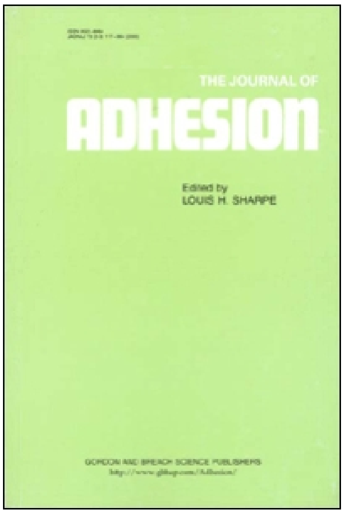

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Synthesis and characterization of a new acrylic adhesive mixture for use in ocular strabismus surgery

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SYNTHESIS AND CHARACTERIZATION OF A NEW ACRYLIC ADHESIVE MIXTURE FOR USE IN OCULAR STRABISMUS SURGERY

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A new series of acrylic adhesive mixtures was specifically designed for use in strabismus surgery, more precisely to join the rectus muscles to the sclera. These two-part adhesives consisted of a mixture of ethyl cyanoacrylate (CN) and ethyl carboxyacrylate (ECA). ECA acted as a plasticizer imparting flexibility to the CN, and also as a nonreactive diluent, serving to reduce the exotherm in the reaction between CN and eye tissues. In this article, the synthesis of the ethyl carboxyacrylate is described, and the properties of different ethyl cyanoacrylate + ethyl carboxyacrylate mixtures were studied.

The curing reaction of the adhesive mixtures was monitored using Fourier transform infrared (FTIR) spectroscopy and scanning differential calorimetry (DSC). The rheological properties of the cured CN-ECA adhesive films were studied using plate-plate rheometer experiments. To quantify the adhesion, single lap-shear tests produced between a rubber and the adhesive mixtures were performed and, to evaluate the adhesion to eye tissues, tensile strength measurements of superior rectus muscle/adhesive mixture/sclera joints were carried out.

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The 70CN-30ECA (v/v) adhesive mixture provided the most adequate balance between adhesion and mechanical properties in the joining of the superior rectus muscle to the sclera. The glass transition temperature of the CN-ECA adhesive mixtures linearly decreased with increase in the ECA content, and a lower degree of conversion during polymerization was obtained by increasing the ECA content. As a consequence, the CN-ECA mixtures were less stiff than CN, giving better performance in the joining of the rectus muscles to the sclera. Finally, the adhesion of CN was sufficiently decreased in CN-ECA mixtures, and the locus of failure was directed to the adhesive film in the joint between the rectus muscles and the sclera.

Keywords: Adhesion; Acrylic adhesive; Strabismus surgery; DSC; Rheology

INTRODUCTION

Adhesives intended for use in the bonding of human tissues are generally called bioadhesives. The advantage of the use of bioadhesives to join human tissues as compared with the traditional suture is the creation of a more homogeneous and uniform distribution of stresses along the joint. Furthermore, the bioadhesives are easy to apply, reduce the surgical time, avoid the damage produced by sutures, inhibit scar formation, and eliminate the need to remove sutures or bandages after surgery.

Tissues can be effectively joined by means of bioadhesives. Since 1950, cyanoacrylate adhesives have been used in surgical practice [1]. Coover *et al.* [2], Bloomfield *et al.* [3], and Refojo *et al.* [4] applied cyanoacrylate adhesives to join different human tissues. Several recent studies [5–7] have shown appropriate effectiveness of the bioadhesives as an alternative to suturing. Cañizares-Grupera *et al.* [5, 6] carried out research using alkyl cyanoacrylates as skin sealants for plastic surgery. The study compared the effectiveness of the suture and the application of bioadhesives in 100 patients with 225 skin wounds and 16 nasal implants. Similar performance was obtained by using the suture and the bioadhesives. López-Martínez *et al.* [7] studied the difference between the adhesive joint produced with a cyanoacrylate and the nylon suture in surgical wounds of female rats. The performance was satisfactory using both techniques.

Cyanoacrylates show polymerization in the presence of bases, such as water. Ocular tissues have a high concentration of water, so in most cases cyanoacrylate adhesives for ophthalmic surgical practice are not adequate due to their high reactivity. The joints achieved are very stiff and the exothermicity of the polymerization reaction is high, producing tissue necrosis.

However, bioadhesives have scarcely been used in ophthalmic surgical practice. Their application in eye surgery was not properly developed mainly due to the stiffness of the currently existing adhesives. Although several cyanoacrylate adhesives exhibit excellent performance (Dermabond, and Tissuacryl, notably) [8], none of them are flexible enough to allow the joining of the sclera to the rectus muscles in eye surgery. Therefore, ocular tissues adhesives are still an area of research.

Gasset *et al.* [9] tested different cyanoacrylates for corneal surgery; a mild inflammatory reaction was found. Robin *et al.* [10] proved that the application of an excess of cyanoacrylate adhesive for corneal surgery produced a chronic inflammatory reaction. Sakla *et al.* [11] and Alió *et al.* [12] evaluated the efficiency of several alkyl cyanoacrylate adhesives for cataract surgery, conjunctival surgery [13], and closure of scleral tunnel surgery [14]. In 1981, Flick [15] carried out Faden's operation (*i.e.*, the correction of strabismus) using a cyanoacrylate adhesive. The sealing of the superior and inferior rectus muscles and sclera was so fast that repositioning was not possible and, therefore, the adhesive was not adequate.

In this study, the synthesis and characterization of a series of acrylic adhesive mixtures based on the mixture of a new acrylic derivative (ethyl carboxyacrylate) and ethyl cyanoacrylate, for use in strabismus surgery, was carried out. The ethyl cyanoacrylate-ethyl carboxyacrylate mixtures are able to polymerize in a high moisture content environment, producing less exothermal reaction than cyanoacrylate adhesives, and the polymer obtained after curing is less stiff (*i.e.*, more flexible).

Strabismus, more commonly known as crossed-eyes, is a vision condition in which a person can not align both eyes simultaneously under normal conditions. Strabismus involves deviation of the alignment of one eye in relation to the other. It is caused by a lack of coordination between the eyes. As a result, the eyes look in different directions and do not focus simultaneously on a single point. There are 6 muscles attached to the ocular globe—4 rectus muscles and 2 oblique muscles. To alleviate many strabismus conditions, one or more of the 6 ocular muscles are repositioned on the sclera of the eye. Initially, strategies to strengthen the weakened muscles and, thereby, realign the eyes, consists in producing a small incision on each side of the eyeball in the tissue between the eye and eyelid. One or more of the muscles of the eye are strengthened (resected) or weakened (recessed) to allow proper position and movement of the eyeball. Often, an adjustable suture will be used so that minor adjustments can be made later that day or the next day. One alternative to suturing is the joining of the muscles to the sclera by using adhesives. This strategy was followed in this study.

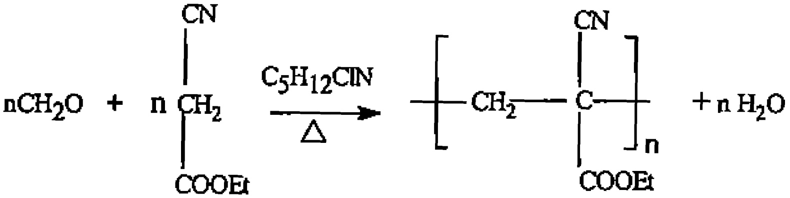
The ethyl cyanoacrylate-ethyl carboxyacrylate mixtures have already been tested in strabismus surgery and compared with suture performance [16]. *In vitro* tests were carried out in postmortem lamb eyes and *in vivo* tests were done with New Zealand white rabbits. The control group was treated with the classical suture (Dexon 6/0, Dexon, Barcelona, Spain) in both cases. The results obtained indicate that higher immediate adhesion was obtained using the suture as compared with the ethyl cyanoacrylate-ethyl carboxyacrylate adhesive mixtures, although the immediate adhesion with the bioadhesive was enough to bear ocular motions. However, 7 days after surgery there was no difference between the performance of the suture group and that of the bioadhesive group.

