesting a pronounced increase in intermolecular interactions between the CD molecules above 60 wt. % 2HP-*β*-CD. Similarly, 2HP-*β*-CD/H$_2$O exhibited elastic behaviour with a G' significantly higher than G'', at all concentrations (Figure 7A). In contrast, 2HP-*β*-CD/Hb-D solutions showed lower values of G' and G'' at low concentrations (55% to 60%) in comparison to higher concentrations of 2HP-*β*-CD/Hb-D solutions (Figure 6). Moreover, Hb-D based solutions with 65 or 70 wt. % 2HP-*β*-CD could not be electrospun into fibres even though $G' > G''$. In contrast, 2HP-*β*-CD/H$_2$O solutions showing $G' > G''$ could be electrospun into fibres. Also, the fact that 60 wt. % 2HP-*β*-CD/H$_2$O solutions displayed poor electrospinnability, in contrast to 60 wt. % 2HP-*β*-CD/Hb-E solutions showing similar viscoelastic behaviour ($G' > G''$) yet good electrospinnability (Figure 5D and 5E); further suggests that low surface tension and high conductivity might indeed have a noticeable effect on the electrospinnability of 2HP-*β*-CD (Figure 3 and 4). Certainly, viscosity and G' did not directly correlated to electrospinnability, adding evidence to the observations that influence of hydration on the electrospinnability of CDs on aqueous systems, is complex [40-42]. Moreover, the development of a plateau in G', over a wide range of angular frequencies, also suggests that the presence of aggregates of 2HP-*β*-CD causes the solution to exhibit gel-like behaviour (Figure 7). Furthermore, no crossover between G' and G'' was observed, hence Rousse relaxation times of tested solutions were not detectable over the range of frequencies investigated. Such non-linear visco-elastic behaviour is typically associated with materials with a high number of "associating networks", such as those described by the sticky reptation

model proposed by Rubistein *et al.* [43]. The sticky reptation model of associating networks proposes that fast reversible (short-term) bonds in supramolecular polymers, such as hydrogen bonds, can act as "sticky points" for the so called "associative supramolecular networks", and so dictate the long-term stress and strain dynamics of the bulk solution [43]. In other words, the

Figure 6. The dynamic viscosity as a function of the shear rate and 2HP-*β*-CD concentration at 50 °C; for A) 2HP-*β*-CD/H_2O, B) 2HP-*β*-CD/Hb-E and C) 2HP-*β*-CD/Hb-D.

Similarly, 2HP-*β*-CD/Hb-E samples exhibited $G' > G''$ for all 2HP-*β*-CD concentrations, however electrospinnability was not observed for 55 wt. % 2HP-*β*-CD/Hb-E (Figure 7). In contrast,

solution behaves as an interconnected network for time scales shorter than the lifetime of these reversible bonds. Moreover, dielectric or light scattering spectroscopy has shown that the oxygen atoms in a saturated aqueous CD solution could act as open-close stickers [44-46], with noticeable differences between α-, *β*- and γ-cyclodextrin (CDs) [40].

