Technology of an adhesive silicone film as drug carrier in transdermal therapy. I: Analytical methods used for characterization and design of the universal elastomer layers

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ABSTRACT

Silicone polymers possess unique properties, which make them suitable for many different applications, for example in the pharmaceutical and medical industry. To create an adhesive silicone film, the appropriate silicone components have to be chosen first. From these components two layers were made: an adhesive elastomer applied on the skin, and a non-adhesive elastomer on the other side of the film. The aim of this study was to identify a set of analytical methods that can be used for detailed characterization of the elastomer layers, as needed when designing new silicone films. More specifically, the following methods were combined to detailed identification of the silicone components: Fourier transform infrared spectroscopy (FTIR), proton nuclear magnetic resonance (^{1}H NMR) and size exclusion chromatography with evaporative light scattering detector (SEC-ELSD). It was demonstrated that these methods together with a rheological analysis are suitable for controlling the cross-linking reaction, thus obtaining the desired properties of the silicone film. Adhesive silicone films can be used as universal materials for medical use, particularly for effective treatment of scars and keloids or as drug carriers in transdermal therapy.

1. Introduction

At present, there is an increasing number of studies related to the development of new products intended for use on skin, such as dressings and patches [1–5]. They are made from different polymers, and the most popular ones are nylon (polyamides), polyethylene, polypropylene, polyvinyl, polyacrylates, cellulose derivatives, chitosan, carrageenan and silicone polymers [2,6,7].

Current research on the use of polymers on skin is focused on elimination of allergic reactions and improving the stability of patches and dressings, but also on increasing the range of their action. They are currently used not only as material protecting skin injuries or as carriers for antiseptic substances, but also as active dressings used for treatment of chronic wounds [3–5]. Polymers are also used in transdermal therapeutic systems (TTS), as active substance carriers with a controlled release rate, and for products with a prolonged action [2,8–10]. Another important application, closely related to dermatology and surgery, is their use to treat keloids and scars with different etiology [11,12]. For keloids, a potential thera-

peutic effect has been observed when silicone polymers were used in the treatment.

In this project silicone elastomers were investigated. A great number of unique properties and features that determine their medical application (intended for use on skin) are described by many authors. Each property and feature was assumed and commented by authors of this paper (Table 1).

The aim of this study was to demonstrate the use of certain analytical methods to design elastomer layers from which an adhesive silicone film was made. For detailed identification of the rubbers the following methods were used: Fourier transform infrared spectroscopy (FTIR), proton nuclear magnetic resonance (^{1}H NMR) and size exclusion chromatography with evaporative light scattering detector (SEC-ELSD). It was demonstrated that through the use of these methods, together with rheological analysis to determine the properties of the components, it was possible to control the cross-linking reactions and develop an optimal silicone film. The adhesive silicone film technology requires suitable silicone rubbers from which two different layers are combined through cohesion to form a patch: an adhesive elastomer, used on the skin, and a non-adhesive one for the other side of the film. The non-adhesive layer is a base layer, which could be the matrix for an active substance. The desired properties of both layers depend not only on the properties

Table 1
Properties of silicone elastomers intended for medical use on skin.

No.	Property	Reference	Advantage	Potential use
1.	Biocompatibility	[13–17]	No influence on human immune system No cancerogenic action No skin irritation	Patches and dressings of all types
2.	Highly non-toxic	[18]	Low health risk	Patches and dressings of all types
3.	Adhesion	[2,16,19]	Proper contact with the skin, facilitates occlusion	Layer of patch or dressing
4.	Anti-adhesion	[19]	No adhesion to other materials (e.g. clothes)	Layer of patch or dressing
5.	Low reactivity	[13,16,17,20]	Low possibility for reactions with active substances or other substances contained in a product	Patches and dressings of all types
6.	High permeability	[21–25]	Facilitates diffusion of active substances	- Transdermal therapeutic systems - Drug formulations with prolonged action - Wound dressings with active substances
7.	Resistance to atmospheric conditions	[26]	Increases product stability and safe use	Patches and dressings of all types
8.	Resistance to UV radiation	[14,19]	Increases product stability and safe use	Patches and dressings of all types
9.	Resistance to microorganisms	[14]	Increases product stability and safe use	Patches and dressings of all types
10.	Hydrophobicity	[18]	Provides durability in contact with humid surface of skin	Patches and dressings of all types
11.	High molecular weight	[18]	Safety of use by lack of penetration through cell membranes	Patches and dressings of all types
12.	Resistance to extensibility and deformation	[13]	Desired mechanical properties, which affect the resistance and facilitates multiple use of the same material	Some patches and dressings
13.	Flexibility	[14,19]	Promotes occlusion when covering skin surface, which is beneficial for scar treatment	Patches used in scar therapy
14.	Transparency	[14,17]	Products are almost invisible on skin	Patches used in visible places
15.	Similarity of hydrophilic/lipophilic properties to human skin	[17]	Compatible with the human skin Physiological meaning Predictable and controllable delivery of active substances into stratum corneum Promotes the bioavailability, and hence the effective action, of active substances	- Transdermal therapeutic systems - Drug formulations with prolonged action - Wound dressings with active substances
16.	Similarity to biological membranes	[21–23,25]	Beneficial permeability for active substances Promotes the bioavailability, and hence the effective action, of active substances Useful when designing new drug formulation and optimizing their diffusion parameters	- Transdermal therapeutic systems - Drug formulations with prolonged action - Wound dressings with active substances

of the rubbers used, but also on the cross-linking mechanism. The analytical methods demonstrated here enable verification of this experimentally.