In addition, the effectiveness and tolerance of the suture and adhesive joints were evaluated [17]. Experimental results show that 80% of the muscles remained attached to the original position where the joints were made, whereas 20% were slightly displaced. On the other hand, no biological risk has been checked through histopathological and morphoscopic studies on New Zealand white rabbit eyes in which adhesive joints were produced.

EXPERIMENTAL

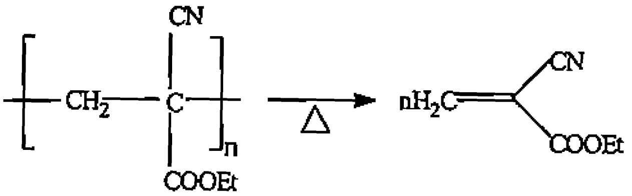
Materials

The two components of the adhesive mixture are ethyl cyanoacrylate (CN) and ethyl carboxyacrylate (ECA). Polyethyl cyanoacrylate is obtained using the Knoevenagel reaction, by reacting ethyl cyanoacetate and formaldehyde (both CP grade and provided by Aldrich, Barcelona, Spain) in the presence of a base catalyst.



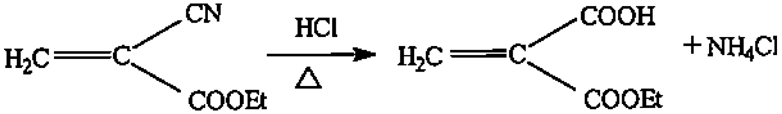
$$nCH_2O + n\,\overset{CN}{\underset{COOEt}{CH_2}} \xrightarrow[\Delta]{C_5H_{12}ClN} \left[CH_2 - \overset{CN}{\underset{COOEt}{C}} \right]_n + n\,H_2O$$

The base catalyst produces hydrogen abstraction in the α position to the carboxylate group, and then the resulting carbanion is added to the formaldehyde, giving the condensation product. The monomer was produced by depolymerizing the polyethyl cyanoacrylate in a sealed container by heating with a burner [18]:



The resulting CN monomer is purified through low pressure distillation. The CN has an Ubbelhode viscosity of 2.21 cStokes.

Ethyl carboxyacrylate (ECA) is obtained by acid hydrolysis of ethyl cyanoacrylate.



The resulting product is purified by liquid-liquid extraction. The ECA has an Ubbelhode viscosity of 1.83 cStokes.

The adhesion properties of CN-ECA adhesive mixtures were obtained using two procedures.

1. Single lap-shear test of joints of R1 rubber/adhesive mixture/R1 rubber. This test allows the evaluation of the adhesion properties of the adhesive mixtures under atmospheric humidity. R1 rubber is a synthetic sulfur-vulcanized styrene-butadiene rubber, and its formulation is given in Table 1. This rubber contains carbon black and precipitated silica as fillers. The R1 rubber (150 × 30 × 3 mm) has a tensile strength of 18 MPa and a Shore A hardness of 93 [19]. R1 rubber was selected for adhesion tests because of its low deformation in lap-shear tests.
2. Tensile strength test of joints of superior rectus muscle of lamb eye/adhesive mixture/sclera of lamb eye. Due to the difficulty of obtaining postmortem human eyes for this study, postmortem lamb eyes were used due to the similarity in size to human eyes. Furthermore, the stresses that the rectus muscles suffer with the ocular motions are similar in both human and lamb eyes, and the cohesion properties of the biological tissues are also similar. This test was carried out at room temperature and was used to measure the initial adhesion of the adhesive mixtures to eye tissues and, consequently, in contact with naturally moisturized eye tissues. The final adhesion was not evaluated because healing is not produced in postmortem eyes, and the results obtained cannot be correlated with performance of *in vivo*-adhesive mixtures.

TABLE 1 Formulation of the Vulcanized Synthetic Styrene-Butadiene Rubber (R1 Rubber)

Ingredient	Percentage (phr)
SBR 1502	65.0
SBR 1904	35.0
Carbon black	23.0
Precipitated silica	25.0
Cumarone-indene resin	3.5
Sulfur	1.8
N-cyclohexyl-2-benzophenol sulphenamide	1.1
Tetramethyl tiuram disulfide	0.2
Stearic acid	0.8
Zinc oxide	3.8
Polyethyleneglycol ($M_w = 4000$)	1.1
Phenolic antioxidant	0.8

Composition is given in parts per hundred parts of rubber (phr).

Experimental Techniques

Transmission-IR Spectroscopy

A Nicolet FTIR 205 (Thermo Nicolet, Madison, WI, USA) spectrometer was used to obtain the IR spectra of the CN, ECA, and their mixtures. IR spectra were used to identify the chemical composition of the adhesives and to follow their kinetics of polymerization. A liquid adhesive drop was placed on a KBr window, and the IR measurements were obtained at room temperature and different times. Sixty scans were obtained and averaged with a 4 cm^{-1} resolution.

Differential Scanning Calorimetry (DSC)

The thermal behaviour of CN, ECA, and their mixtures was studied in a *Q-100* TA (TA Instruments, Newcastle, UK) DSC instrument. About 10 mg of adhesive was placed in a hermetic pan and sealed in a TA Instruments Sample Encapsulating Press (Thermo Nicolet). Then, the sample was placed in the DSC oven, using an empty identical hermetic pan as a reference. The adhesive mixtures were polymerized inside the DSC oven. The temperature range over which the curing was done was 0–150°C depending on the adhesive mixture. Different consecutive runs were carried out on the same sample to obtain complete cure of the adhesive mixtures. A heating rate of 10°C/min was always used. The experiments were carried out under nitrogen atmosphere using a flow rate of 50 ml/min. The experimental results were analyzed using Universal Analysis 2000 software provided by TA Instruments.

Plate-Plate Stress Controlled Rheometer

The rheological properties of the cured CN-ECA adhesive mixtures were obtained in a Bohlin CS-50 (Bohlin Instruments, Cirecester, UK) rheometer using a plate-plate geometry (the diameter of the upper plate is 10 mm). The solid films were heated up to the softening point and then cooled down using a cooling rate of 5°C/min. The gap between the plates was always 1 mm, and the frequency was 1 Hz.

Single Lap-Shear Tests

Single lap-shear tests of joints of R1 rubber/adhesive mixture/R1 rubber were carried out to obtain the adhesion properties of CN-ECA adhesive mixtures. Before joint formation, the R1 rubber was wiped with butanone. Fifteen minutes afterward, 0.1 ml of the adhesive mixture was placed on each R1 rubber test piece and they were joined immediately without applying pressure in a square contact area of 9 cm^2 (3 × 3 cm). Shear tests were carried out using an Adamel L'Homargy DY32 (Adamel L'Homargy, Paris, France) test machine at 24 h, 72 h, and 15 days after joint formation. The pulling rate during the single lap-shear test was 20 mm/min. Five replicates were measured and averaged. The error was less than 60 kN/m^2.

