Controlled Destruction of Residual Crosslinker in a Silicone Elastomer for Drug Delivery

ANDERS KARLSSON,[1] SATISH K. SINGH,[2] ANN-CHRISTINE ALBERTSSON[3]

[1] Pharmacia Corp., Marketed Product Support, S-751 82 Uppsala, Sweden

[2] Pharmacia Corp., Pharmaceutical Sciences, 7000 Portage Road, Kalamazoo, Michigan 49001-0199

[3] Department of Polymer Technology, Royal Institute of Technology, S-100 44 Stockholm, Sweden

Received 25 May 2001; accepted 5 September 2001

ABSTRACT: In drug delivery systems that use silicone elastomers as a diffusion matrix for the active drug, it is common to crosslink the material by the hydrosilylation reaction. In this platinum-catalyzed reaction, vinyl groups on a polymer add to the methyl siloxane hydride (MHS) groups on a low molecular mass crosslinker. With an excess of crosslinker, a fast curing is achieved and a fully crosslinked material is formed. Unreacted MHS groups were shown to remain in the elastomer after curing because of the excess crosslinker. In this work, a simple procedure was developed to eliminate the unreacted MHS groups from the final product. We found that storage of the product at +40°C and 75% relative humidity for a few weeks will effectively destroy the residual MHS groups in the elastomer. The effects of varying levels of humidity, oxygen, and temperature on this postcuring procedure were studied. The amount of MHS groups was measured with NMR and IR spectroscopy. We also found that the hardness of the material increased by approximately 25% as a consequence of this postcuring treatment. This increase is probably due to a secondary crosslinking reaction between MHS and silanol groups. Heat treatment at higher temperatures led to an even further increase in the hardness and compression modulus. Because no MHS groups remained in the elastomer when this heat treatment was started, it is apparent that another secondary crosslinking reaction is occurring, probably silanol condensation. J Appl Polym Sci 84: 2254–2264, 2002

Key words: poly(dimethyl siloxane); crosslinker; methyl hydrogen siloxane; silicone hydride; postcuring; aging; humidity

INTRODUCTION

During development work on drug delivery systems with a medical grade silicone elastomer, we have observed that the elastomer becomes harder and that the modulus increases on storage (i.e., a postcuring of the elastomer takes place). We have also found that a newly prepared silicone elastomer matrix contains residues of unreacted methyl hydrogen siloxane (MHS) groups from the crosslinker. It is common to add an excess of crosslinker to vinyl groups to achieve complete crosslinking, and the reaction is much faster when an excess of crosslinker is used.[1] A problem arose with the residual MHS groups, however, related to the method of determination of the deg-

Correspondence to: A.-C. Albertsson (aila@polymer.dth.se).
* *Present address:* Medical Products Agency; Box 26, S-751 03 Uppsala, Sweden.

Journal of Applied Polymer Science, Vol. 84, 2254–2264 (2002)

radation products in the case of one of the incorporated drugs, where an internal standard was added to the extraction media. With of the newly cured elastomers, there was a significant loss of the internal standard during these analyses, and this led to errors in the determination of the degradation products. This phenomenon was not observed on samples that had been stored for more than 1 month at room temperature. We hypothesized that the loss of internal standard was due to a reaction between the MHS group in the crosslinker and the unsaturated aliphatic group in the internal standard (hydrosilanization). Because this loss of internal standard was not found in the case of stored samples, we concluded that the MHS groups decompose during storage.

The postcuring reactions that change the mechanical properties of the elastomer are probably reactions that increase the crosslinking density. In addition, hydrogen bonding between the filler and the polymer and bonding between polymer chains may also affect the mechanical properties of the elastomer. There is little published literature that discusses chemical reactions causing the postcuring of silicone elastomers after the hydrosilanization reaction. Reactions between residual vinyl and MHS groups and the reaction between silanols and MHS will both increase the crosslinking density.[2]. Another postcuring reaction is the decomposition of MHS. This reaction will not change the crosslinking density, but will merely convert the silicone hydride into a silanol group. It was found that this reaction does not occur if the aging of the elastomer is carried out in dry nitrogen. However, it was not reported whether oxygen or humidity is the major cause of the decomposition of the MHS groups.[3]

In this article, we describe a way to efficiently eliminate the MHS groups in the elastomer. The objective was to find the optimal conditions for the rapid elimination of this component from the silicone elastomer, without changing the drug delivery properties of the system. We also made mechanical measurements to monitor the physical changes in the elastomer caused by these chemical reactions.

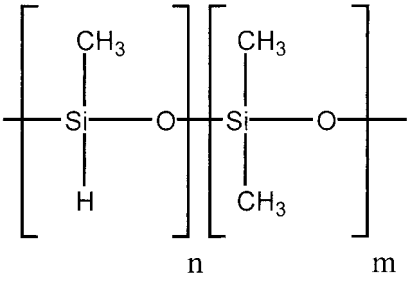
EXPERIMENTAL

Materials

Silicone preelastomer samples, Parts A and B, Silastic™ Q7–4735, were received from Dow Corning France S.A., Sophia-Antipolis, France.