In the scientific literature on silicone elastomers there is no standard analytical method proposed for identification of rubber components and estimation of their properties – a necessary step for development of new drug formulations and biomedical materials. Neither of Pharmacopoeia monographs contains proposals of analytical methods for use in this research field [27–29].

2. Materials and methods

2.1. Materials

Silicone rubber RTV Gumosil AD-1 part A and Gumosil AD-1 part B were obtained from Silikony Polskie (Nowa Sarzyna, Poland) and the other silicone rubbers Soft Skin Adhesives DC 7-9800 part A, DC 7-9800 part B were obtained from Dow Corning Corporation (Wiesbaden, Germany). Chloroform (HPLC grade) was purchased from Sigma Aldrich (St. Louis, MO, USA).

Certificated polystyrene standards (molecular weights ranging from 376 to 2,570,000 Da, with a polydispersity coefficient ranging from 1.02 to 1.11) were purchased from Sigma Aldrich (St. Louis, MO, USA), and PDMS (polydimethylsiloxane) standard (molecular weight 90,200 Da) was obtained from Aldrich Chemical Company (Milwaukee, WI, USA).

2.2. Preparation of samples

2.2.1. Polystyrene standards

75 ml of chloroform was added to each of three tubes containing four polystyrenes of various molecular weights ranging from 376 to 2,570,000 Da. Thus polystyrene solutions of concentration in the range 0.067–0.134% (w/w) were obtained. The solutions were left for 2 h to allow the polystyrene mixtures to dissolve. This testified that the standards used were characterized by a low molecular weight dispersion distribution.

2.2.2. PDMS 90,200 Da standard

The PDMS standard (molecular weight 90,200 Da) was prepared by dissolving the substance in chloroform to a concentration of the solution obtained was 0.5% (w/w).

2.2.3. Silicone components

The silicone components Gumosil AD-1 part A and B, as well as DC 7-9800 part A and B were dissolved in chloroform to a concentration of 0.5% (w/w).

2.3. Analysis of silicone components by FTIR and ATR-FTIR

The silicone components were identified by FTIR spectroscopy. Spectra in the range from 4000 to 400 cm^{-1} were registered by means of a FTIR-4100 spectrophotometer (Jasco, Cracow, Poland) with a resolution of 0.9 cm^{-1}. FTIR spectra were calculated as the average of 32 scans and standardized for signal by wavenumber 1260 cm^{-1}.

For identification of silicone components by means of FTIR, the transmission technique with KBr disc was used. Spectra were registered according to Pharmacopoeias [27–29] by a thin film of the liquid sample on the KBr disc. Furthermore, the attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR) technique was also used, with ZnSe crystal.

2.4. Analysis of silicone components by ^{1}H NMR

The ^{1}H NMR spectra of the four components were registered with a NMR spectrometer (Unity 500, Varian, Palo Alto, CA, USA). All the analyzed solutions were prepared with deutered chloroform (CDCl$_3$).

2.5. Rheological analysis of silicone components

The rheological analyses were made with a rotary viscometer (ViscoTester HAAKE type VT 550, Karlsruhe, Germany) working in a stand cone and plate system (measurement system PK 1 1°, cone radius 14 mm, cone angle 1°). Shear stress as a function of shear rate (CR mode) was measured, and the data obtained processed using the Haake RheoWin 3.5 Data Manager Program.

Approximately 100–300 mg of each silicone component was put on the base plate and analyzed after 15 min (time measured from the moment of filling the slit) in a temperature (thermostat system) of 20 °C and with a measurement slit of 0.05 mm. Flow curves were made with increasing shear rate (from 0 to 40.0 s^{-1}, in 30 s).