Tensile Strength Measurements

Tensile strength values of joints of rectus muscle of lamb eye/adhesive mixture/sclera of lamb eye were measured to estimate the adhesion properties of the CN-ECA adhesive mixtures in contact with naturally moisturized eye tissues. Figure 1 shows a scheme of the experimental setup used in this study to determine the tensile strength of the joints. First, a square of the sclera of about 1 cm^2 (1 × 1 cm) and a square of the superior rectus muscle of 2 cm^2 (2 × 1 cm) were cut using a scalpel. The cuts were always produced maintaining the directionality of the tissues in the eye, to assure an adequate mimic of the application of the adhesive in live eyes. Two EVA (ethylene vinyl acetate) copolymer square pieces of 5 cm^2 (1 cm × 5 cm) and having a hole at about 0.5 cm from the edge were used to hang the superior rectus muscle and the sclera pieces. A small hanger was placed in the hole of each EVA piece and the superior rectus muscle and the square sclera pieces were placed in the two EVA pieces. The hangers did not affect the adhesion performance because they were far away from the joint. A drop of about 5 μl of the CN-ECA mixture was applied to the sclera by means of a syringe having a bevel edge (dimensions = 25G × 5/8″ = 0.5 × 16 mm), and the superior rectus muscle was immediately placed on the adhesive drop and pressed using a clamp for 20 s to produce the adhesive joint. The two EVA pieces were placed in the clamps of a

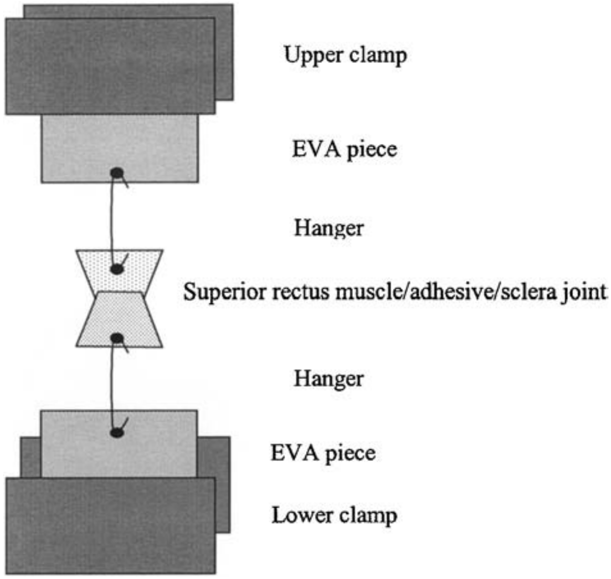


FIGURE 1 Scheme of the experimental setup used to measure the tensile strength in superior rectus muscle of lamb eye/adhesive mixture/sclera of lamb eye joints.

TA-XTi texture analyser (Anime, Pozuelor, Spain) provided with an adequate software to measure small tensile strength values. The tensile strength value was obtained 5 min after joint formation, and a pulling rate of 0.3 mm/s was used. At least three replicates were measured and averaged. The experimental error was less than $0.5\,\text{kN/m}^2$.

RESULTS AND DISCUSSION

The adhesives used in this study are mixtures of ethyl cyanoacrylate and ethyl carboxyacrylate. The ethyl cyanoacrylate shows a fast polymerization rate and high adhesion in the presence of a base. The base acts as a catalyst to begin the anionic reaction of the C=C double bonds. On the other hand, the ethyl carboxyacrylate is an inhibitor of the polymerization of the ethyl cyanoacrylate due to its acidity ($\text{pH} = 2.2$). Therefore, to design the adhesive mixture to join the rectus muscle to the sclera an adequate ratio must be chosen to achieve good adhesion, with reduced stiffness and without producing a high exotherm. For this reason, several CN-ECA adhesive mixtures were considered in this study.

Different CN-ECA adhesive mixtures containing 100CN-0ECA (v/v), 70CN-30ECA (v/v), 50CN-50ECA (v/v), 30CN-70ECA (v/v), and 0CN-100ECA (v/v) were prepared. The Ubbelhode viscosities of these mixtures are given in Figure 2. The viscosities of the CN-ECA adhesive mixtures are between the viscosities of the pure components and a linear trend is observed. The viscosity decreases as the content of ECA in the mixture increases.

Curing of the CN-ECA Adhesives

The curing of the CN-ECA adhesive mixtures was monitored using FTIR spectroscopy. The absorption bands due to the stretching of $=CH_2$ and C=C groups at 3120 cm^{-1} and 1620 cm^{-1}, respectively, disappear when CN is cured (the anionic polymerization of the CN occurs by reacting the C=C double bonds). On the other hand, the band corresponding to the C=O stretching (1740 cm^{-1}) remains almost constant during the curing process, because the carbonyl groups do not participate in the reaction, and this band was taken as a reference to follow the curing reaction.

The FTIR spectra of the CN and ECA before mixing are given in Figures 3a and 3b. The FTIR spectrum of the ethyl cyanoacrylate

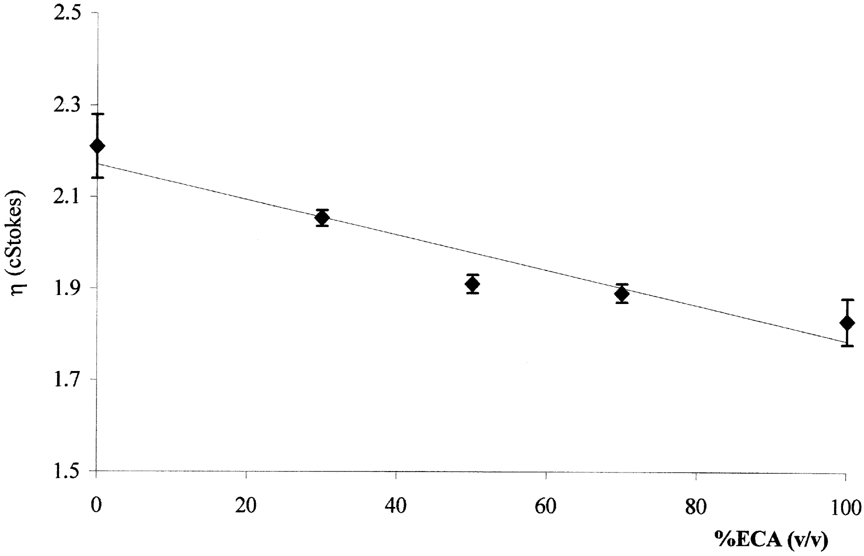
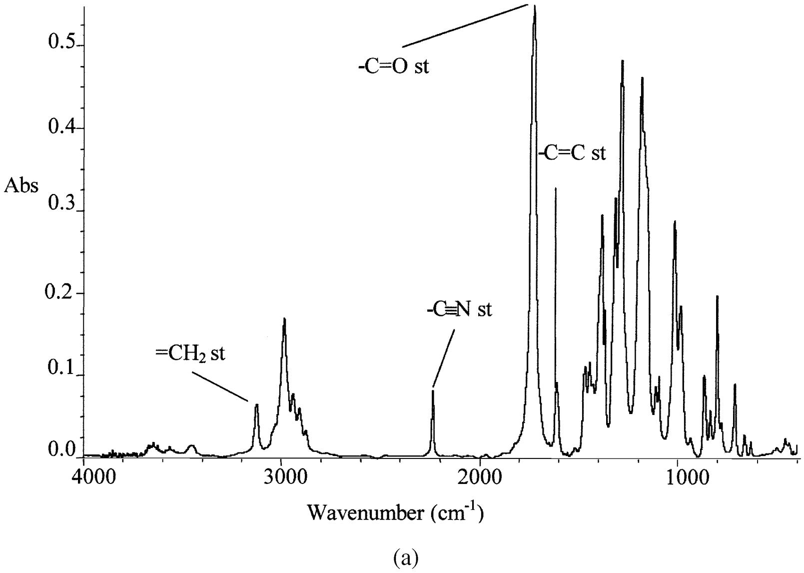


FIGURE 2 Ubbelhode viscosities (22°C) of the CN-ECA adhesive mixtures as a function of their ECA content.

shows typical bands at 3120 cm^{-1} (=CH_2 stretching), 1620 cm^{-1} (C=C stretching), and 805 cm^{-1} (C=C–C=O out of plane bending). The absorption bands of methyl and methylene groups are located at 3000, 2945, 2900, and 2870 cm^{-1} (–CH_3 stretching, –CH_2– stretching), 1440 and 1370 cm^{-1} (–CH_3 asymmetric and symmetric bending, respectively), and 1470 cm^{-1} (–CH_2– bending). At 2240 cm^{-1} the stretching of the nitrile group is observed (–C≡N stretching). On the other hand, the FTIR spectrum of the ethyl carboxyacrylate shows typical bands at 3120 cm^{-1} (=CH_2 stretching), and the main IR absorption bands due to O–H stretching (3500–3200 cm^{-1}), stretching of the carbonyl group (1740 cm^{-1}), and CO–O and C–O stretching (1245 cm^{-1} and 1190 cm^{-1}, respectively). The CN-ECA adhesive mixtures show the IR absorption bands of the two components, but the absorption band corresponding to the stretching of the nitrile group and the hydrogen-associated carboxylic acid stretching band of the ECA can be more easily distinguished (Figures 4b–4d).