Both Part A and Part B contain a high molecular mass poly(dimethyl siloxane) with a minor amount of vinyl groups. In addition, Part A contains the platinum catalyst and Part B contains the crosslinker. The crosslinker is a copolymer with MHS and dimethyl siloxane groups.

The MHS standard was a 30–35% methyl hydrogen–65–70% dimethyl siloxane copolymer, PS123 ABCR, Karlsruhe, Germany. The copolymer composition was measured with ^{1}H-NMR spectroscopy, and it was found that the copolymer contained 30 mol % MHS.



MHS group

Poly(dimethyl siloxane) (DC 200, 10 cSt), was obtained from KEBO Lab, Stockholm, Sweden.

Sample Preparation

The two parts of the preelastomer (Part A and Part B) were thoroughly blended in equal weight portions (~ 50 g of each part) on a two-roll mixer (Polymix 150 L/O, Schwabenthan Maschinen GbmH and Co. KG, Berlin, Germany), to produce a homogeneous material. The mixer rolls were continuously cooled with tap water circulating internally to prevent precuring. The gap between the rolls was 1.0 mm and the rotation speed was 10 rpm, the same for both rolls (i.e., no friction was applied). The actual mixing was achieved by removing the sheet of elastomeric material that eluted from the mixer, rolling it into the shape of a cylinder, and then again feeding it to the mixer rolls. This procedure was repeated 10 times. The homogeneous elastomeric blend was then put into a stainless steel mold and cured into silicone slabs of 10 × 10 cm with a thickness of 0.6 cm. These slab samples were cured on a heat press Polystat 200 S (Schwabenthan Maschinen GbmH), the sample being placed in a mold between two preheated Teflonized steel plates at 120°C for 90 s. Immediately after curing in the mold, the slabs

(silicone elastomer) were placed in a desiccator containing the phosphorous pentoxide drying agent. The desiccator was finally flushed with nitrogen to give an inert and dry atmosphere and to prevent postcuring.

After cooling at room temperature for 2 h, the slabs were cut into pieces approximately 2 × 2 cm in size, and each piece was transferred to a gas-tight aluminum pouch. A factorial design of the different storage conditions was established with a combination of atmosphere (nitrogen or oxygen), humidity (0 and 100%), temperature (20 and 40°C), and storage time (1 and 14 days). This factorial experiment resulted in 16 different samples. A small amount of water (1 mL) was added to half the samples and they were either flushed with oxygen or nitrogen before sealing. The samples were then stored at 20 and 40°C for 1 and 14 days, before the analytical evaluation was performed. As this part of the study was a screening to find the major important factors in the MHS decomposition, only single samples were analyzed.

NMR

^{1}H-NMR spectroscopy was used to determine the residual amounts of the functional groups involved in curing (i.e., the vinyl and hydride groups). The vinyl groups can either be distributed along the polymer chain, poly(methyl vinyl siloxane-dimethyl siloxane), or be present at the chain ends as dimethyl vinyl siloxane. The crosslinker is a low molecular mass poly(dimethyl siloxane-methyl hydrogen siloxane) (MHS). Measurements were made on silicone elastomer samples swollen in deuterated chloroform.

A small plug with a diameter of 3 mm was punched out from the stored silicone elastomer sample. The sample plug was inserted into a 5-mm NMR tube containing 0.6 mL deuterated chloroform in which it was allowed to swell for 2 h. The ^{1}H-NMR spectrum was recorded on a Bruker Avance DRX 500 MHz spectrometer at 30°C with the following instrumental settings: sweep width, 20.5 ppm; carrier frequency, 4.0 ppm; number of scans, 1500. As reference for quantification of the MHS amount in the sample, the integrated methyl signal at 0.3 ppm was set to 10,000. Integral regions were 4.4–5.0 ppm for the MHS signal and −1.9–2.6 ppm for the methyl signal.

Infrared Spectroscopy

Infrared spectroscopy (IR) was used to determine the amount of MHS in the samples. The intensive absorption band around 2160 cm^{-1} for the silicone MHS was used for this purpose. The overtone absorption band at 2500 cm^{-1} from the siloxane methyl group was used as an internal reference.

A small 0.5-mm-thick slice was cut from the sample with a scalpel and mounted in the sample holder. The transmission infrared spectrum was recorded on a Nicolet Magna 560 with a resolution of 4 cm^{-1} between 1500 and 3300 cm^{-1}. The A_{2160}/A_{2500} absorption ratio was evaluated and used as a measure for the amount of residual MHS in the silicone elastomer samples.

A standard was set up for this method to calculate the absolute amount of MHS residue in the samples, in contrast to ^{1}H-NMR, where only the relative amount was measured. Homogeneous solutions with known concentrations of the MHS standard polymer were prepared in a silicone oil standard in a concentration range from 0.1 to 1 mol % MHS. Spectra of these standard solutions were recorded by using the fluid measuring cell. The absorbencies for the two bands were then measured and a calibration curve of A_{2160}/A_{2500} ratio versus content of MHS was finally constructed.

