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Glass transitions and viscoelastic properties of Carbopol® and Noveon® compacts

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Abstract

Glass transitions of five varieties of Carbopol® (acrylic acid polymers cross-linked with allyl sucrose or allyl pentaerythritol) and two varieties of Noveon® (calcium salts of acrylic acid polymer cross-linked with divinylglycol) differing in cross-linking density and nature and content in residual solvents, were analysed (as compressed probes) by differential scanning calorimetry (DSC), modulated temperature differential scanning calorimetry (MTDSC), and oscillatory rheometry. All carbopol compacts showed a main glass transition, at a temperature between 130 and 140 °C, Tg, independently of their cross-linking degree and molecular weight. Additionally two batches of Carbopol® 971P, which had greater contents in residual solvents, also presented a secondary transition at 65–70 °C. Sorption of water during storage of carbopol compacts at different relative humidity environments caused the Tg to strongly decrease. Compacts stored at 97.5% relative humidity have Tg below 0 °C and behave, at room temperature, as flexible hydrogels. The Gordon-Taylor/Kelley-Bueche equation only fit the dependence of Tg on water content well for carbopol compacts containing less than 15% water. The plasticizing effect of water was clearly evidenced in the considerable decrease in the storage and loss moduli of the compacts. Although the energy associated to the glass transitions of carbopol polymers, 0.40–0.50 $\mathrm{J\,g^{-1}\,{}^{\circ}C^{-1}}$, is high enough to be clearly detected by DSC, in some cases the evaporation of residual solvents may make it difficult to observe the Tg. This inconvenience is overcome using MTDSC or oscillatory rheometry. The decrease in Tg of carbopol caused by water sorption when compacts were stored at 97.5% R.H. explains why their loss (G'') and storage (G') moduli at room temperature decreased four orders of magnitude. In contrast, in noveon varieties, calcium ions act as ionic cross-linkers of the carboxylic groups, providing rigid networks with much higher Tg, and storage and loss moduli. This explains that despite sorbing similar amounts of water to carbopol, the changes on the mechanical properties of noveon compacts were much less important (i.e., G' and G'' decreased up to one order of magnitude).

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Keywords: MTDSC; Poly(acrylic acid); Calcium polycarbophil; Water sorption; Cross-linking degree; Residual solvents

1. Introduction

The glass transition of an amorphous polymer, i.e., the change from a hard glassy form to a rubber-like plastic structure or a viscous fluid, is related to the onset of a certain degree of movement in the main chain and the rotation of side segments (Salmen and Back, 1977). At the temperature of the glass transition, Tg, the physical and mechanical properties of the material suffer considerable changes (Okhamafe and York, 1988). In consequence, the performance of numerous excipients during processes such as compaction (van der Voort Maarschalk et al., 1998), drying and storage

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(Her and Nail, 1994; Ferrero et al., 1999), thermal annealing (Omelczuk and McGinity, 1993) or film formation during coating of solid drug dosage forms (Okhamafe and York, 1988) strongly depends on their Tg.

Drugs or other excipients may act as plasticizers and significantly modify the Tg of the amorphous polymers on which the formulations are based (Nair et al., 2001; Schubnell and Schawe, 2001). Also, the dosage forms may contain significant amounts of water, intentionally added or spontaneously absorbed from the environment during processing or storage, which results in a decrease in the Tg of this kind of excipients (Hanckock and Zografi, 1994). On the other hand, glass-rubber transition that occurs in polymeric matrices during the penetration of water determines the drug release profile (Korsmeyer and Peppas, 1981; Alvarez-Lorenzo et al., 2000). These facts should be taken into account to optimise the performance of the formulation; for example, the storage of pellets or beads, made with cellulose derivatives, under adequate humidity and temperature conditions may make it possible to obtain sustained drug release (Williams and Liu, 2001; Kojima and Nakagami, 2002). Therefore, the determination of Tg of pharmaceutical excipients and the knowledge of the factors that may alter its value are of a great importance in the development of any solid drug dosage form.