Figure 4a (CN adhesive) shows that by increasing the time there is a decrease in the intensity of the bands due to C–H symmetric and asymmetric stretching (3000, 2945, 2900, and 2870 cm^{-1}), CH_2 bending, and CH_3 asymmetric and symmetric bending (1470, 1440, and 1380 cm^{-1}). Furthermore, the intensity of the C–O band at 1180 cm^{-1} decreases with time. Figures 4b–4d corresponding to the different CN-ECA adhesive mixtures show similar features, and whereas the IR spectrum of the 70CN-30ECA adhesive mixture shows a relatively similar IR spectrum to that of the CN adhesive, the other mixtures show the –COOH stretching band corresponding to hydrogen-associated carboxylic acid moieties (3100–3500 cm^{-1}) and more intense bands due to C=O.

Figures 4a–4d show the FTIR spectra of the CN-ECA adhesive mixtures as a function of the time after mixing. ECA is not able to polymerize, so similar IR spectra were obtained by increasing the time. The time at which the measurements were taken differs in the different CN-ECA mixtures due to different kinetics of polymerization. The absorption bands at 3120 cm^{-1} (=CH_2 stretching), 1620 cm^{-1} (C=C stretching), and 805 cm^{-1} (C=C–C=O out-of-plane bending) gradually disappear with increasing time, because the anionic polymerization reaction takes place. New bands in the IR spectra of the CN-ECA adhesive mixtures cannot be distinguished. The intensity of the band at 2240 cm^{-1} (–C≡N stretching) also decreases with the time. Although the –C≡N group does not take part in the polymerization reaction, its relative intensity becomes less important during curing because of the dominant effect of the groups produced.



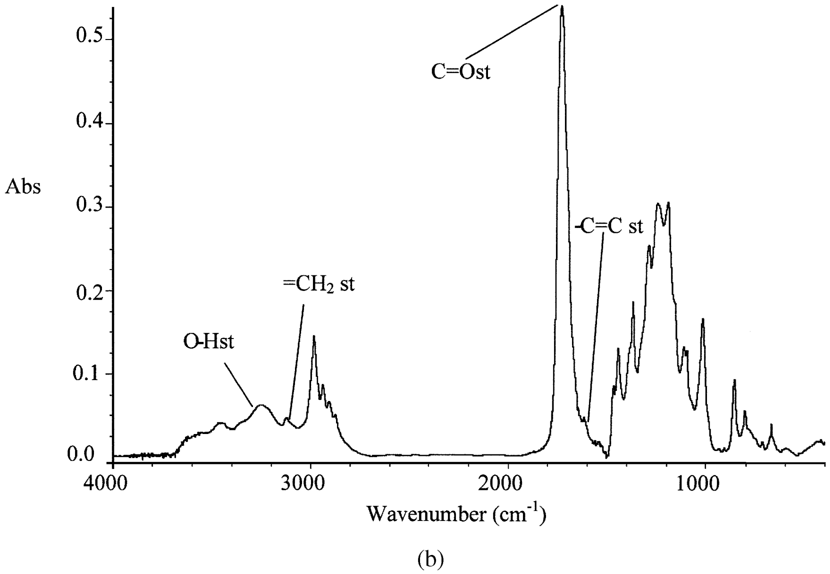
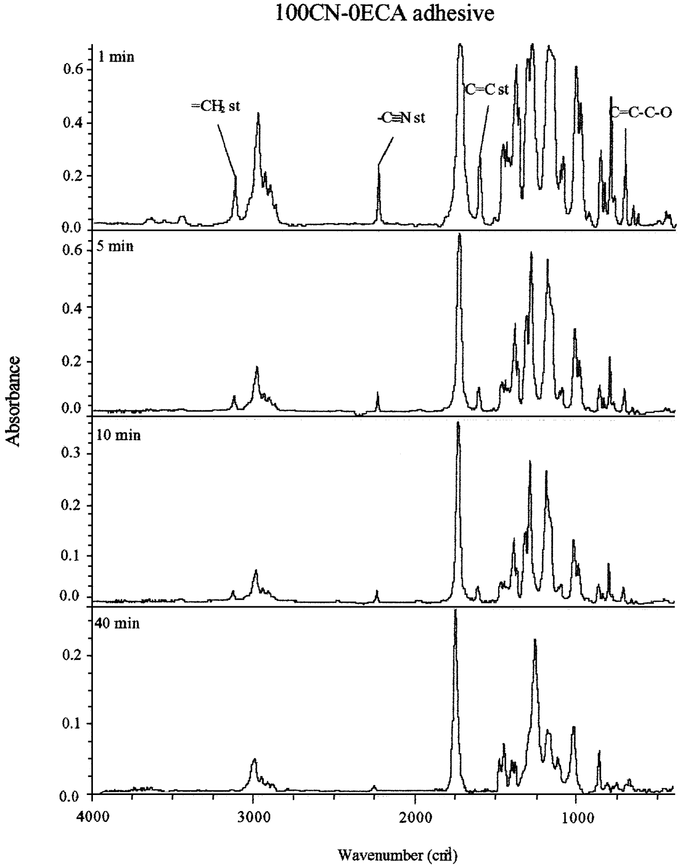


FIGURE 3 IR spectra of (a) ethyl cyanoacrylate (CN) and (b) ethyl carboxyacrylate (ECA).



100CN-0ECA adhesive

(a)

FIGURE 4 IR spectra of the adhesive mixtures as a function of time: (a) 100CN-0 ECA (v/v), (b) 30CN-70ECA (v/v), (c) 50CN-50ECA (v/v), and (d) 30CN-70ECA (v/v). Experiments were carried at room temperature. (*Continued*).

The ratio between the height of the C=C band (1620 cm^{-1}) in the IR spectra of Figures 4a–4d with respect to the absorption band of the carbonyl group (1740 cm^{-1}) has been used to estimate the degree of conversion of the adhesive mixtures during polymerization. The degree of conversion of the CN-ECA mixtures as a function of the time is given in Figure 5. The degree of conversion sharply increases during the initial 60 min of reaction, being less marked for longer reaction times. The initial slope of the curves becomes less steep as the ECA