2.6. Analysis of silicone components by SEC-ELSD

The molecular weights of the silicone components were determined using SEC-ELSD as previously described [30,31]. Briefly, the detection was made with evaporative light scattering (ELSD 030195, BBT Automatyka, Gdansk, Poland) equipped with a laser diode 10 mV 635 nm (Toshiba, Tokyo, Japan) as the radiation source, and a photoelectric multiplier K-372 HA (Hamamatsu, Herrsching am Ammersee, Germany) as photodetector. The signal measurement range was 0–200 nA, the temperature range of the drift tube was 25–120 °C, and of the measurement cell 25–120 °C. Carbon dioxide was used as evaporation gas, a TSK-GEL H$_{HR}$GMH$_{HR}$-M column with polystyrene–divinylobenzene packing (5 μm, 300 mm × 7.8 mm) of Tosoh Biosep Company (Poznan, Poland) was used as the stationary phase and chloroform as the mobile phase. SEC measurements were performed using the Pump Mini Star K 500 (Knauer, Berlin, Germany). The injection loop volume was 20 μl (Knauer, Berlin, Germany). Data were accumulated and processed using the Eurochrom 2000 (Knauer, Berlin, Germany).

Constant measurement conditions were maintained during all analyses. The samples were eluted with chloroform during 15 min with a flow rate of 1.0 ml/min. The temperature of the drift tube and measurement cell was 60 °C and the CO$_2$ pressure was 130 kPa. The calibration curve for polystyrene samples ranging from 376
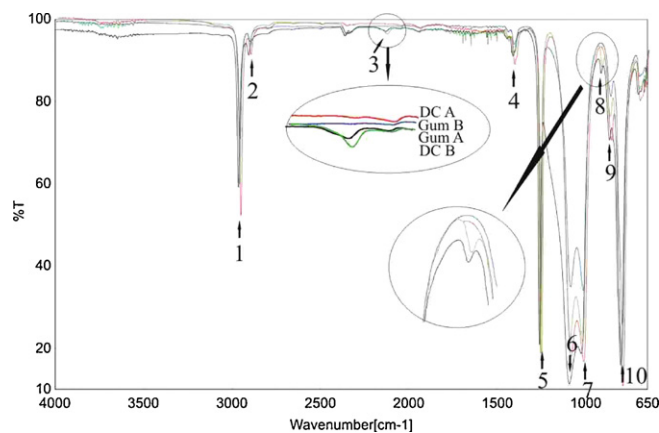

Fig. 1. FTIR spectra of four silicone components, Gum-A (black), Gum-B (blue), DC A (red) and DC B (green), registered as a thin liquid film on KBr disc with characteristic bands assignment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

to 2,570,000 Da was fitted by log(M) = t, where M is the molecular weight (Da) and t is the retention time (min). For each of the three polystyrene mixtures, seven independent separations were carried out.

3. Results and discussion

Experiments were carried out in many directions and may be divided into three main phases.

Phase I – the identification of silicone components, from which elastomers were made, by interpretation of spectra obtained by means of FTIR and ^{1}H NMR method and by determination of molecular weights by means of SEC-ELSD.
Phase II – the evaluation of properties of polymers chosen based on rheological methods. Flow curves and dynamic viscosity were calculated.
Phase III – the observation of cross-linking reaction (vulcanization) of silicone components by means of FTIR method and rheological parameters were determined.

Table 2 presents the names of the silicone components, their predicted function in the adhesive silicone film (after the cross-linking reaction), abbreviations that are used in this paper and the results obtained by mentioned methods.

3.1. Identification of silicone polymers (components of elastomers) by the FTIR method

The FTIR spectra of the four silicone components were quite similar (Fig. 1), which suggests that they had an identical basic of structure.

Table 3 presents the structure of the silicone component chosen (Gumosil AD-1 part A, Gum A), as confirmed by interpretation of the FTIR spectrum (Fig. 1).

It is known that the cross-linking reaction depends on the presence of components with a similar structure but possessing different functional groups at the ends of the molecule. When analyzing the FTIR spectra (Fig. 1), it could be seen that the differences between components Gum A and Gum B, as well as between DC A and DC B are not too visible. It can result from the limitation of the method used, based on too small percentage of functional groups at the ends of molecule in comparison to other groups. However, there were noticeable differences between the spectra in the region of wavenumber 2100 and 800 cm^{-1}, which could be interpreted

Table 2
Silicone rubbers analyzed in this paper, their properties and predicted function in an adhesive silicone film.

No.	Name of the component	Abbreviation	Molecular weight (Da)	Consistency factor, k (Pa s)	Apparent viscosity (mPa s)		Dynamic viscosity (mPa s)		Function of the layer after cross-linking reaction
					Shear rate (s^{-1})		Experimental	Declared by manufacturer	
					20	30			
1.	Gumosil AD-1 part A	Gum A	61,015	93.659	25,000	20,000	–	20,000	First non-adhesive basic matrix for active substance from the outer side
2.	Gumosil AD-1 part B	Gum B	44,027	2.190	–		2192	No information	
3.	Soft Skin Adhesive DC 7-9800 part A	DC A	13,653	0.574	–		574	400	Second adhesive intended for use on skin (FDA)
4.	Soft Skin Adhesive DC 7-9800 part B	DC B	12,644	0.345	–		345	400	

Table 3
Confirmation of silicone component structure based on FTIR spectrum of Gum A.