Hardness

The Shore A hardness was measured with a digital hardness instrument, Shore Durotronic 1000, with an automatic stand, series 900. The hardness of the 6-mm-thick sample was measured 1 s after application of the measuring sensor. Six measurements were performed on each individual sample slab and the mean was calculated.

Compression Modulus

The storage compression modulus (E') was measured at room temperature in air with a dynamic mechanical analyzer (DMA), Netzsch DMA 242. A cylindrical test piece with a diameter of 12 mm was punched out from the sample. This cylindrical piece was then mounted in the compression sample holder. The frequency was set to 1 Hz; the dynamic force was 4.0N and the static applied force was 4.8N. The maximum amplitude was set to be 60 μm. A flat probe with a diameter of 15 mm was fixed to the sample before force was applied.

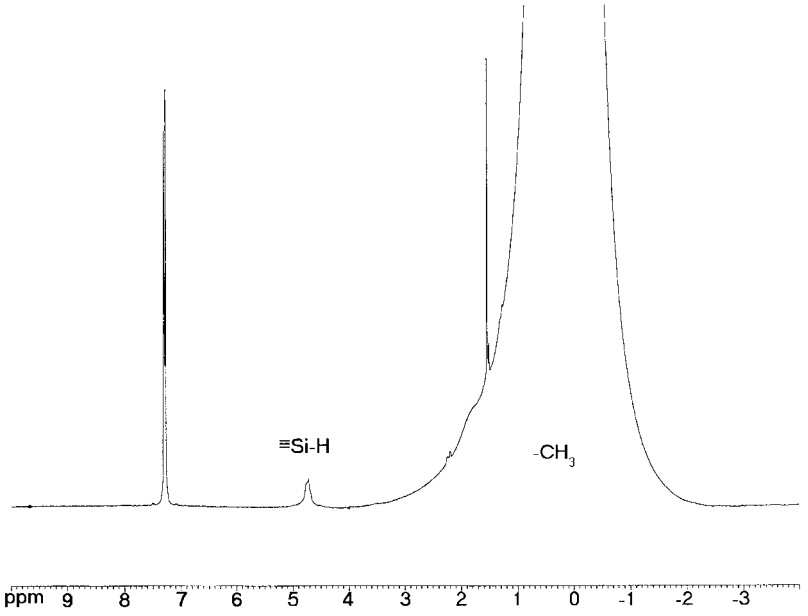


Figure 1 ^{1}H-NMR spectrum of the crosslinked sample 1, stored for 1 day in dry oxygen, showing the signal from the remaining MHS group (≡Si—H) and the reference peak from the methyl group.

RESULTS AND DISCUSSION

Factors Affecting the MHS Decomposition

When the blended but uncured sample was analyzed by ^{1}H-NMR, the multiple bands representing vinyl groups were found in the region from 5.7 to 6.2 ppm; the hydride singlet signal was found at 4.7 ppm and the large singlet from the methyl group was found in the region around 0 ppm. The vinyl and MHS amounts relative to the methyl groups in the uncured sample were estimated from the integrated vinyl, hydride, and methyl signals in the NMR spectrum. Approximately 0.2 mol % of vinyl groups (methyl vinyl siloxane and dimethyl vinyl siloxane) and 0.7 mol % of MHS were found. This result shows that the excess of crosslinker to vinyl before crosslinking was $\sim$ 3.5 : 1. This method for quantification of low levels of MHS assumes that a high-performance NMR spectrometer is used where a linear signal response over a large concentration range is achieved. In the method validation, we controlled the accuracy by performing standard additions of the crosslinker. Full recoveries of MHS were found.

The NMR spectrum of the cured sample 1 (stored for 1 day in dry oxygen) (Fig. 1) shows no detectable signals of vinyl groups in the region from 5.7 to 6.2 ppm. The same observation was made for the other seven cured and stored samples, indicating that the primary crosslinking reaction, the platinum-catalyzed hydrosilanization between vinyl and hydride groups

$$\equiv\text{Si—H} + \text{H}_2\text{C}{=}\text{CH—Si}{\equiv} \xrightarrow{\text{Pt}} {\equiv}\text{Si—CH}_2\text{—CH}_2\text{—Si}{\equiv} \quad (1)$$

was complete. Sample 1 was also found to have the highest relative amount of MHS remaining in the sample. Table II lists the residual amounts of MHS found by NMR.

The other signals in the NMR spectra are due to chloroform, which gives a signal at 7 ppm, whereas the signals between 1 and 2 ppm are probably due to the presence of silanol groups and/or water. Furthermore, the ethylene group formed in the hydrosilanization reaction should be evident in the region around 2 ppm. Identification and quantification of this ethylene group would be a direct measurement of the primary crosslinking density. However, we have not further investigated this possibility in the present work.