electrospinnability was not observed for any 2HP-*β*-CD/Hb-D solutions, regardless of $G' > G''$ at higher CD concentrations (Figure 7). Hence, 2HP-*β*-CD/Hb-D solutions can still form aggregates with themselves and bounded water in the presence of urea, possibly due to steric effects, as evidence by their viscoelastic behaviour ($G' > G''$) at higher 2HP-*β*-CD concentrations.
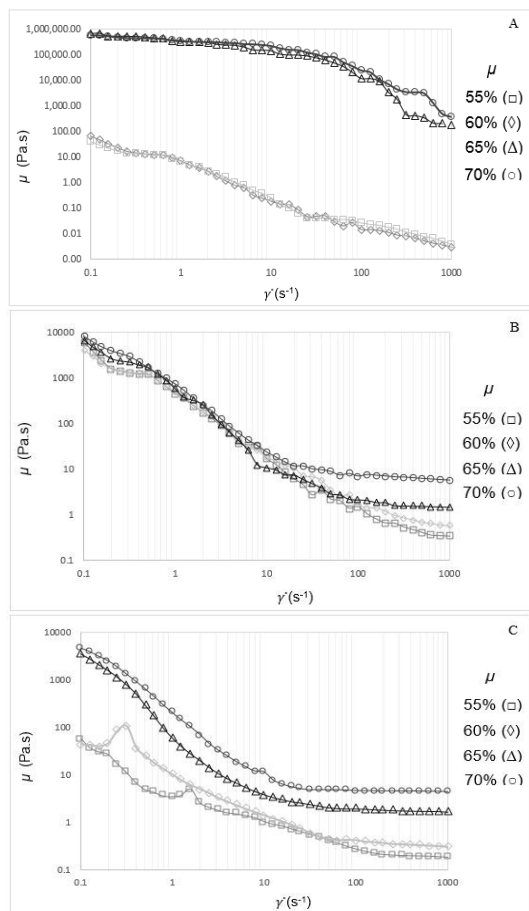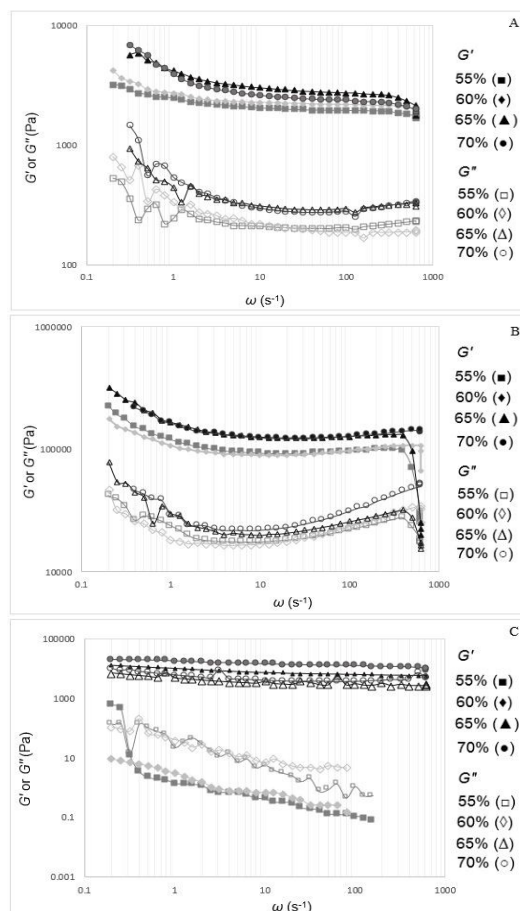
Figure 7. The storage and loss modulus as a function of the angular frequency and 2HP-*β*-CD concentration at 50 °C; for A) 2HP-*β*-CD/H$_2$O, B) 2HP-*β*-CD/Hb-E and C) 2HP-*β*-CD/Hb-D.

Alternative mechanisms for electrospinnability based on self-assembly have been proposed by others as a complementary mechanism to chain entanglement [14-18]. However, it is still not clear how Debye's length and other complex electrodynamic interactions caused by the high voltages that drive the electrospinning process relate to hydrogen bonding driven electrospinnability.

4. Conclusions

It is concluded that the electrospinnability of 2-hydroxypropyl–*β*-cyclodextrin (2HP-*β*-CD) solutions is strongly linked to the physical-chemical properties of tested solvent system based on the following observations.

- Hydrogen bonding disrupting solutions (2HP-*β*-CD/Hb-D) were not electrospinnable, whilst the hydrogen bonding promoting solutions (2HP-*β*-CD/Hb-E) could in turn be electrospun into fibres more easily (at lower concentrations), than aqueous solutions (2HP-*β*-CD/H$_2$O) (Figure 5).
- The electrical conductivity of 2HP-*β*-CD/Hb-E solutions at all 2HP-*β*-CD concentrations was higher than 2HP-*β*-CD/H$_2$O and 2HP-*β*-CD/Hb-D solutions (Figure 3). However, only 2HP-*β*-CD/Hb-E solutions at lower concentrations (60 wt. %) showed electrospinnability (Figure 5).
- 2HP-*β*-CD/Hb-E solutions exhibited lower surface tension and higher conductivity, compared to the other solutions, correlating with improved electrospinnability at lower concentrations (60 wt. %) (Figure 4 and 5).
- 2HP-*β*-CD/H$_2$O solutions showed the highest viscosity and improved electrospinability at higher concentrations, regardless of the presumed improved electrospinnability by increased solvent volatility, as evidence by 2HP-*β*-CD/Hb-E solutions (Figure 6).
- Linear viscoelasticity cannot be directly related to the hydrogen bonding capacity of the solutions, since the condition of $G' > G''$ could not be consistently related to the electrospinnability of the solutions as exemplified by 2HP-*β*-CD/Hb-D (Figure 7).

Conclusively, electrospinnability of 2HP-*β*-CD solutions depends on the formation hydrogen bonding networks, as evidence by the non-linear viscoelasticity and physical-chemical properties of tested solutions.

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