No.	Wavenumber (cm^{-1})	Vibrational modes
1.	2962	ν_{as} C–H (CH$_3$)– Asymmetrical valence (stretching) vibrations C–H of group CH$_3$
2.	2905	ν_s C–H (CH$_3$)– Symmetrical valence (stretching) vibrations C–H of group CH$_3$
3.	2136	ν Si–H Valence (stretching) vibrations Si–H
4.	1414	δ C–H (CH$_2$) Deformation (bending) vibrations C–H of group CH$_2$ (vinyl)
5.	1260	δ C–H (Si–CH$_3$)– Deformation (bending) vibrations C–H of group Si–CH$_3$
6.	1092	ν_{as} Si–O–Si–
7.	1021	Valence (stretching) vibrations Si–O of group Si–O–Si
8.	909	δ Si–H Deformation (bending) vibrations Si–H
9.	867	ν Si–C (Si–CH$_3$)– Valence (stretching) vibrations Si–C of group Si–CH$_3$
10.	800	δ_ρ C–H (CH$_3$)– Deformation (bending) rocking vibrations C–H of group CH$_3$

as structural differences between the silicone components. Those regions corresponded to peaks 3 and 8 (Fig. 1), which were characterized by low intensity, and originate from vibrations of group Si–H (Table 3). Those peaks were only present in Gum A and DC B, which suggests that the Si–H group necessary for the cross-linking reaction was not present in the other two components. Interpretation of the FTIR spectra (Fig. 1) suggests that the components Gum A and DC B consist of a mixture of polydimethylsiloxane polymers with a dimethylvinyl group at the end of the chain and polydimethylsiloxane polymers with hydrogen at the end of the chain. In contrast, components Gum B and DC A consist of a mixture of polydimethylsiloxane polymers with only dimethylvinyl group at the end of the chain, but they also contain an added platinum (Pt) catalyst [32]. The most commonly used one is Karstedt catalyst Pt$_2\{[(CH_2 = CH)Me_2Si]_2O\}_3$ [32–34]. Some differences between the spectra could also be seen in the bands at 1100–1000 cm^{-1} and at 900 cm^{-1} (Fig. 1). They could result not only from, for example, the length of the siloxane chains, which depends on the degree of polymerization, but also from different additives like mechani-

cal amplifiers for hardness regulation (polysiloxane with hydrogen atoms at the end or in the chain) or fillers (different silica components). In conclusion, no significant structural differences were detected between the components Gum A and DC B, or between the components Gum B and DC A. Therefore, the cross-linking reaction mechanism would be similar for both rubbers.

3.2. Identification of silicone polymers (components of the elastomers) by the ^{1}H NMR method

Because the FTIR method cannot be used to prove that there are significant structural differences between different silicone components, the proton nuclear magnetic resonance (^{1}H NMR) method was used to confirm differences detected in the FTIR spectra. Structure confirmation for one chosen component (in this case Gum A, Fig. 2) is presented in Table 4.

The spectra of the four components were quite similar except in the regions with a chemical shift of 4.6–4.8 ppm and 0.15–0.25 ppm (Fig. 3). Resonance signals with a chemical shift of 4.74 ppm result

Table 4
Confirmation of the silicone component structure based on ^{1}H NMR spectrum of the component Gum A.

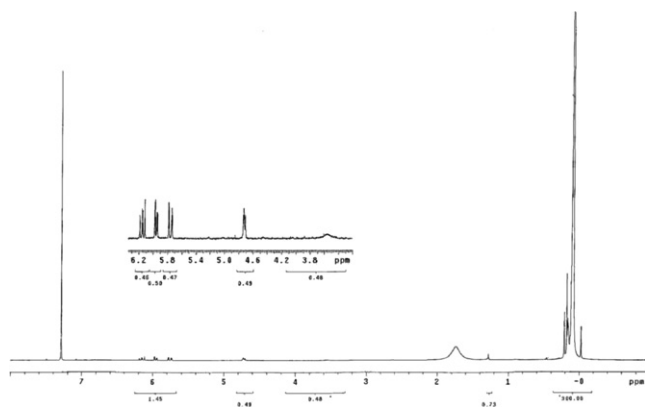| No.	Chemical shift (δ, ppm)	Group	Multiplicity	Integration
1.	0.10	Si(CH$_3$)$_2$	Singlet	300
2.	0.18	(CH$_3$)$_2$SiCH=CH$_2$	Singlet	3
3.	0.21	Coupling of C–H and (CH$_3$)$_2$SiH	Deformed singlet	6
4.	4.74	(CH$_3$)$_2$SiH	Septet	1
5.	5.79–6.15	(CH$_3$)$_2$SiCH=CH$_2$	Multiplet	1.5

Fig. 2. ^{1}H NMR spectrum of the Gum A component.