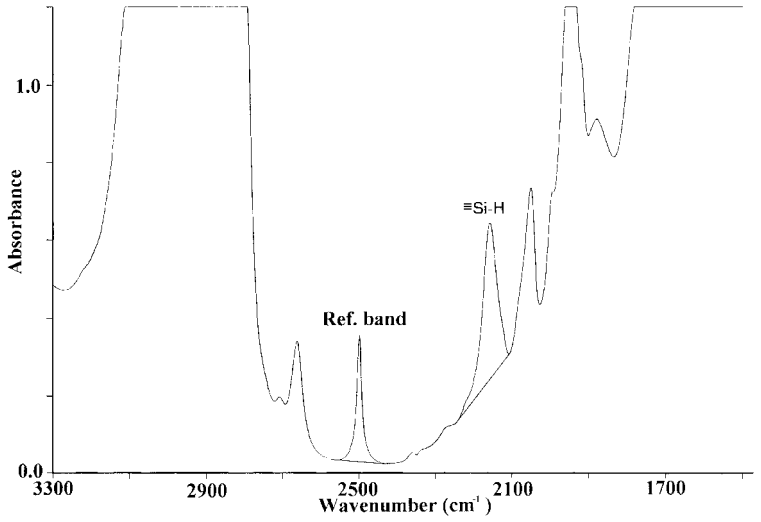


Figure 2 IR spectrum of the crosslinked sample 1, stored for 1 day in dry oxygen, showing the MHS band at approximately 2160 cm^{-1} and the reference band from the polymer backbone at 2500 cm^{-1}.

The IR spectra evaluations of the stored samples were primarily used for quantification of the MHS group.

As shown in Figure 2, the MHS group has an absorption band at approximately 2160 cm^{-1}. As an internal reference for quantification, the band at 2500 cm^{-1} was used. This absorption band is an overtone band of the symmetric deformation for the silicon-bonded methyl group found at 1260 cm^{-1}. This overtone band was described as being suitable for measurements on thick samples because of its low absorptivity.[4] From the standards, it was found that the amount of MHS in the sample was equal to $0.307 \times A_{2160}/A_{2500}$ expressed as mol %. As the MHS content measured with IR did not reach zero for samples 4 and 8 as in the NMR measurements, the selectivity of the IR method was examined. The stored sample with the lowest MHS content (i.e., sample 8) was heated at 150°C for 4 h in an oven to decompose all MHS groups. After cooling the sample to room temperature, a new IR spectrum was recorded and the relative amount of MHS was then found to be < 0.01 mol %. This experiment shows that the absorption at 2160 cm^{-1} is highly selective for MHS in this type of silicone elastomer. Data for residual MHS found in the samples from the factorial experiment measured by IR are given in Table II.

In the IR measurements, small test pieces with a thickness of 0.5 mm were cut from the surface of the samples. As the samples were 6 mm thick, it is possible that an inhomogeneity in the MHS content could arise (i.e., the decomposition could be faster at the surface than within the sample). A study was therefore undertaken to investigate this possibility. One of the samples was cut into two parts with a scalpel giving a fresh surface to analyze. This new surface was immediately analyzed with respect to MHS content at different positions from the top to the bottom of the sample. The measurements were performed with the IR instrument equipped with an IR microscopic SpectraTech model 40. The rectangular surface analyzed in this fashion was 0.1×1 mm in size. Six IR spectra were taken, evenly distributed over the sample. Table I shows the result of this study. It can be clearly seen that the MHS decomposition rate is uniform.

The data from the factorial experiment in Table II were evaluated by Modde v. 5 (Umetrics AB, Sweden) by using multiple linear regression analysis. Figure 3 shows how the factors, atmosphere,

Table I Residue MHS Distribution at Different Depths in the Cured Silicone Sample Measured by IR

Distance from Top Surface (mm)	Amount of MHS (mol %)
1	0.27
2	0.26
3	0.26
4	0.26
5	0.26

Table II Residual Amount of MHS in the Cured and Stored Silicone Elastomers Measured by NMR and IR

Sample No.	Atmosphere	Relative Humidity (%)	Storage Temperature (°C)	NMR $I_{MHS}/I_{SI—CH_3}$/ 10,000		IR MHS (mol %)	
				1 day	14 days	1 day	14 days
1	O_2	0	20	2.75	1.84	0.38	0.34
2	O_2	0	40	2.29	1.02	0.37	0.26
3	O_2	100	20	2.54	0.84	0.37	0.22
4	O_2	100	40	1.54	< 0.10	0.29	0.06
5	N_2	0	20	2.43	1.70	0.38	0.33
6	N_2	0	40	2.05	0.97	0.37	0.27
7	N_2	100	20	1.89	0.82	0.35	0.22
8	N_2	100	40	1.47	< 0.10	0.28	0.06

humidity, temperature, and time influenced the MHS content. The more negative the bar, the greater is the effect of that variable in reducing the MHS content. The variance for the experiment is given on top of each bar, indicating the significance of each variable.