Tg determination of amorphous polymers is usually carried out by differential scanning calorimetry (DSC) as powders (Greenberg and Kusy, 1980; Hancock and Zografi, 1994) or films (Nair et al., 2001). The glass transition is accompanied by an increase in heat capacity and, in many cases, it is shown as a relaxation endotherm. When the associated change in heat capacity is too small to be detected using a conventional DSC, modulated temperature differential scanning calorimetry (MTDSC) may be very useful (Coleman and Craig, 1996; Nyamweya and Hoag, 2000). The ability of MTDSC to divide the total heat flow into heat capacity and kinetic components (DSC only measures the total heat flow) permits the separation of overlapping phenomena and deconvolution of complex transitions, greater resolution without loss of sensitivity (signal-to-noise ratio at least double that of DSC), and greater ease of collection of heat capacity data (Verdonck et al., 1999; Hill et al., 1999; Schubnell and Schawe, 2001). The advantages of this technique have been outlined, for example, for cellulosic derivatives (McPhillips et al., 1999; Nyamweya and Hoag, 2000). Oscillatory rheometry has recently been adapted to the analysis of solid systems (TA Instruments, DE, USA). This technique, which is based, as the dynamic mechanical analysis (DMA), on the application of a sinusoidal stress at a fixed frequency to the material while the temperature is varied, allows a more complete characterization of the viscoelastic behaviour of a variety of materials, not only as films but also as relatively thick solids or even as probes obtained by compaction of powders (Alvarez-Lorenzo et al., 2002; Gómez-Carracedo et al., 2003). Applying oscillatory rheometry, the primary glass-rubber transition, α-transition, is characterized by a large decrease in the storage modulus, G', and a maximum in both the loss modulus, G'', and in the ratio of the loss to the storage moduli, $\tan\delta$ (Rieger, 2001). Secondary transitions, β- or γ-transitions, may also be detected in some polymeric materials (Alvarez-Lorenzo et al., 2002).

Table 1
Structural characteristics and residual solvents content of the polymer studied (Noveon, 2002)

Polymer	Variety	Calcium content (%)	Molecular weight between adjacent cross-links (Mc)	Residual solvent
Carbopol®	971P	0	237600	Ethylacetate (<0.5%)
	974P	0	104400	Ethylacetate (<0.7%)
	71G	0	237600	Ethylacetate (<0.7%)
	934	0	104400	Benzene (<0.2%)
	934P	0	104400	Benzene (<100 ppb)
Noveon®	CA-1	18.3	144[a]	Water (7.0%)
	CA-2	18.5	144[a]	Water (8.7%)

[a] Estimated from their content in calcium ions.

Poly(acrylic acid)s are widely used excipients to prepare tablets, pellets, and other dosage forms (Dittgen et al., 1997). The Carbopol® resins are composed of acrylic acid polymers that have been cross-linked to different extents with allyl ethers of either sucrose or pentaerythritol, while the Noveon® ones are calcium salts of acrylic acid polymer cross-linked with divinylglycol (Table 1; Noveon, 2002). The information regarding their Tg values is mostly limited to the influence of some plasticizers on the Tg of carbopol films (Kanis et al., 2000). The aim of this study was: (a) to characterize the glass transitions of several varieties—including various batches of some of them—of Carbopol® and Noveon®, differing in cross-linking density and in nature and content in residual solvents; (b) to evaluate the effect of water content on the Tg of the products and establish its repercussion on the mechanical properties of their compacts at room temperature; and (c) to ascertain the usefulness of DSC, MTDSC, and oscillatory rheometry in the characterization of these products.

2. Materials and methods

2.1. Materials

Carbopol® 971P (batches aj01276, aj00695, cc7naaj041, and cc76aaj022), Carbopol® 974P (batches ab17796, ab17196, cc85aab447, cc78aab278), Carbopol® 71G (batch C7075GJ013), Carbopol® 934 (batch CC75HBB582), Carbopol® 934P (batch BB039D5), Noveon® CA-1 (batch Z837096) and CA-2 (batch Z765094) were provided by Noveon Inc., Cleveland, Ohio.

2.2. Sample preparation

Rectangular probes (14 mm × 10 mm) of 1.5–2.0 mm thickness of carbopol or noveon were prepared by direct compression in a Korsch Eco (Erweka, Germany) eccentric tableting machine, using rectangular punches, and applying a compression force of 20,500 ± 500 N. Compacts were stored at 20 °C in environments of relative humidity (RH) of 18.8, 47.2, 70.4 (three months) or 97.5% (three or eight months), created with sulphuric acid solutions of different concentrations (West, 1990). For DSC and MTDSC studies, pieces of compacts were cut and used directly.

2.3. Determination of water content

The total water content of the polymers and the compacts was determined by thermogravimetrical analysis as the loss in weight, after heating 3–4 mg samples at 10 °C min^{-1} up to 105 °C and maintaining this temperature for 120 min, in a TGA-50 (Shimadzu, Japan). Additionally, experiments were carried out with samples in aluminium pans covered with the lid, as for the DSC experiments and at the same ramp of temperature (see below), in order to estimate the exact content in water of the polymers at the Tg (Royall et al., 1999).