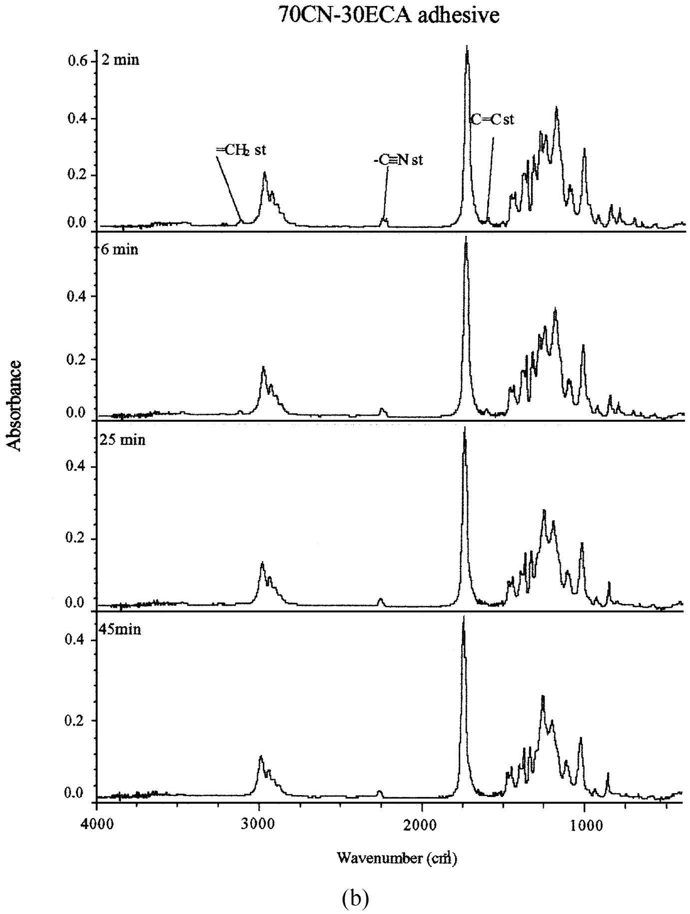
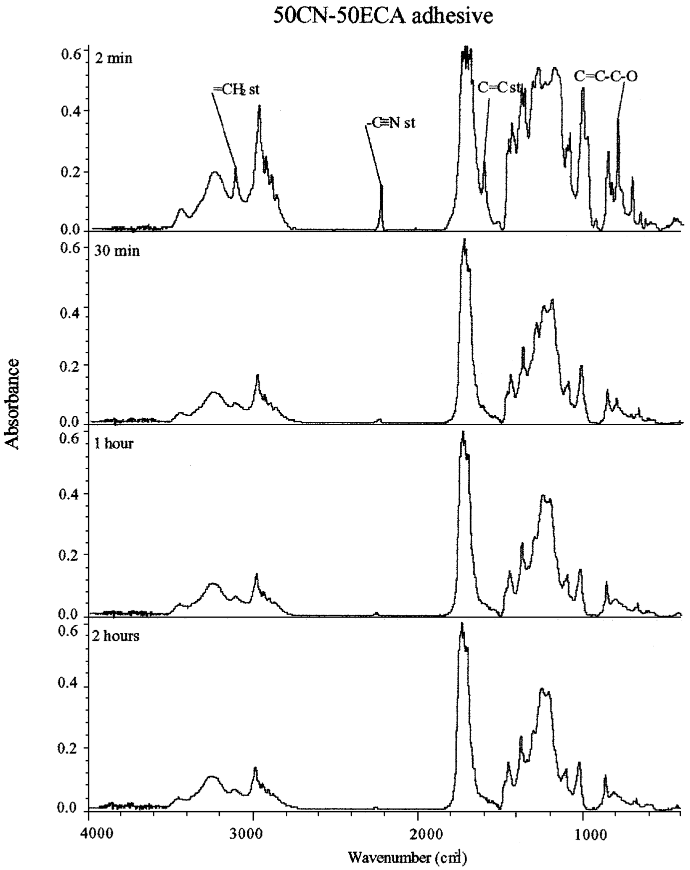


FIGURE 4 (*Continued*).

content in the mixture increases, confirming that the ECA acts as a plasticizer and delays the CN curing reaction. Furthermore, whereas the CN adhesive reached 100% conversion in 40 min, the addition of ECA produced lower degrees of conversion even after 350 min. Thus, the 70CN-30ECA and 50CN-50ECA mixtures reach only 90% conversion; the lowest rate of conversion (about 70%) is obtained with the 30CN-70ECA mixture. Therefore, the addition of ECA retards the kinetics of polymerization of CN to a greater extent upon increasing the amount of ECA. Because addition of ECA produces a decrease in pH (due to its acidity), the polymerization becomes slower. As complete reaction of the CN does not occur in the presence of ECA,

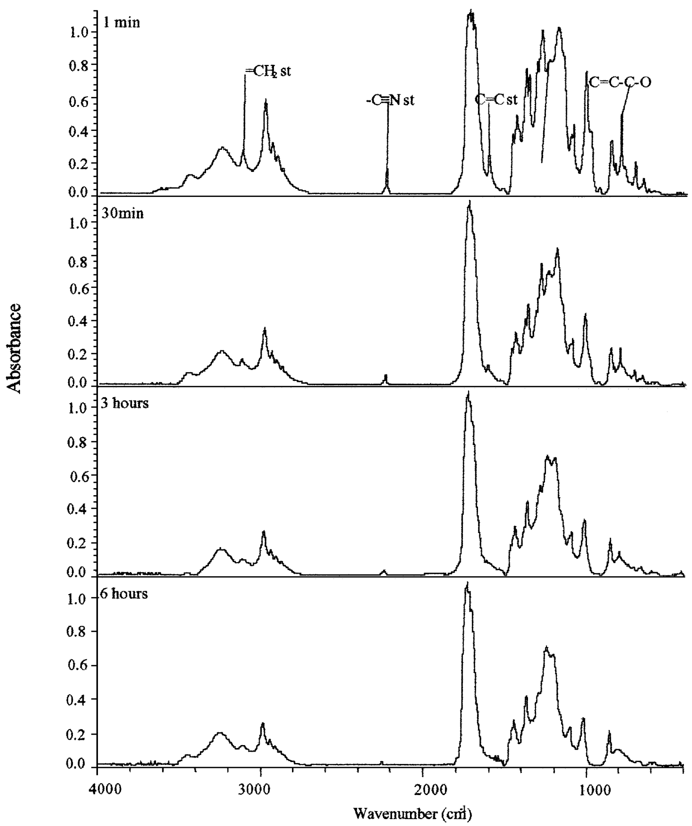


(c)

FIGURE 4 (*Continued*).

the cured CN-ECA adhesive mixtures should be less stiff than the CN adhesive.

As the curing reaction of the CN-ECA adhesive mixtures is exothermal, DSC was also used to monitor the polymerization reaction. Liquid adhesive mixtures were placed in the DSC and heated up. Figure 6a shows as a typical example the DSC thermograms of the 50CN-50ECA adhesive mixture. A low glass transition temperature is obtained ($T_g = 44°C$) and further curing is produced during the heating run in the DSC. Therefore, several consecutive DSC heating-cooling runs were carried out until completely cured adhesive was



30CN-70ECA adhesive

(d)

FIGURE 4 (*Continued*).

obtained ($T_g = 65°C$). Figure 6b shows the DSC thermograms of the fully cured CN-ECA adhesive mixtures. Only one glass transition temperature (T_g) is obtained (indicated by arrows in Figure 6b), except for ECA, which does not show any T_g in the temperature range studied. The CN adhesive exhibits the highest T_g (140°C) which gradually decreases as the ECA content in the adhesive mixtures increases. There is a linear decrease of T_g as the ECA content in the mixtures increases (Figure 7). Consequently, the stiffness of the cured CN-ECA adhesive mixtures decreases with increasing ECA content, due to the inhibition of the polymerization reaction of the ethyl cyanoacrylate.

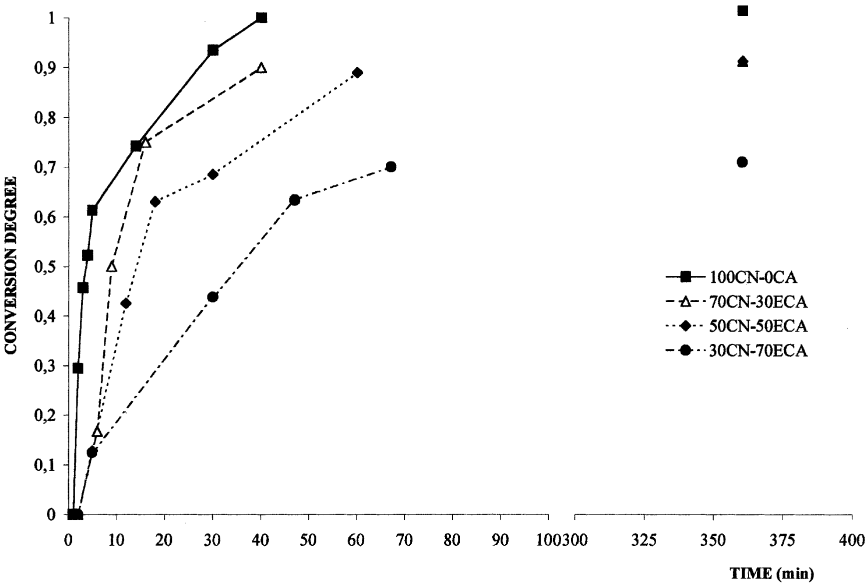


FIGURE 5 Conversion degree of the CN-ECA adhesive mixtures as a function of the time. Data obtained from the relative disappearance of the C=C peak (1620 cm^{-1}) with respect to the C=O peak (1740 cm^{-1}) in the IR spectra.