Both the NMR and the IR results clearly show that the atmosphere (nitrogen or oxygen) around the silicone samples during storage had no effect on the MHS content. On the other hand, the humidity, temperature, and time had a significant impact on the rate of decomposition of the MHS groups in the samples. This suggests that the MHS groups primarily undergo a hydrolysis reaction where the silicon-bonded hydrogen is hydrolyzed into a silanol, according to the reaction:

$$\equiv\text{Si—H} + \text{H}_2\text{O} \xrightarrow{\text{Pt}} \equiv\text{Si—OH} + \text{H}_2 \qquad (2)$$

This reaction must be catalyzed by platinum, because the crosslinker in the preelastomer Part B raw material is stable for well over a year at room temperature. The oxidation of the MHS groups in the cured material seems to proceed very slowly compared to the hydrolysis reaction. The small decrease in MHS content found between the two measuring occasions, for the samples stored for 1 and 14 days under dry conditions in oxygen or nitrogen, is probably due to a hydrolysis reaction with the small amount of water remaining in the sample after curing. This water is probably both adsorbed on the surface of the silica filler and dissolved in the silicone polymer network. The water content in the newly cured samples was estimated by thermal desorption at 150°C in combination with Karl Fischer coulometric titration and was found to be ~ 0.05%.

Procedure to Eliminate MHS in Various Environmental Conditions

A separate study was performed to investigate the rate of MHS decomposition in elastomers

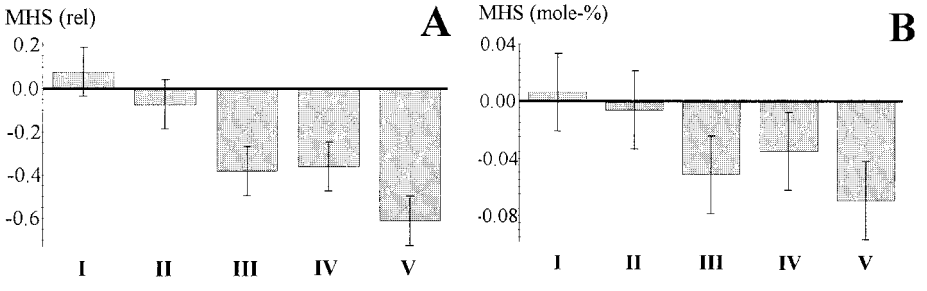


Figure 3 Results from the evaluation of the factorial design experiments, by (A) NMR and (B) IR. The variables are oxygen (I), nitrogen (II), humidity (III), temperature (IV), and time (V). The more negative the bar, the more effective is the factor in promoting decomposition the MHS.

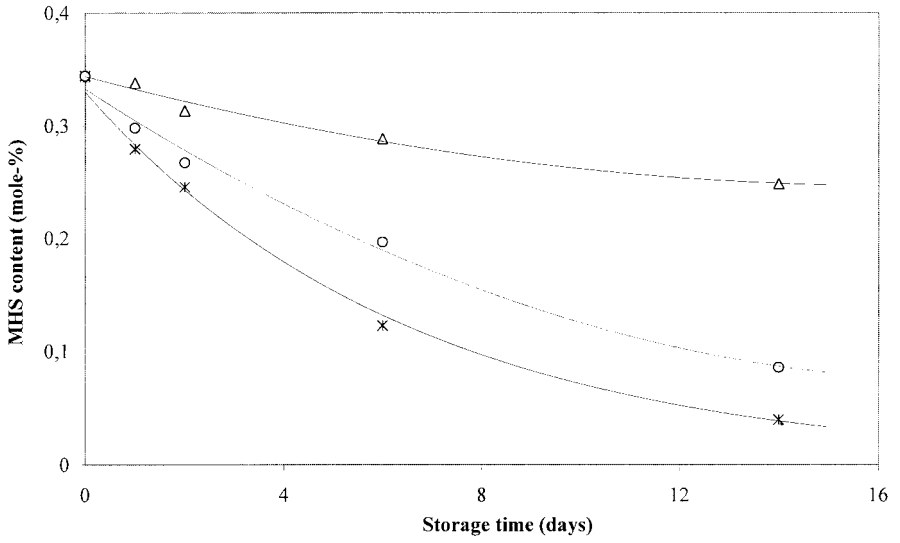


Figure 4 MHS content versus time, showing the decomposition rates in different environments; 22°C/56% RH (△), 40°C/48% RH (○), and 40°C/75% RH (*)

stored at various temperatures and humidities. A set of silicone elastomer slab samples was prepared according to the method described above. The samples were stored under various conditions which may be relevant to silicone elastomer drug release products. In this case, the maximum storage temperature for the product was estimated to be 40°C to avoid degradation of the incorporated drug. Exposure to various humidity levels was achieved by storing the samples in desiccators filled with either saturated $Mg(NO_3)$ giving 56% relative humidity (RH) at 22°C and 48% RH at 40°C or saturated NaCl giving an RH of 75% at 40°C.[5] Higher humidities are not recommended because of the risk of microbiological growth. The MHS content was measured by the IR method already described. Figure 4 shows the MHS content as a function of storage times under the various conditions.