2.4. Determination of glass transition temperature

2.4.1. DSC and MTDSC studies

Calorimetric characterization of carbopol and noveon as powders and compacts was carried out, in triplicate, using a DSC Q100 (TA Instruments, DE, USA) with a refrigerated cooling accessory and modulated capability. Nitrogen was used as the purge gas at a flow rate of 50 ml min^{-1}. The calorimeter was calibrated for baseline using no pans, for cell constant and temperature using indium (melting point 156.61 °C, enthalpy of fusion 28.71 J g^{-1}), and for heat capacity using sapphire standards. All experiments were performed using non-hermetic aluminium pans, in which 5–10 mg samples were accurately weighed, and then just covered with the lid. The samples were loaded on an autosampler tray. Samples for the DSC study were program-heated from 30 to 220 °C, then cooled to 0 °C, and finally heated to 220 °C again, always at the rate of 20 °C min^{-1}. MTDSC experimental conditions were as follows: after equilibration at 40.0 °C, the temperature rises to 260 °C, at 3 °C min^{-1}, using a modulation amplitude of ±1 °C every 100 s. For the compacts stored at 97.5% RH, the temperature scan was started at −30 °C. The total heat flow signal was separated (applying the Fourier Transform algorithm; Universal Analysis 2000, v.3.3B, TA Instruments) into a heat capacity component (reversing heat flow) and a kinetic component (non-reversing heat flow), as shown in Eq. (1),

$$\frac{dQ}{dt} = C_p \frac{dT}{dt} + f(t, T) \qquad (1)$$

where d*Q*/d*t* is the total heat flow, C_p is the heat capacity, d*T*/d*t* is the heating rate, and *f*(*t*,*T*) represents the heat flow from events which are a function of time and absolute temperature (kinetic events) (Verdonck et al., 1999; Hill et al., 1999; Schubnell and Schawe, 2001). Tg was reported as the midpoint of the temperatures at which the beginning and the ending of glass transition were observed by DSC or MTDSC.

2.4.2. Oscillatory rheometry

The temperature dependence of the storage and loss moduli (G' and G'', respectively) and of $\tan\delta$ ($=G''/G'$) of dry carbopol and noveon compacts was recorded in a Rheolyst AR1000N rheometer (TA Instruments, New Castle, DE, USA) equipped with an AR2500 data analyser, an environmental test chamber and a solid torsion kit. The sample was fixed between two clamps separated 9.5 ± 0.5 mm. The experiments were carried out in triplicate for an angular frequency of 1 rad/s by measuring these parameters while increasing the temperature from 25 to 220 °C at 3 °C min^{-1}. The temperature at which $\tan\delta$ reached the maximum was considered the Tg.

2.4.3. Influence of water on the Tg

A simplified Gordon-Taylor/Kelley-Bueche equation (Hancock and Zografi, 1994) was fitted to the plot of Tg versus water content as follows:

$$\mathrm{Tg}_{\mathrm{mix}} = \frac{w_1 \mathrm{Tg}_1 + K w_2 \mathrm{Tg}_2}{w_1 + K w_2} \qquad (2)$$

where w is the weight fraction of water (component 1) and polymer (component 2) and K is a constant calculated from the densities of the two components ($K = \rho_1 \mathrm{Tg}_1 / \rho_2 \mathrm{Tg}_2$). If the densities were equal, the equation simplifies to:

$$\frac{1}{\mathrm{Tg}_{\mathrm{mix}}} = \frac{w_1}{\mathrm{Tg}_1} + \frac{w_2}{\mathrm{Tg}_2} \qquad (3)$$

which is known as the Fox equation.

2.5. Characterisation of the viscoelastic behaviour at room temperature

The storage and loss moduli of freshly prepared compacts and after being stored at different relative humidity environments (see Section 2.2) were evaluated in triplicate at 20 °C, applying 0.5% strain and angular frequencies of 0.05–50 rad s^{-1} in the Rheolyst AR1000N rheometer described above.

2.6. Determination of the crushing strength

The crushing strength was determined in an Erweka TB24 apparatus (Heusenstamn, Germany) laying the compacts on the longer side.

3. Results and discussion

To carry out the study five varieties of carbopol and two varieties of noveon, differing in cross-linking degree and molecular weight were chosen. It is known that batches of the same carbopol variety may differ significantly in thickening capacity or carboxylic acid groups content. These differences could affect the behaviour of the dosage forms in which this polymer is used as base excipient (Pérez-Marcos et al., 1993). Therefore, to evaluate the incidence of inter-batch differences, four batches of Carbopol® 971P and four batches of Carbopol® 974P were also analysed (Table 1). Carbopol® 971P and 71G varieties have higher molecular weight between adjacent cross-links, Mc, and conversely lower cross-linker densities (loose *fishnet* conformation) than Carbopol® 974P, 934 and 934P varieties (*fuzzball* structure) (Noveon, 2002). Although the determination of the total molecular weight of cross-linked polymers is quite complex compared to linear polymers, values of about 1.25×10^6 (Carbopol® 971P and 71G) and 3×10^6 (Carbopol® 974P, 934 and 934P) have been reported (Noveon, 2002).