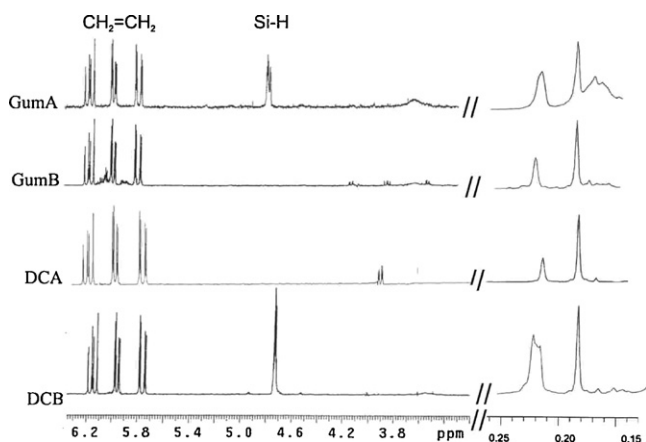**Fig. 3.** Fragment of ^{1}H NMR spectra of silicone components.

from the presence of Si–H group from $(CH_3)_2SiH$ and that was only observed for the components Gum A and DC B. Hence, this confirmed the results from the FTIR spectra.

The singlet appearing with the chemical shift of 0.21 ppm comes from the C–H coupling (satellite signal), whereas the deformation in the case of components Gum A and DC B (Fig. 3) was the result of a spin–spin coupling between protons from the $Si(CH_3)_2$ group and protons in the Si–H group (Fig. 4). This was confirmed by couplings that could be seen in the COSY spectra (Fig. 4).
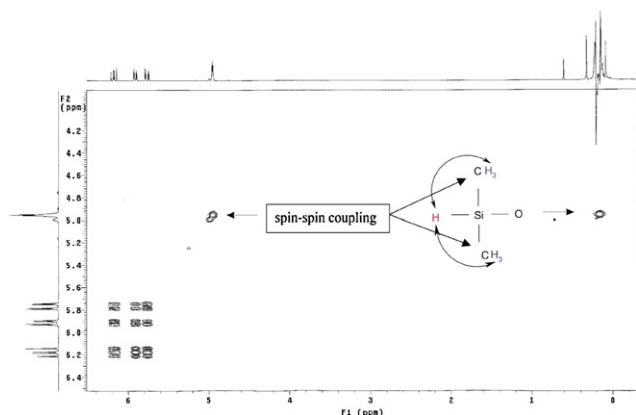
Fig. 4. An example of COSY ^{1}H NMR spectrum (component DC B).

Table 5
The accuracy and trueness of the SEC-ELSD method used to determine the molecular weights of silicon rubber compounds.

Values for PDMS with molecular weight 90,200 Da	Accuracy	Trueness
	Single result $n = 1$	Mean value $n = 10$
Retention time (min)	6.92	6.89
Calculated molecular weight (Da)	86,196	91,305
Relative error (%)	−4.44	+1.23

3.3. Assessment of the molecular weight of the silicone polymers using the SEC-ELSD method

To use size exclusion chromatography for assessment of molecular weight of examined polymers, the calibration curve of chromatography column and its working range, which is placed between the exclusion limit and permeation limit, was determined. The results obtained for polystyrene standards were used to determine the dependence between the logarithm of the peak molecular mass (M_p) and the retention time (t_r). The parameters of the standard curve were $\log M_p = -0.8336 t_r + 10.704$ and the correlation coefficient was $R^2 = 0.9938$. It was found that the column TSK-GEL $H_{HR}GMH_{HR}$-M had a wide working range (2,570,000–376 Da) and the relative standard deviation (RSD), calculated from retention times, in the range of 0.26–0.94 proved that the separation process was highly repeatable. The reliability of the molecular weights of the silicone polymers was confirmed by assessment of the accuracy and trueness of the method. This was done with a PDMS standard with the molecular weight 90,200 Da, as declared by the manufacturer and considered as a true value. The accuracy of the molecular weight determination was calculated from a single retention time, and the trueness from ten independent results. The relative error values are given in Table 5.

The results of molecular weights obtained for silicone polymers are given in Table 2. Based on the molecular weight results obtained it was concluded that there was no significant difference between components DC A and DC B. However, they differed significantly from the Gum A and Gum B components. The Gumosil rubbers had a molecular weight above 40,000 Da, or 3–5 times higher than the DC A and DC B components. Moreover, a significant difference between the molecular weight of Gum A and Gum B could be observed. Fig. 5 presents representative chromatograms showing the separation of the four polymers.