The best procedure to eliminate the residual MHS groups in the elastomer is therefore to store the products at 40°C and a RH of 75%. By using this treatment, the MHS groups were practically gone after a few weeks.

Factors Affecting the Mechanical Properties

The results of the mechanical analysis of the stored samples in the factorial experiment, hardness and compression storage modulus, are shown in Table III. Figure 5 shows the mathematical evaluation of these data.

Table III Mechanical Properties of Cured and Stored Silicone Elastomers

Sample No.	Atmosphere	Relative Humidity (%)	Storage Temperature (°C)	Hardness Shore A		Compression Storage Modulus (MPa)	
				1 day	14 days	1 day	14 days
1	O_2	0	20	38.5	40.1	2.9	2.6
2	O_2	0	40	39.3	41.7	3.3	2.7
3	O_2	100	20	38.4	40.4	3.3	2.6
4	O_2	100	40	39.8	44.3	2.8	3.0
5	N_2	0	20	38.5	41.0	2.9	3.1
6	N_2	0	40	39.2	42.4	2.5	3.3
7	N_2	100	20	38.5	41.1	2.9	3.0
8	N_2	100	40	40.0	47.0	2.6	3.4

Sample No.	Atmosphere	Relative humidity (%)	Storage temperature (°C)	Hardness Shore A		Compression storage modulus (MPa)	
				1 day	14 days	1 day	14 days
1	O_2	0	20	38.5	40.1	2.9	2.6
2	O_2	0	40	39.3	41.7	3.3	2.7
3	O_2	100	20	38.4	40.4	3.3	2.6
4	O_2	100	40	39.8	44.3	2.8	3.0
5	N_2	0	20	38.5	41.0	2.9	3.1
6	N_2	0	40	39.2	42.4	2.5	3.3
7	N_2	100	20	38.5	41.1	2.9	3.0
8	N_2	100	40	40.0	47.0	2.6	3.4

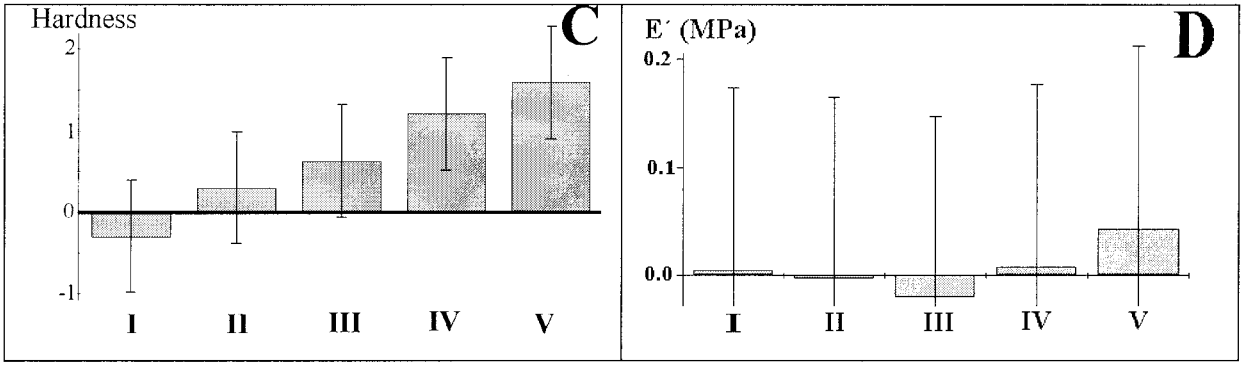


Figure 5 Results of the evaluation of the factorial experiments showing (C) Shore A hardness and (D) compression storage modulus. The variables are oxygen (I), nitrogen (II), humidity (III), temperature (IV), and time (V). The more positive the bar, the more effective is the factor in increasing the postcuring.

Only temperature and time seem to have any significant impact on the hardness. There is a tendency for the humidity to be of importance, although this effect is not statistically significant. The choice of atmosphere has no significant effect on the hardness development. On the other hand, the storage conditions seem to have no significant influence on the compression modulus. A probable explanation of this result is that the variation of the method was too large to enable the different effects to be resolved for this response. Measurements on several samples would probably have improved the significance in this test. In addition, other methods to measure degree of crosslinking