Fig. 1 shows the DSC thermograms of some carbopol and noveon compacts. The first scan showed an endotherm between 50 and 100 °C corresponding to the evaporation of the moisture content (around 2–4% for carbopol samples and 9–10% for noveon products) and a poor resolved change in the baseline of carbopol samples, related to the Tg, at 120–130 °C. The second heating run was similar for all batches of carbopol, which showed Tg values around 130–140 °C, as previously reported for carbopol films (Kanis et al., 2000). However, two of the four batches of the variety 971P, aj00695 and cc76aaj022, had an additional glass transition at lower temperatures, detected by DSC (Fig. 1), MTDSC (reversing heat flow signal, Fig. 2) and oscil-

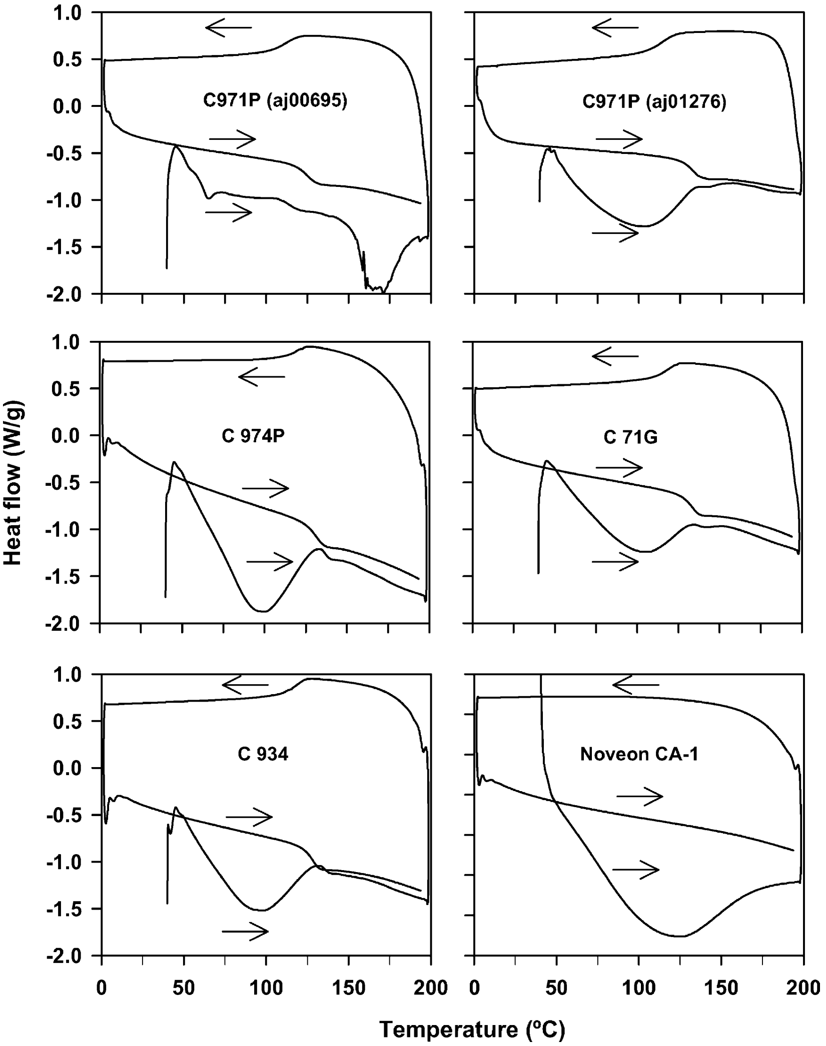

Fig. 1. DSC thermogram of compacts of some varieties and batches of carbopol and noveon.

latory rheometry (Fig. 3). This behaviour may be related to the different content of the batches in residual solvents that act as plasticizers but evaporate easily when temperature increases, the polymer then showed the characteristic Tg at around 135 °C. The occurrence of several Tgs was also seen by DSC in linear poly(acrylic acid)s by Park et al. (1991). The lower Tgs were related to the plasticizing effect of the remaining solvent used for synthesis. In the case of our products, the information supplied by the manufacturer about Carbopol® 971P varieties, indicates that batches aj00695 and cc76aaj022 contain more benzene (275–300 ppm) and residual solvents (0.22%) than the other two batches (150–170 ppm; 0.17%), although below the USP 24ed. limit. In the FT-IR spectra, the residual solvent produces a decrease in the absorption intensity at 3000–3500 cm^{-1}, owing to a lower degree of hydrogen bonding among the carboxylic acid groups (Fig. 4; Park et al., 1991).