3.4. Determination of rheological parameters of the silicone components

The knowledge of rheological properties of pharmaceutical materials is necessary for accurate preparation or dosage of new
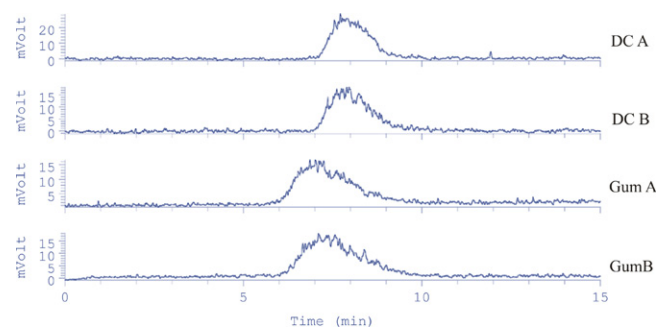

Fig. 5. Representative chromatograms from the distribution of silicone polymers by SEC-ELSD method.
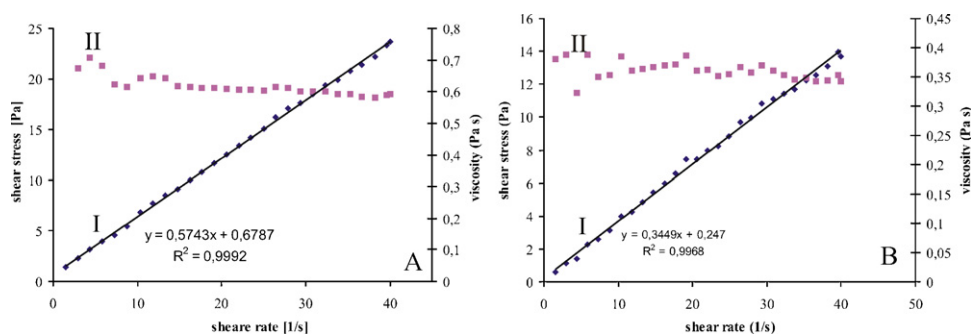
Fig. 6. Dependence of the shear stress against shear rate (I) and dependence of the viscosity against shear rate (II) for silicone polymer DC A (A) and DC B (B).
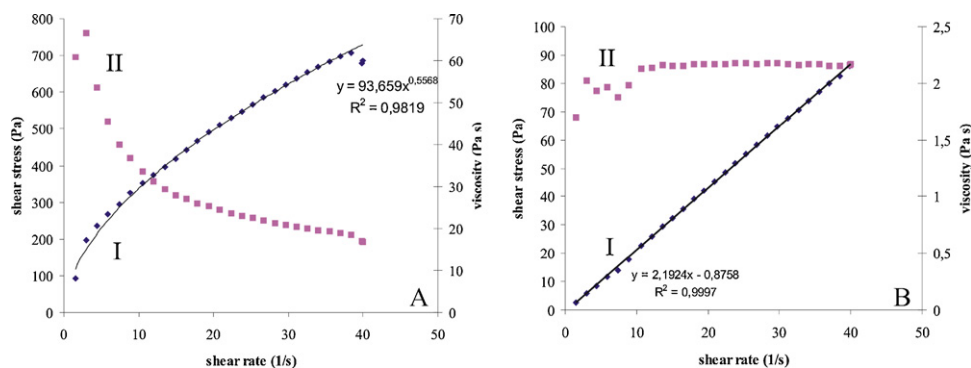

Fig. 7. Dependence of the shear stress against shear rate (I) and dependence of the viscosity against shear rate (II) for silicone polymer Gum A (A) and Gum B (B).

drug formulations. In case of our study the determination and interpretation of the rheological parameters were necessary to evaluate the properties of the silicone components. A second purpose was to study the cross-linking reaction. If the rheological parameters are known, it is possible to evaluate the cross-linking reaction kinetics, as well as to control the repeatability of the process and the predicted stability of the elastomers. Figs. 6 and 7 present flow curves of silicone polymers expressed as dependence of shear stress (τ) against shear rate (γ), and viscosity curves expressed as dependence of viscosity (η) against shear rate (γ) for representative silicone components.

Experiments were connected with determination of rheological properties and flow curves (dependence of shear stress – τ against shear rate – γ) which were used for evaluation of polymers studied. The shape of the flow curves restricted the amount of rheological models considered. For determination of the best function describing the relationship between the shear stress (τ) and the shear rate (γ), the following rheological models were considered: Newton's equation, Ostwald de Waele's equation and Herschel–Bulkley's equation. Based on the R^2 value for each model, it was concluded that for DC A, DC B and Gum B the best fit to approximate the experimental data was Newton's rheological model (Eq. (1)), which describes the dependence of shear stress on shear rate as a linear function:

$$\tau = k \cdot \gamma \qquad (1)$$

For Gum A, the Ostwald de Waele's model was the most appropriate (Eq. (2)). This describes the dependence of shear stress on shear rate as a power function:

$$\tau = k \cdot \gamma^n \qquad (2)$$

where τ, shear stress; k, consistency factor; γ, shear rate; n, flow behavior index.