Characterization of the Cured CN-ECA Adhesive Mixtures

The mechanical and rheological properties of the cured CN-ECA adhesive mixtures were obtained using a plate-plate rheometer. These properties are important to assess the degree of flexibility reached by the CN-ECA mixtures. Figures 8a and 8b show typical examples of the variation of the storage (elastic component) and loss (viscous component) moduli of the cured CN and the 30CN-70ECA adhesive mixture as a function of the temperature. The cured CN adhesive film shows the glass transition at 133°C, and the storage modulus is high and dominant in the entire temperature range (Figure 8a). This corresponds to a stiff material. For the cured CN-ECA mixtures the loss modulus is dominant at high temperature (Figure 8b). Therefore, addition of ECA changes the mechanical and rheological properties of CN, decreasing stiffness and giving a less marked elastic behaviour at high temperature. The modulus and temperature at the crossover in the rheological curves are given in Table 2. The modulus at the crossover is displaced to a higher value as the ECA content increases, whereas the temperature at the crossover is displaced to a lower

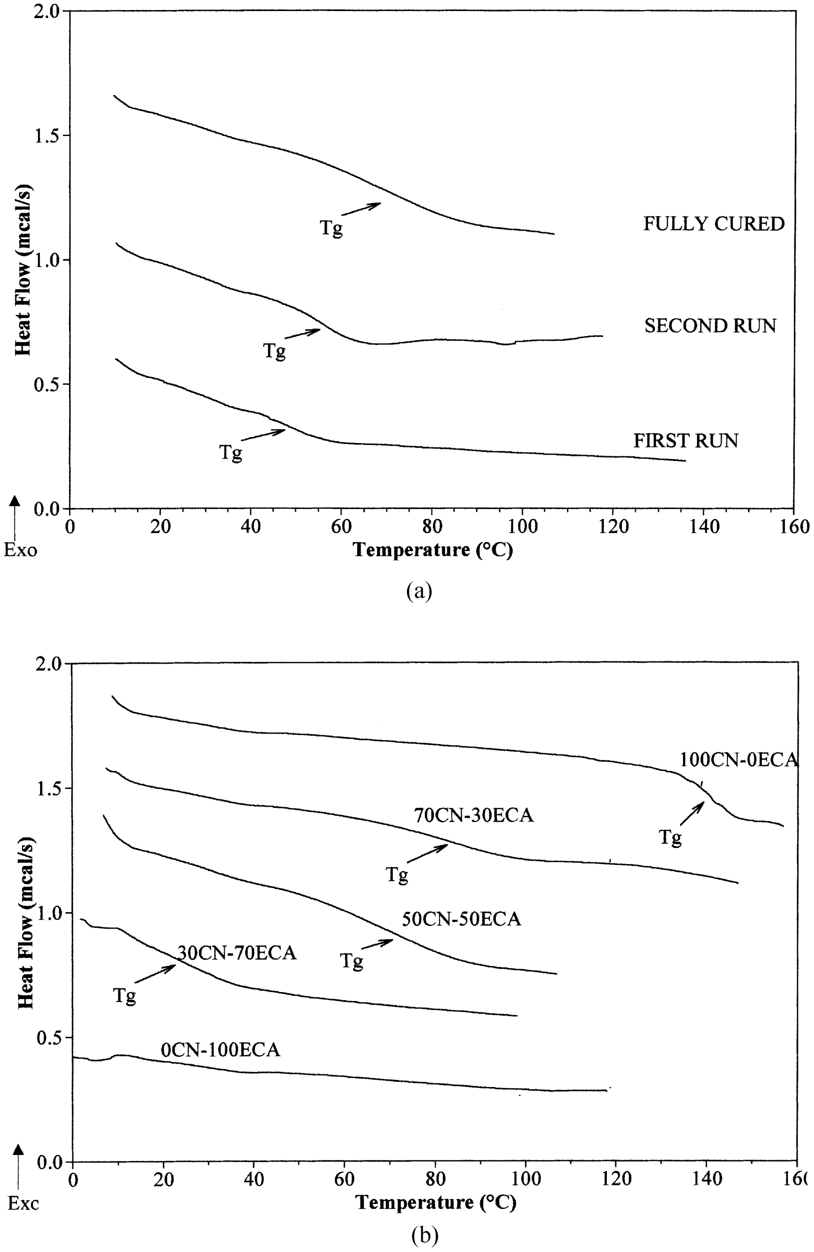


FIGURE 6 DSC thermograms of (a) 50CN-50ECA adhesive mixture using different consecutive heating-cooling DSC runs, and (b) fully cured CN-ECA adhesive mixtures.

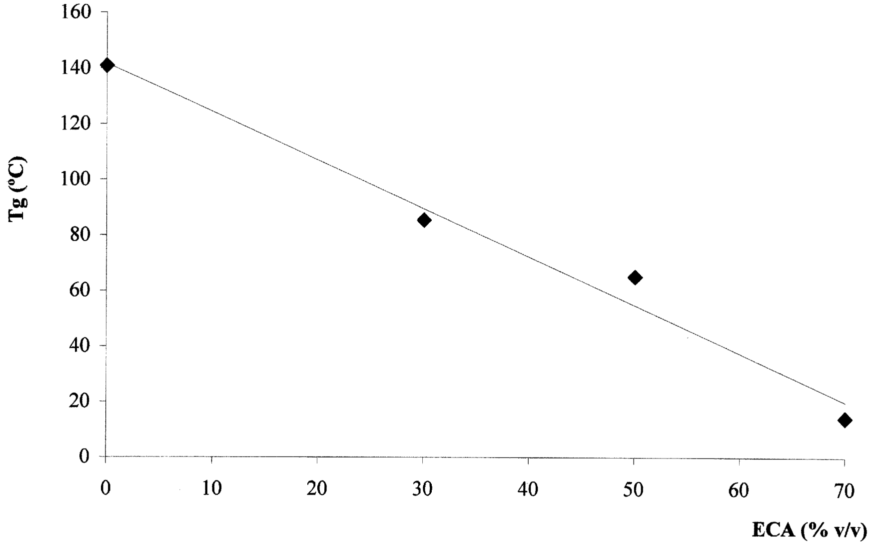
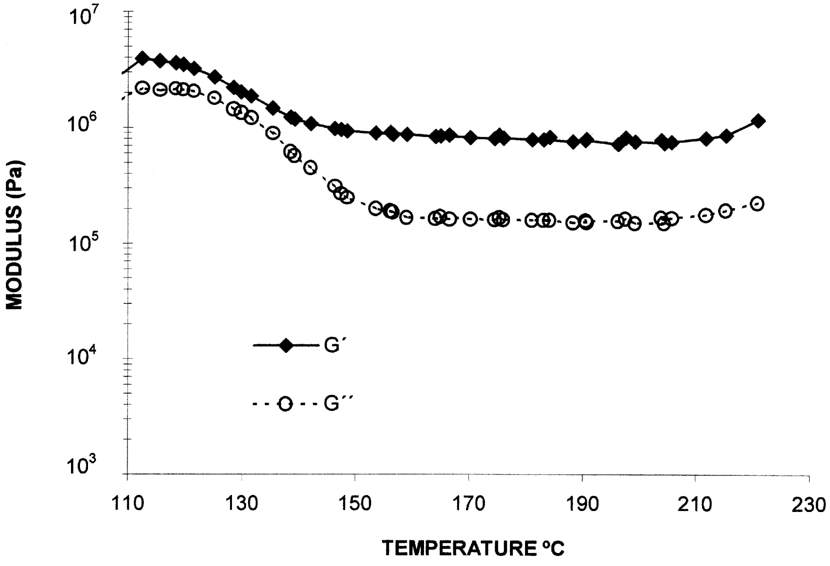


FIGURE 7 Variation of the glass transition temperature (T_g) of the fully cured CN-ECA adhesive mixtures as a function of the ECA content.

temperature by increasing the ECA content in the adhesive mixtures (about 90°C for cured 70CN-30ECA and 50CN-50ECA, and about 60°C for cured 30CN-70ECA). Therefore, the higher the ECA content in the cured CN-ECA adhesive mixture, the lower the stiffness. In fact, Figure 8c shows how the elastic modulus gradually decreases upon increasing the ECA content in the cured adhesive mixtures. A comparison of the storage and loss moduli at 115°C for all the CN-ECA mixtures (Table 2) show the highest values for the cured CN adhesive and the lowest for the cured 30CN-70ECA mixture.