No glass transitions were found for noveon varieties by any of the techniques used. The main difference between carbopol and noveon products is that, while in the first one the carboxylic acid groups remain protonized, in the second they are forming complexes

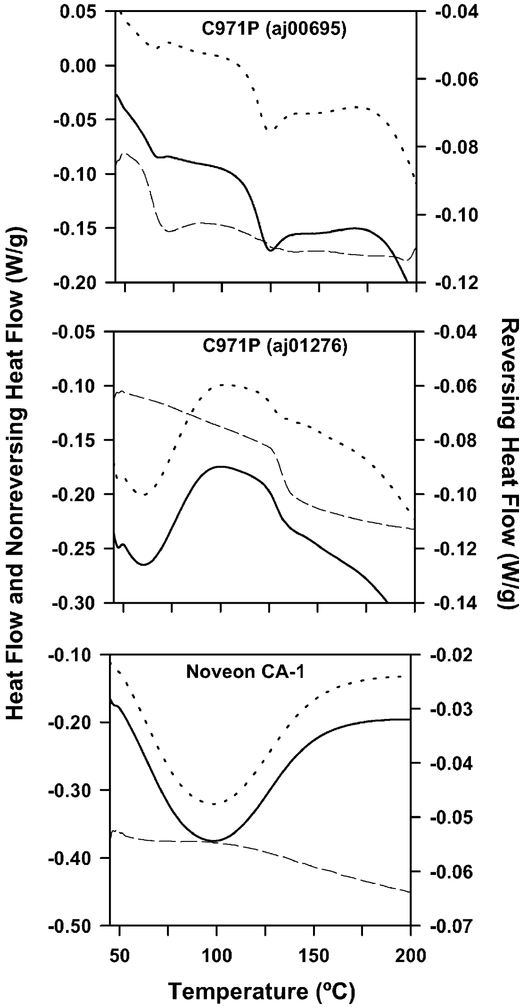

Fig. 2. MTDSC scans of compacts of Carbopol® 971P (two batches) and of Noveon® CA-1 (one batch), showing separation of the response into reversing (dashed line) and non-reversing (dotted line) heat flow signals.

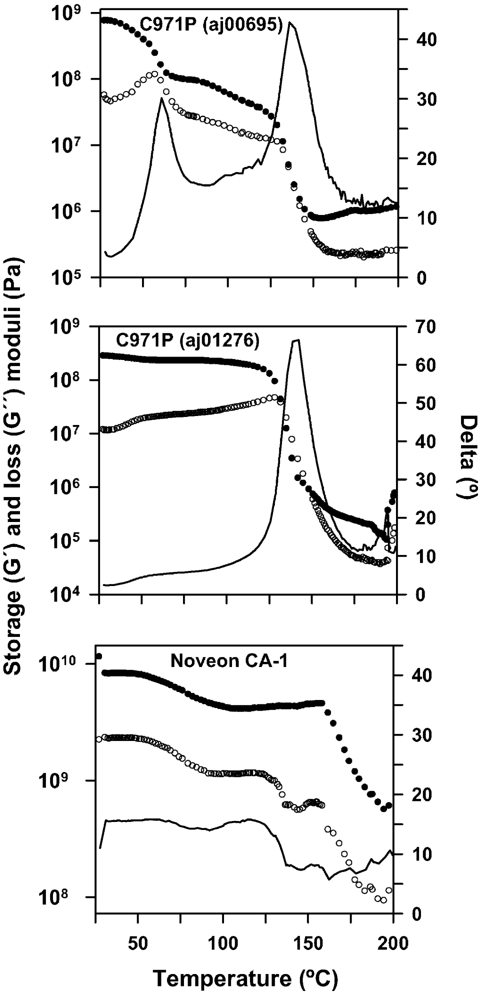

Fig. 3. Influence of the temperature on the storage modulus (G', solid symbols), loss modulus (G'', open symbols), and delta values (δ, line) of compacts of Carbopol® 971P (two batches) and of Noveon® CA-1 (one batch), determined by oscillatory rheometry.

with calcium ions. These structural differences are clearly seen in their FT-IR spectra (Fig. 4): carbopol samples have a strong band at 1710 cm^{-1}, which is characteristic of non-ionized carboxylic groups, while in noveon products a broad band at around 1550 cm^{-1} and a medium intensity band at 1410 cm^{-1} indicate that the carboxylic groups are ionized (Juang and Storey, 1998). Therefore, the characteristic intra- and inter-molecular interactions through hydrogen bonding among carboxylic acid groups of carbopol (Park et al., 1991; Dong et al., 1997; Barreiro-Iglesias et al., 2002) are disrupted in noveon and a rigid ionically cross-linked network, with a much higher Tg, is formed. Even increasing the DSC scanning up to 350 °C, no glass transition was found for noveon compacts. Greenberg and Kusy (1980) and Zawadzki et al. (1996) observed that increasing the degree of cross-linking of acrylic polymers, the Tg also increases. When the cross-linker is above 30 mol%, the Tg is accompanied by a shallower, less distinct transition region that can no longer be resolved. The differences in cross-linking degree among carbopol