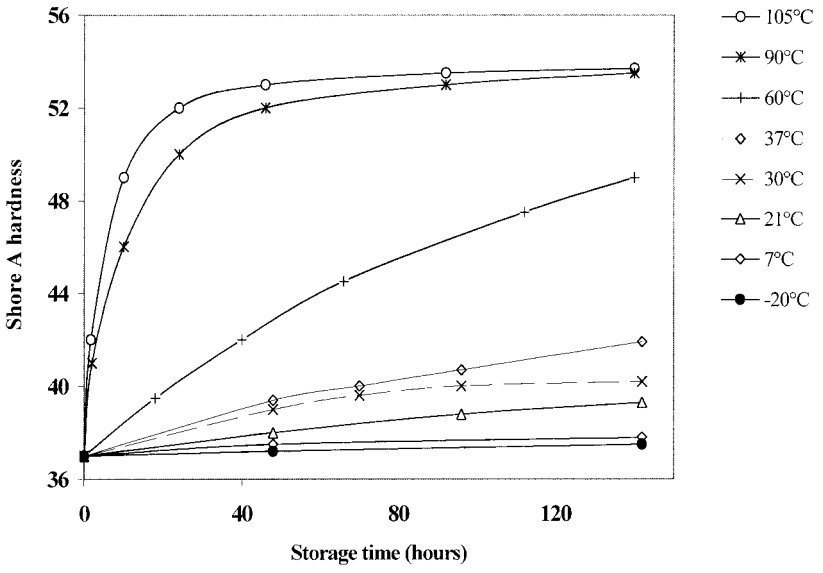


Figure 6 Hardness development on newly cured silicone samples versus storage time at different temperatures.

could have been used to improve the evaluation of factors affecting the change in mechanical properties (e.g., swelling measurements).

The increase in hardness indicates that the crosslinking density increases on storage. There is a possibility that the primary curing reaction between vinyl and hydride groups was not complete during the manufacturing of the samples. Although no detectable vinyl groups were found with NMR spectroscopy, minor amounts may still remain, below the detection limit for the NMR method. This reaction will thus continue during the subsequent storage. Another possible chemical reaction explaining the change in hardness is the addition between MHS and silanol groups given in reaction (3)[6]:

$$\equiv Si{-}H + HO{-}Si\equiv \xrightarrow{Pt} \equiv Si{-}O{-}Si\equiv + H_2 \quad (3)$$

Silanol groups can be present in the preelastomers before curing, but they are also formed during the postcuring reaction when MHS is decomposed with water according to the hydrolysis reaction (2).

The reaction according to eq. 3 would also increase the degree of crosslinking in the elastomer, as in the case of the hydrosilanization reaction, and would consequently increase the hardness and modulus of the samples.

Postcuring by Thermal Treatment

In stability studies on the silicone elastomer, it was found that the hardness increased over time. The normal conditions in drug stability studies are storage at room temperature for at least as long as the product shelf life. A temperature of 40°C is normally used for accelerated studies over 6 months. To find the plateau value for the hardness (i.e., after total postcuring), a study was carried out in which the samples were stored at different temperatures and the Shore A hardness was measured on different occasions.

The silicone elastomer slabs were prepared as described above. The samples were stored at different controlled temperatures for 1 week. The results of the Shore A hardness development are shown in Figure 6.

The postcuring conditions at 90 and 105°C seem to result in a plateau value of the hardness for the elastomers, with a value of ~ 53 Shore A. The hardness had increased by as much as 40% from the initial value after curing. The samples stored at lower temperatures also showed an increase in hardness, but this was less pronounced than that at the higher temperatures. Furthermore, these samples did not reach any steady-state value during the rather short time of investigation (Fig. 6).

The effect on the compression modulus of the treatment at high temperatures was also mea-