Adhesion of CN-ECA Adhesive Mixtures

To quantify the adhesion properties of the CN-ECA adhesive mixtures, single lap-shear tests of joints of R1 rubber/CN-ECA adhesive/R1 rubber were carried out 24 h, 72 h, and 15 days after joint formation (Figure 9). The highest shear strength value corresponds to the joint produced with only ethyl cyanoacrylate, and the joint fails cohesively in the rubber. The increase in the time after joint formation always produces a similar shear strength value and locus of failure, indicating that good adhesion was obtained 24 h after joint formation. Addition of ECA to CN always produces a decrease in shear strength. Because the

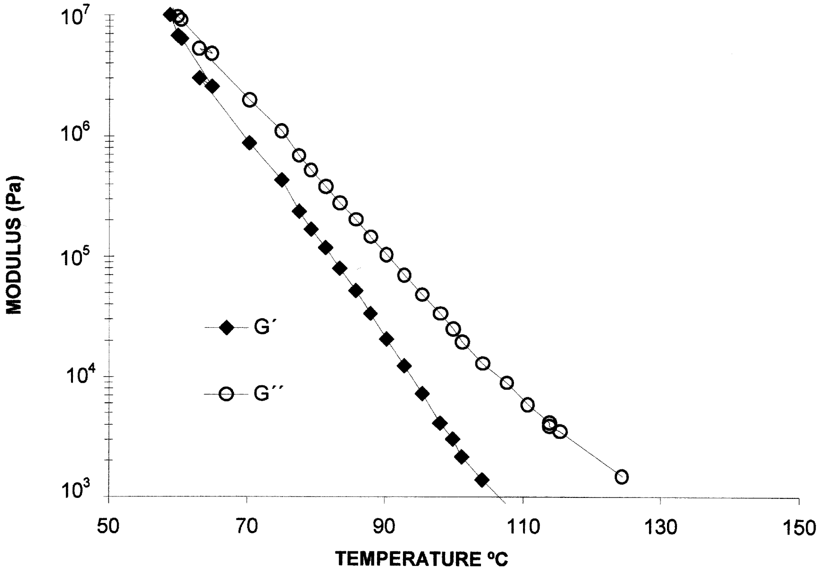


(a)

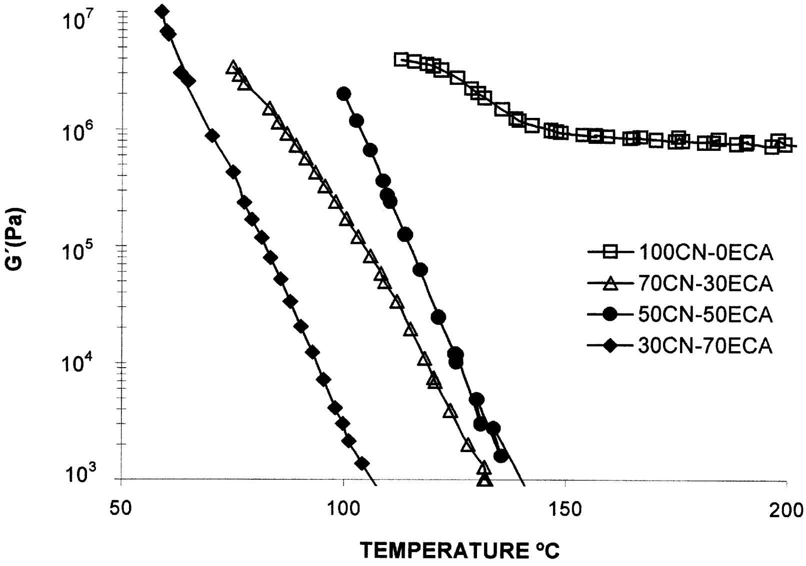
FIGURE 8 Variation of the storage (G′) and loss (G″) moduli as function of the temperature for (a) Cured 100CN-0 ECA (v/v) and (b) Cured 30CN-70ECA (v/v). (c) Variation of the storage modulus as a function of the temperature for all cured CN-ECA adhesive mixtures. (*Continued*).

addition of ECA reduces the stiffness of the adhesive (*i.e.*, imparts flexibility), the cohesion of the CN-ECA mixtures is lower than for CN and, therefore, the joint fails cohesively in the adhesive. Therefore, although the adhesion between the rubber and the adhesive is maintained, the cohesion properties of the CN-ECA mixtures decrease. Similar shear strengths are obtained in the joints produced with all CN-ECA mixtures, regardless of the time after bond formation (24 or 72 h).

Tensile strength tests were carried out to estimate the initial adhesion properties of the CN-ECA mixtures to rectus muscles and sclera. Tensile strength values of joints of superior rectus muscle/CN-ECA adhesive/sclera are given in Figure 10. The highest initial tensile strength value is obtained with the joint produced with 70CN-30ECA, and the adhesion decreases in the joints produced with the adhesive mixtures containing higher amounts of ECA. The joint produced with only CN shows tissue necrosis due to the high reactivity of the cyanoacrylate and the high exothermal reaction. Further, the cured CN is very stiff, facilitating the failure of the joint under tensile



(b)



(c)

FIGURE 8 (*Continued*).

TABLE 2 Some Rheological Properties of the CN-ECA Adhesive Mixtures

Adhesive mixture	$T_{cross\text{-}over}$ (°C)	$Modulus_{cross\text{-}over}$ (Pa)	G′ (Pa) at 115°C	G″ (Pa) at 115°C
100CN-0ECA	—	—	2.0×10^6	3.7×10^6
70CN-30ECA	88.9	9.1×10^5	2.0×10^5	4.3×10^5
50CN-50ECA	93.7	2.0×10^6	1.2×10^5	5.4×10^5
30CN-70ECA	58.7	1.2×10^7	5.7×10^2	4.2×10^3

stresses. The tensile strength of the joints of superior rectus muscle/CN-ECA mixtures/sclera is determined by three factors.

1. Due to the high amount of water in the sclera and superior rectus muscle, the exothermal reaction due to CN polymerisation is reduced by addition of ECA which reduces the extent of curing, and which also plasticizes the adhesive.
2. The adhesion promotion caused by the presence of carboxylic acid moieties in the CN-ECA adhesive blend [20, 21] may favour the specific adhesion to polar substrates.