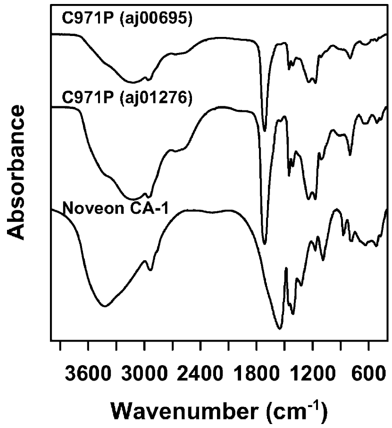

Fig. 4. FT-IR spectra of compacts of Carbopol® 971P (two batches) and of Noveon® CA-1 (one batch).

varieties seem not to be high enough to be detected as changes in Tg. As an average, carbopol resins have 1450–3300 monomer units between adjacent covalent cross-linkers (Carnali and Naser, 1992; Noveon, 2002). In contrast, considering the amount of calcium ions in noveon products, less than two monomer units remain free between adjacent ionic cross-linkers. This explains why Tg is not observed in noveon compacts.

Table 2 summarizes the Tg values obtained for each product applying the three techniques. The small discrepancies that are observed may be due to the sample size and the fact that the physical properties measured with each procedure are different (Rieger, 2001). The main advantage of using MTDSC compared to DSC is that the first technique permits the separation of accompanying enthalpic events (e.g., evaporation of residual moisture) and a single sample run is enough to measure the change in heat capacity. The MTDSC conditions were chosen based on previous work which reported that long period times (100 s) and large modulation amplitudes (±1 °C) are able to obtain good accuracy and signal-to-noise ratios (Coleman and Craig, 1996). At least four modulation cycles took place during each transition. The energy associated to the glass transitions of carbopol products, 0.40–0.50 $\mathrm{J\,g^{-1}\,{}^{\circ}C^{-1}}$, is sufficient to be clearly detected by DSC and much greater than that associated to the transitions of other polymeric excipients, such as cellulose ethers (0.03–0.10 $\mathrm{J\,g^{-1}\,{}^{\circ}C^{-1}}$; Gómez-Carracedo et al., 2003).

In all cases, the different behaviour of the polymers was more clearly seen applying oscillatory rheometry (Fig. 3), since the changes in the storage, G', and loss, G'', moduli around Tg were particularly intense. At temperatures below Tg, all carbopol compacts showed high values of storage and loss moduli. Glass transition caused G' and G'' to decrease by about three or-

Table 2
Tg of compacts of the poly(acrylic acid) resins, determined by DSC, MTDSC and oscillatory rheometry

Polymer	Variety	Batch	Glass transition temperatures (°C)			
			DSC		MTDSC	Oscillatory rheometry
			Powder	Compacts		
Carbopol	971P	aj01276	134	130	140	141
		aj00695	70, 134	70, 124	70, 134	72, 140
		cc7naaj041	133	133	126	139
		cc76aaj022	65, 134	65, 126	65, 130	60, 135
	974P	ab17796	135	132	126	141
		ab17196	135	119	128	139
		cc85aab447	134	128	144	138
		cc78aab278	134	115	125	141
	71G	c7075gj013	133	133	142	141
	934	cc75hbb582	132	128	126	139
	934P	bb039d5	134	131	139	140
Noveon	CA-1	Z837096	n.d.	n.d.	n.d.	n.d.
	CA-2	Z765094	n.d.	n.d.	n.d.	n.d.

The values were reproducible to about ±1 °C ($n = 3$); n.d.: not detected.

ders of magnitude. Tg is shown as a peak in the plots of tan δ against temperature, except in the case of two batches of Carbopol® 971P (aj00695 and cc76aaj022) for which a secondary peak was also recorded. In contrast, noveon compacts presented greater rigidity and stability against temperature. Only above 160 °C, did G' and G'' slowly begin to decrease. Nevertheless, at 200 °C, their values were still as great as the values shown by carbopol compacts at room temperature, which is again related to the greater cross-linker degree of noveon products.