The R^2 values for the DC A, DC B and Gum B components (using Eq. (1)) were 0.9968–0.9997, whereas for Gum A (using Eq. (2)) the

R^2 was 0.9819. The consistency factor, k, expresses the dynamic viscosity (Pa s) for Newtonian fluids (Eq. (1)) or apparent viscosity (Pa s) for non-Newtonian fluids (Eq. (2)). The larger the k value, the more viscous is the fluid. It was concluded that the silicone components DC A, DC B and Gum B behaved as Newtonian fluids in the examined shear rate range. This was confirmed by the viscosity curves (Figs. 6A and B and 7B), which showed that the viscosity was constant and independent from shear rate. The values of the dynamic viscosity agreed well with the values declared by the manufacturer (Table 2). The flow curve was significantly different for Gum A. The flow behavior index (n) was clearly different from 1, i.e. 0.5568 (Fig. 7A), and the viscosity curves had the shape characteristic for rheostable fluids, with shear-thinning without a yield point. Such fluids are called pseudoplastic fluids. This was confirmed by the dependency of the viscosity on the shear rate (Fig. 7A). The higher the shear rate, the lower the apparent viscosity. Table 2 presents the values of the apparent viscosity for two representative shear rates: 20 and 30 s^{-1}. The results of the rheological analyses (Table 2) showed that the four silicone components had different physiochemical properties. The consistency factor, k, may be useful to make a preliminary distinction between different silicone com-
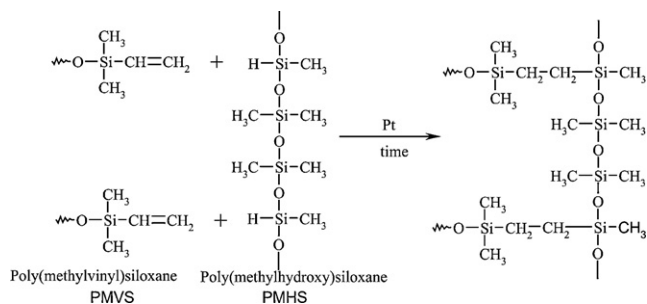

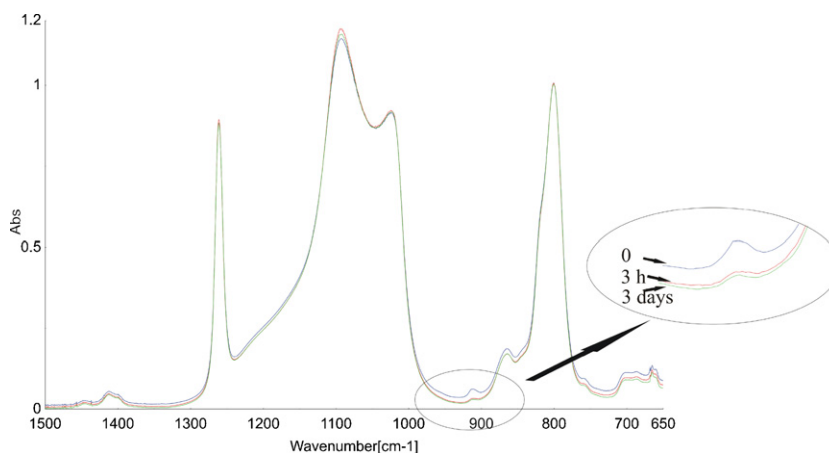**Fig. 8.** The linking reaction of silicone rubbers resulting in addition reaction.

Fig. 9. Overlaid FTIR spectra of Gumosil AD-1 rubber part A and B during linking reaction.

ponents that could be chosen to obtain elastomers with particular properties. Its value is characteristic for silicone polymers used for obtaining adhesive and non-adhesive layers.

3.5. The method of obtaining silicone elastomers

In the cross-linking reaction of silicone rubbers, two parts A and B of a particular component are involved. The cross-linker is a multifunctional polysiloxane with a hydrosilane group Si–H (Gum A and DC B), and the second part is the base siloxane polymer with vinyl groups (CH=CH$_2$) and a catalyst (Gum B oraz DC A). When the two components are mixed, a fast addition reaction occurs (so-called hydrosilylation) whereby one molecule is added to the other, resulting in only one product with no by-products. The addition occurs due to breaking of the multiple carbon–carbon bonds from the vinyl group, and leads to the formation of carbon–silica bonds (Fig. 8).

The polyaddition of Si–H bonds to the vinyl groups occurs, resulting in the formation of many hydrocarbonate bridges connecting the polysiloxane chains, i.e. an endlinking reaction. Silicone elastomers were prepared according to manufacturer directions. Components Gumosil AD-1 were mixed in room temperature in A:B = 10:1 (w/w) ratio, and for components Dow Corning Soft Skin Adhesive DC 7-9800 this ratio was A:B = 1:1.