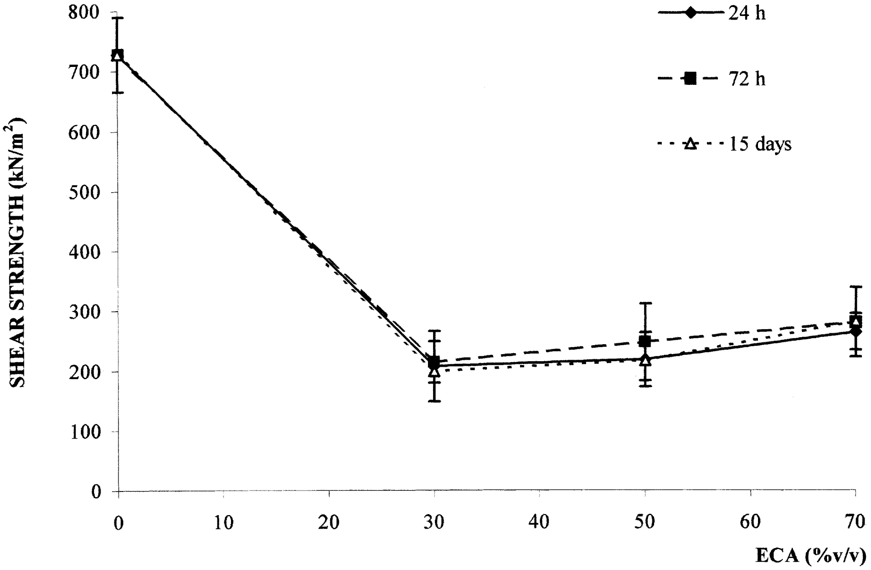


FIGURE 9 Single-lap shear strength values for the R1 rubber/CN-ECA mixture/R1 rubber joints obtained at 24 h, 72 h, and 15 days after bond formation.

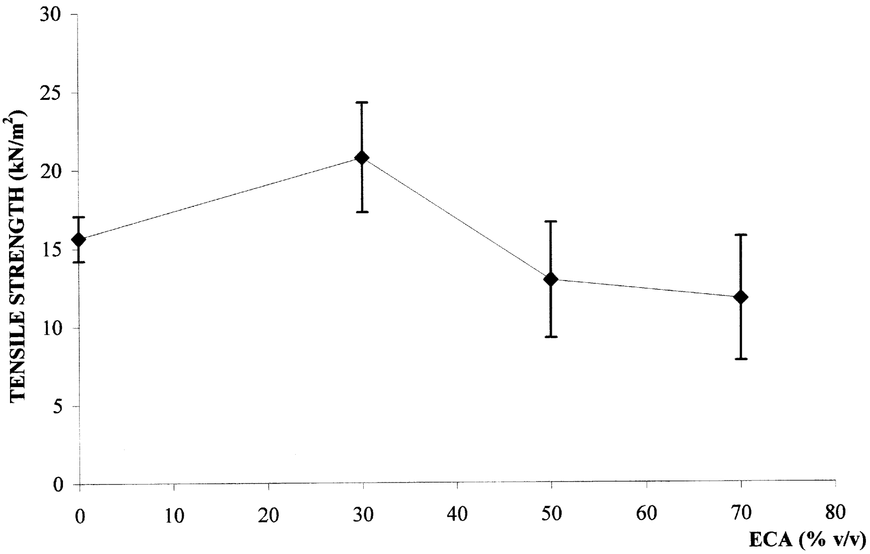


FIGURE 10 Tensile strength values of superior rectus muscle of lamb eye/CN-ECA mixture/sclera of lamb eye joints obtained 5 min after bond formation.

3. The decrease in pH of the adhesive caused by addition of high amounts of ECA. The decrease in pH retards the curing of the adhesive and, thus, the initial adhesion decreases as the ECA content in the adhesive mixture increases.

CONCLUSIONS

The experimental results obtained in this study suggest that the 70CN-30ECA (v/v) adhesive mixture provided the most adequate balance between adhesion and mechanical properties in the joining of the rectus muscles to the sclera. It has a relatively short time of polymerization, provided adequate immediate adhesion to the eye tissues for surgery practice, and the adhesive mixture is less stiff than the CN by itself. The glass transition temperature linearly decreased with increasing ECA content in the CN-ECA adhesive mixture, and the degree of conversion during polymerization became smaller with increasing ECA content. As a consequence, the cured CN-ECA adhesive mixtures, were less stiff than the CN, giving better performance in the joining of the superior rectus muscle to the sclera. Finally, adhesion of CN is sufficiently decreased by adding ECA so that the joints produced with CN-ECA adhesive mixtures fail in the adhesive.

REFERENCES

[1] Lee, H., *Cyanoacrylate Resins—The Instant Adhesives* (Pasadena Technology Press, Los Angeles, 1981). Chapter 21, pp. 155–157.

[2] Coover, H. W., Joyner, F. B., Shearer, N. H., and Wicker, T. H., *J. Soc. Plast. Eng.* **15**, 413–417 (1959).

[3] Bloomfield, S., Barnet, A. H., and Kanter, P., *Am. Arch. Ophthal.* **55**, 742–748 (1963).

[4] Refojo, M., Dolhman, C. H., Ahmad, B., Carroll, J. M., and Allen, J. C., *Surg. Arch. Ophthal.* **80**, 645–656 (1968).

[5] Cañizares-Grupera, M. E., Carral-Novo, M. J. M., and de la Torre-Rufo, J. E., *Rev. Cubana Med. Militar.* **29**, 57–60 (2000).

[6] Cañizares-Grupera, M. E., and Carral-Novo, M. J. M., *Rev. Cubana Med. Militar.* **30**, 15–20 (2001).

[7] López-Martínez, J. J., Arenas-Osuna, J. A., and Galindo-Rujano, M. E., *Educación e Investigación Clínica* **1**, 51–58 (2000).

[8] Reece, T. B., Maxey, T. S., and Kron, I. L., *Am. J. Surg.* **182**, 40s–44s (2001).

[9] Gasset, A. R., Hood, J. C., Ellison, E. D., and Kaufman, H. E., *Invest. Ophtalmol. Vis. Sci.* **9**, 3–11 (1970).

[10] Robin, J. B., Riley, J., and Lee, C. F., *Refract. Corneal Surg.* **5**, 302–306 (1989).

[11] Sakla, H. F., Mulet-Homs, M. E., and Alió y Sanz, J. L., *Vision Res. (Suppl.)* **35**, 126–135 (1995).

[12] Alió, J. L., Mulet, M. E., and García, J. C., *Ophtal. Surg. Lasers* **27**, 1–5 (1996).

[13] Gómez, J. J., Mulet, M. E., Alió, J. L., Mahiques-Bujanda, M. M., Molina-Alfonso, Y., and Martín-Martínez, J. M., *Arch. Soc. Oftalmol.* **76**, 249–258 (2001).

[14] Alvarado-Valero, M. C., Mulet-Homs, M. E., Fouad Sakla, H., and Alió y Sanz, J. L., *Arch. Soc. Oftalmol.* **5** (1999). Web page: http://www.oftalmo.com/seo/1999/05may99/06.htm

[15] Flick, H., *Klin. Mbl. Augenheilk.* **178**, 193–196 (1981).

[16] Mulet-Homs, M. E., Alió y Sanz, J. L., Fouad Sakla, H., Mahíques-Bujanda, M. M., and Martín-Martínez, J. M., *Arch. Soc. Oftalmol.* **75**, 165–170 (2000).

[17] Mulet-Homs, M. E., Fouad Sakla, H., Mahiques-Bujanda, M. M., Alió y Sanz, J. L., and Martín-Martínez, J. M., *Arch. Soc. Oftalmol.* **76**, 43–52 (2001).

[18] Rosado-Balmayor, E., Almirall-La Serna, A., and Alvarez-Brito, R., *Rev. Iberoamericana de Polímeros* **3** (2002). Web page: http://www.ehu.es/reviberpol

[19] Romero-Sánchez, M. D., Pastor-Blas, M. M., and Martín-Martínez, J. M., *Int. J. Adhesion Adhesives* **21**, 325–337 (2001).

[20] Pastor-Sempere, N., Fernández-García, J. C., Orgilés-Barceló, A. C., Torregrosa-Maciá, R., and Martín-Martínez, J. M., *J. Adhesion* **50**, 25–42 (1995).

[21] Pastor-Sempere, N., Fernández-García, J. C., Orgilés-Barceló, A. C., Sánchez-Adsuar, M. S., and Martín-Martínez, J. M., *J. Adhesion* **59**, 225–239 (1996).