To evaluate the influence of storage at different environmental RH on the Tg and viscoelastic properties of the compacts at room temperature, Carbopol® 971P batches aj01276 (showing one Tg) and aj00695 (showing two Tgs), Carbopol® 974P batch ab17796, and Noveon® CA-1 were chosen. After being stored for three months, all carbopol compacts showed a similar evolution, but significantly different to noveon compacts. Carbopol compacts stored at 18.8, 47.2 or 70.4% RH presented an important increase in weight (up to 8, 15, and 19% final water content, respectively) but kept their initial white colour and consistency. In contrast, the compacts that were kept at 97.5% RH became almost transparent, like flexible pieces of hydrogel (33–35% in water at three months and 40–53% in water at eight months). The glass transition was estimated by DSC and MTDSC. Since the experiments were carried out using non hermetic but covered pans, to avoid overpressure in the most wet samples and to ensure the reproducibility of baselines (Hill et al., 1999), some water may be evaporated during heating. Therefore, the water content at the Tg was calculated as the total content in water of each sample less the amount evaporated during its heating in the covered pan until the Tg was reached (between 0.5 and 1.0 wt.%) (Royall et al., 1999). Only one glass transition was observed in all cases, and the Tg decreased with water content as shown in Figs. 5 and 6. Oscillatory rheometry was not used to determine the Tg of wet compacts because in the environmental conditions of the assay during heating, the samples quickly lose water.

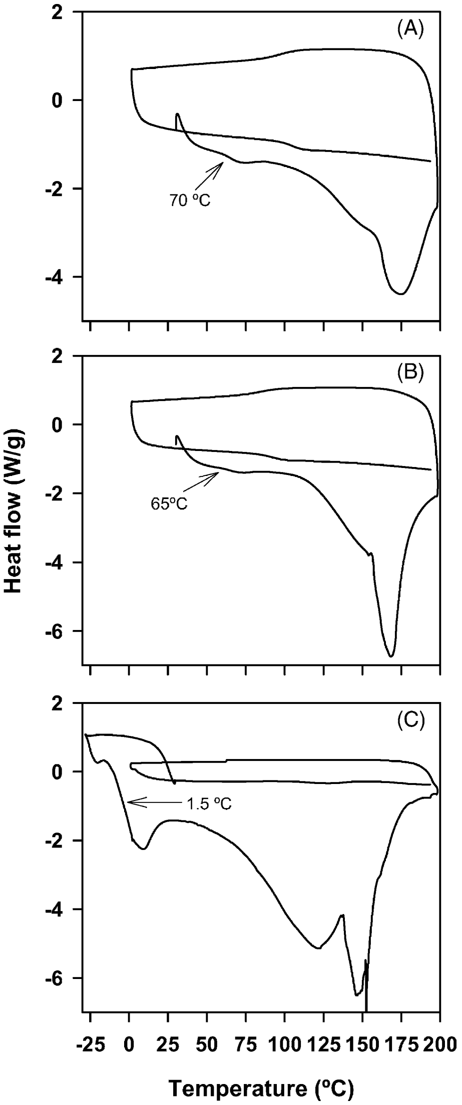

Fig. 5. DSC thermograms of compacts of Carbopol® 974P (batch ab17796) after being stored at 20 °C for three months in environments of relative humidity 47.2% (15.2% water content, A), 70.4% (19.0% water content, B), and 97.5% (33.3% water content, C).

The experimental values of Tg were compared with those predicted applying the Gordon-Taylor/Kelley-Bueche equation (Eq. (2)) that relates the Tg values with the water content of amorphous solids. To estimate the value of the constant K, the values used for density and glass transition temperature of water were 1 kg l^{-1} and 135 K (Hancock and Zografi, 1994). Two limit values of carbopol density were considered: 1.4 kg l^{-1}, reported by the manufacturer, and 1.5 kg l^{-1}, obtained previously in our lab for several batches (Pérez-Marcos et al., 1993). The values of K obtained, 0.2233 and 0.2393, were in the range of other amorphous pharmaceutical excipients

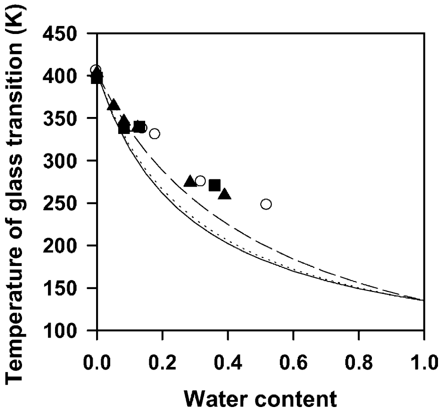

Fig. 6. Dependence of the glass transition temperature determined by DSC of carbopol compacts on their water content ((○) C974P, (■) C971P (aj00695), (▲) C971P (aj01276)). Lines represent the values predicted from Eq. (2) using K values of 0.2233 (solid line) and 0.2393 (dotted line), and from Eq. (3) (dashed line).