3.6. Examination of the cross-linking reaction of rubbers by the FTIR method

For observations of the progress of the cross-linking reaction and determination of the end-point of the process the FTIR spectra were recorded followed by interpretation of the wavenum-

bers 2136 cm^{-1} and 909 cm^{-1}, in which vibrations of Si–H group occurred, as well as 1414 cm^{-1}, with vibrations characteristic for the vinyl group CH=CH$_2$ (Table 3). The cross-linking reaction was carried out for three days, and the spectra were registered in the beginning of the cross-linking process, after 3 h, and after 3 days. FTIR spectra were registered as thin films on KBr disc and standardized on band located by wavenumber 1260 cm^{-1}. It was concluded that the spectra did not differ significantly and only the band near 909 cm^{-1} was considered useful for monitoring of the cross-linking reaction. The decrease in band intensity after 3 h, and its disappearance after 3 days, indicated progression of the cross-linking process, with break-up of the Si–H bonds and addition of the dimethylvinyl groups from the polydimethylsiloxane polymer (Fig. 9).

3.7. Examination of the cross-linking reaction of rubbers by rheological measurements

Rheological measurements, i.e. examination of shear stress as a function of shear rate, were used for observation of the cross-linking reaction for Gumosil and Soft Skin Adhesive Dow Corning elastomers (Fig. 10). They were much more useful than the FTIR spectra, where the intensity of the band near 909 cm^{-1} was too low.

For the Gumosil AD-1 elastomer, the measurements were carried out 15, 45 and 75 min after mixing the components together. During the vulcanization a significant change in structure could be observed, and after 75 min the shear rate was more than 1500 Pa (Fig. 10). After 135 min the elastomer was too viscous to establish the time for the end of the cross-linking reaction in an interchangeable manner. For the Dow Corning elastomer, the measurements were carried out 15, 45, 75, 135 and 195 min after mixing the com-
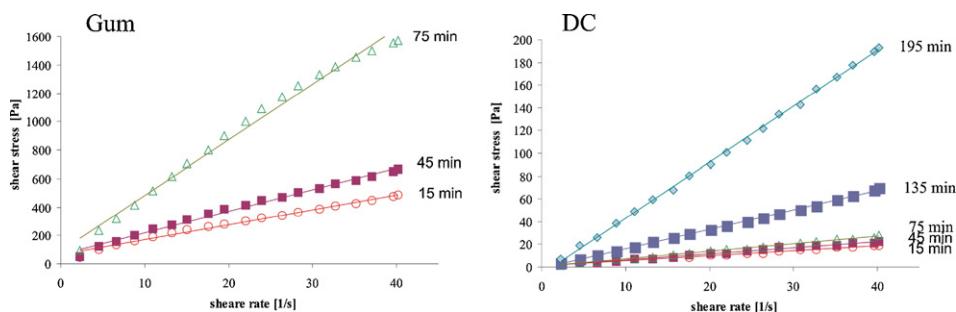

Fig. 10. The flow curves for linking reaction of Gumosil AD-1 and Soft Skin Adhesive Dow Corning rubbers.

ponents together. Although a significant change in the structure had occurred 3 h after mixing the components, the shear rate was still significantly lower than for the Gumosil elastomer (193.3 Pa and 1570 Pa, respectively). These results agreed with visual observations, as the cross-linking reaction of the Gumosil components resulted in a resistant, solid elastomer, whereas the same reaction for the Dow Corning components resulted in a layer possessing adhesive properties. This layer was less hard than the Gumosil, and did not become harden even after a few days. The shape of the respective flow curves of the two silicone polymers showed that the Gumosil AD-1 elastomer was characterized by a higher linkage degree than the Dow Corning Soft Skin Adhesive DC 7-9800. In summary, the rheological measurements were more useful than the FTIR spectra for design of desired elastomer layers, in order to obtain an adhesive silicone film.

4. Conclusions

The technology of an adhesive silicone films used as drug carriers in transdermal therapy requires the choice of suitable silicone rubbers as components of the film. In this study, the film was to be made from two connected layers: an adhesive layer on the skin (using DC 7-9800) and a non-adhesive on the other side (using Gumosil AD-1). The non-adhesive layer is the basic layer, and may be a matrix for the active substances. A permanent connection of these double layers was possible due to cohesion forces. To ensure that the planned film could be obtained, it was necessary to identify the structure and evaluate the physical and chemical properties of the rubbers used. The results showed that the cross-linking reaction could be predicted, which would result in elastomers possessing suitable properties. Each of the methods used ATR-FTIR, ^{1}H NMR, and SEC-ELSD gave partial information which was useful for identification of the components. However, the rheological measurements with determination of the parameters (consistency factor k, flow behavior index n and viscosity) made it possible to evaluate the properties of the fluids and classify them into a particular rheological group. The results from the study showed that it was possible to predict the role of a particular layer when composing the adhesive silicone film. Furthermore, the analytical methods were useful for selection of the appropriate silicone rubber components. The experiments showed practical use of these methods in projecting optimal silicone film, consisted of double layers of elastomers.

In summary, it was demonstrated that the analytical methods presented can serve as appropriate and necessary analytical tools when designing elastomer layers, from which adhesive silicone films, intended for medical use, can be composed.

Acknowledgements

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