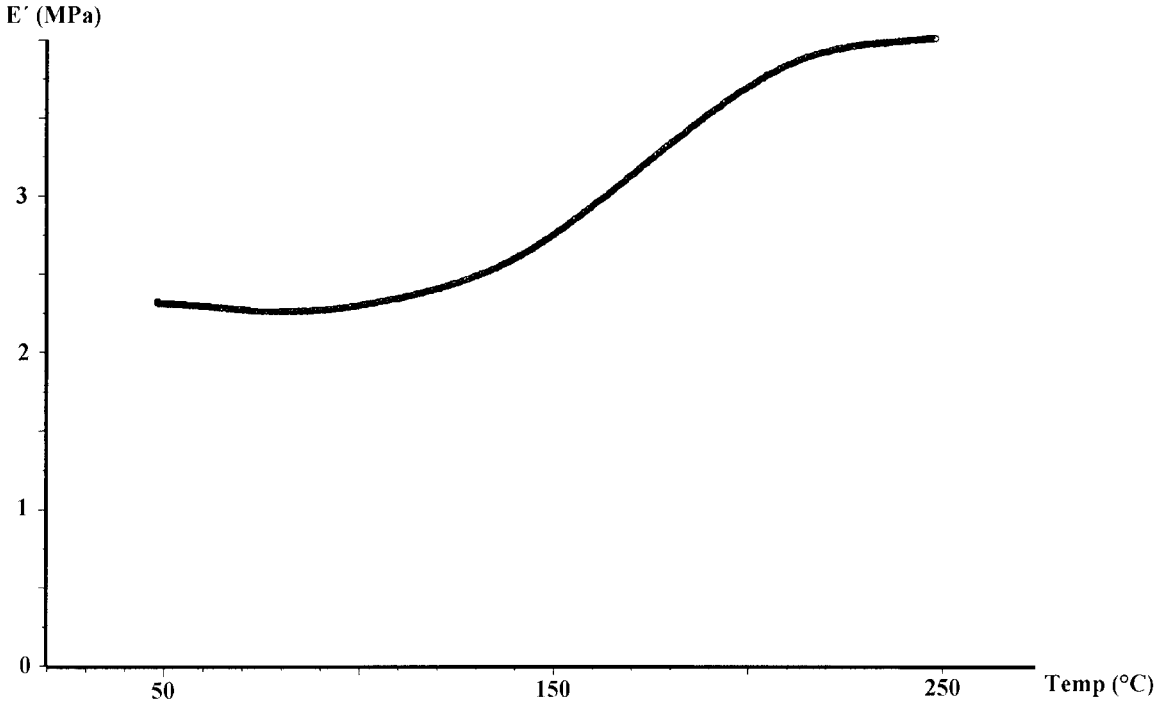


Figure 7 DMA thermogram of sample 1, storage compression modulus (E') versus temperature. The strong increase in E' at higher temperatures indicates a significant increase in crosslinking density.

sured. In this study, the samples from the factorial experiment were used (i.e., the postcuring proceeded differently for the different samples). The storage compression modulus was monitored by the DMA instrument in a temperature-scanning mode. The samples were heated from room temperature to 250°C at a heating rate of 2°C/min. The purge nitrogen gas flow rate was set to 200 mL/min. A cylindrical test piece with a diameter of 12 mm was punched out from the sample. This cylindrical piece was then mounted in the compression sample holder. The frequency was set to 1 Hz; the dynamic force was 4.0*N* and the static applied force was 4.8*N*. The maximum amplitude was set to 60 μm. A flat probe with a diameter of 15 mm was fixed to the sample before the force was applied.

The DMA thermogram for sample 1 (Fig. 7) shows a rather large increase ($\sim$ 80%) in modulus during the heat treatment. A plateau value is just barely reached in the temperature interval between 200 and 250°C. However, on increasing the temperature even more, it was found that the modulus decreased as the elastomer started to degrade.

All thermograms had the same shape, but the increase in modulus varied between the samples. Samples 4 and 8 measured after 14 days showed an increase in modulus of about 10%, even though these two samples contained no measurable amount of MHS. This new observation together with the observation that the hardness of samples 4 and 8 was far from the plateau value of 53 Shore A indicates that a second crosslinking reaction is occurring. One possible chemical reaction that could occur in the high temperature region is the condensation reaction between two silanol groups in different polymer chains:

$$\equiv\text{Si—OH} + \text{HO—Si}\equiv \rightarrow \equiv\text{Si—O—Si}\equiv + \text{H}_2\text{O} \quad (4)$$

CONCLUSION

In the crosslinking of silicones using the hydrosilanization reaction, an excess of crosslinker is used to achieve fast curing and a fully crosslinked material. The residual MHS groups in the elastomer are the main cause of the postcuring where the material hardens over time. However, in our application with a silicone elastomer for drug delivery, the aim was to develop a simple and robust

procedure to decompose the residual MHS groups in the elastomer. We found that temperature and relative humidity are the main parameters that influence this postcuring reaction. Because of the poor thermal stability of the incorporated drug, it was not an option to use temperatures higher than 40°C to increase the silicone hydride decomposition rate. However, by storing the product in a controlled environment with a high relative humidity and at reasonably high temperatures, this postcuring reaction can be controlled and is complete within a couple of weeks.

The decomposition of the silicone hydride with water has no direct effect on the crosslinking density as free silanol groups are formed. However, other chemical reactions can take place that increases the crosslinking density and thereby change the mechanical properties of the elastomer. Traces of residual vinyl groups will react with the silicone hydride; according to the primary crosslinking reaction, silanol groups formed from the decomposition of the MHS groups will also react with silicone hydride groups, and at higher temperatures, the condensation between silanol groups may occur. All these chemical reactions are potentially active in the postcuring of the silicone elastomer.

REFERENCES

1. Wrobel, D. Organosilicon Chemistry II; VCH: Weinheim, Germany, 1996; p 633.
2. Stein, J.; Grade, H.; Williams, E. A.; Codella, P. J.; Smith, J. F. J Appl Polym Sci 1993, 47, 2257.
3. Quam, X. Polym Eng Sci 1989, 29, 1419.
4. Smith, A. L. The Analytical Chemistry of Silicones; Wiley: New York, 1991; p 324.
5. Nyqvist, H. Int J Pharm Tech Prod Manuf 1983, 4, 47.
6. Kobayashi, T.; Saitoh, H.; Fujii, N.; Hoshino, Y. J Appl Polym Sci 1993, 50, 971.