(Hancock and Zografi, 1994). As can be seen in Fig. 6, the Gordon-Taylor/Kelley-Bueche equation fits the Tg values obtained in the lowest RH environments well. However, a significant deviation was found for the compacts with a greater water content, which presented higher Tg than the values theoretically expected. This effect may be related to the strong capacity of carbopol to interact with water; as all water is bound to the polymer, the DSC not featuring the exothermic crystallization of free water (see Fig. 5C). Additionally, the hydration process of carbopol is strongly exothermic (Gómez-Carracedo et al., 2001) and is accompanied by a considerable swelling of the polymer. This may result in a change in its free volume, affecting the value of K, and/or in the formation of the hydrogen bonding network in which water molecules act as binding bridges among carbopol chains, not allowing them to increase their relative mobility as much as expected (Hancock and Zografi, 1994; Nair et al., 2001).

The strong plasticizing effect of sorbed water became evident as a considerable decrease in the rigidity of carbopol compacts after storage at 20 °C (Fig. 7A). However, the effects on G' and G'' were not proportional to their water content. Compacts stored at 47.2% RH showed a less than one order of magnitude decrease in their G' and G'' compared to the freshly prepared compacts. In contrast, the values of G' and G'' for compacts stored at 97.5% RH, which had a Tg below room temperature, were almost four orders of magnitude lower, showing viscoelasticity similar to that of that of the highly hydrated flexible hydrogels used for implants (Refojo and Leong, 1981). The compacts, which when dry had a crushing strength of 90 N, deformed elastically once hydrated, and it was not possible to determine their crushing strength.

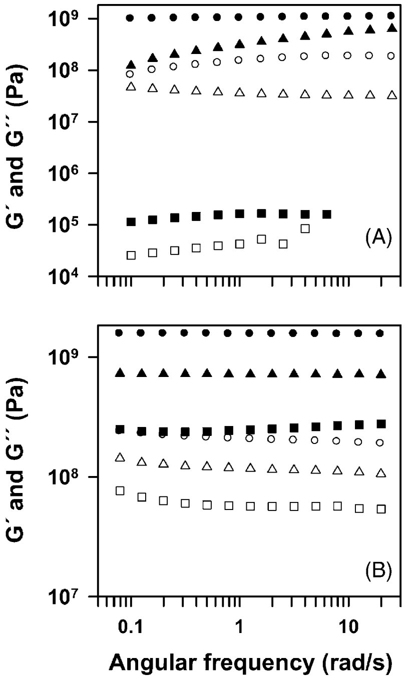

Fig. 7. Dependence on angular frequency, at 20 °C, of the storage, G' (solid symbols) and loss, G'' (open symbols) moduli of (A) Carbopol® 974P (batch ab17796) and (B) Noveon® CA-1 (batch Z837096) compacts stored at 47.2% (●, ○), 70.4% (▲, △), and 93.9% R.H. (■, □).

Noveon compacts sorb less water from the environment than carbopol compacts. When they were stored at 47.2, 70.4 or 97.5% RH gained in weight up to 12, 17 and 27%, increased their dimensions up to 4, 8, and 16%, and decreased their crushing strengths from 55 to 50, 45, and 45 N, respectively. Despite these changes, no glass transitions were observed using any of the three techniques and, at room temperature, only a small decrease in the loss and storage moduli was observed for compacts stored at 97.5% RH (Fig. 7B).

4. Conclusions

Carbopol and noveon compacts present considerable differences regarding their calorimetric and mechanical behaviour. Complex formation of calcium ions with the carboxylic acid groups of poly(acrylic acid) increases the rigidity of the network and, in consequence, the Tg of noveon products is not detected below 350 °C. In contrast, all compacts made of carbopol showed a main glass transition around 130–135 °C, which is not dependent on their cross-linking degree and molecular weight. The remanence of residual solvents, which alter the hydrogen bonding interactions among the carboxylic acid groups, may be responsible for the apparition of a secondary transition at lower temperatures in some batches of Carbopol® 971P. These differences among batches have important repercussions on the mechanical behaviour of their freshly prepared compacts. Sorption of water during storage at different relative humidity environments causes the Tg of carbopol to strongly decrease, but less than predicted by the Gordon-Taylor/Kelley-Bueche equation. Deviations of the theoretical behaviour may be related to the strong interaction between water and carbopol and the subsequent swelling of the polymer. The plasticizing effect of water is clearly evidenced in the considerable decrease in the elastic and viscous moduli of carbopol compacts at room temperature. This effect was not observed for noveon compacts. The three techniques evaluated—DSC, MTDSC, and oscillatory rheometry—provide useful complementary information and make it possible to relate the changes in Tg with the modification of the mechanical properties of the compacts at the temperature at which solid drug dosage forms are usually stored and administered.

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