Original Scientific Paper https://doi.org/10.24867/GRID-2026-p80

Silicone Elastomers as Additives in the Paper Manufacturing Process

ABSTRACT

Silicone elastomers can act as effective lubricants in the paper manufacturing process. They reduce friction between paper fibers and processing equipment, such as rollers and presses, thereby helping to prevent paper breakage and improving the overall efficiency of the production line. This research focuses on the formulation and characterization of silicone elastomer-based emulsions that can be used to improve paper properties. In the first part of the investigation, Fourier transform infrared (FTIR) spectroscopy was employed to analyze the structural properties of the initial silicone elastomers. Following the successful emulsification process, a physicochemical characterization of the obtained system was performed. The quality and stability of the emulsion were evaluated through three key aspects. Particle size and the stability of the dispersed phase were investigated by dispersion analysis, which revealed a predominantly nanoscale droplet distribution with a smaller fraction of larger droplets. The oil-in-water emulsion type was accurately identified using conductometric measurements of the system's electrical conductivity. Surface properties and the interaction of the emulsion with a solid substrate were determined through contact angle measurements using an indirect method. The results indicated a low contact angle, which may present challenges for future applications. The obtained findings confirm the successful formulation of the emulsion and provide insight into the correlation between the structure of the initial elastomers and the final emulsion performance, enabling their precise application in improving paper quality.

Nevena Vukić [1]
Darko Manjenčić [2]
Marijana Vasić [2]
Milica Ivanović [2]

[1] University of Kragujevac, Faculty of Technical Sciences Čačak, Serbia
[2] Academy Kruševac, Department of Technical and Technological Studies, Kruševac, Serbia

KEY WORDS
Silicone composites, emulsification, crosslink density, conductometry, dispersion analysis

1. Introduction

Silicone-based materials represent an important class of polymeric materials with a distinctive combination of chemical, thermal, mechanical, and surface properties, which has enabled their application in a wide range of industrial fields (Clarson, 2003). Their versatility has led to the development of numerous silicone-based products and formulations tailored to specific applications, including those in the paper industry. These additives can have positive effects on papermaking processes and the final properties of paper products (Gu, 2022). One of the primary applications of silicone elastomers in the paper manufacturing is surface modification. Silicone elastomers can be used to provide paper with specific surface properties, such as improved smoothness and water repellency. By incorporating silicone-based release agents into paper coatings or sizing agents, manufacturers can create a non-stick surface that prevents the adhesion of adhesives and other substances (Kelar Tučeková, 2020). This is particularly important in applications such as labels, where easy release of labels from the substrate is essential.

In contrast, silicone can be incorporated into paper coatings to improve the release properties of the paper surface (Abenghal & Brouillette, 2024). These elastomers help enhance the adhesion of the silicone coating,

resulting in a more efficient production process and a paper product with excellent release properties.

Silicone elastomers also act as effective lubricants in the papermaking process. They reduce friction between paper fibers and processing equipment, such as rollers and presses, which helps prevent paper breakage and improves the overall efficiency of the production line. Also, silicone lubricants can reduce the accumulation of static electricity on the paper surface, which can cause problems such as dust attraction and paper jamming. In addition to lubrication, silicone elastomers can prevent blocking, i.e., the tendency of paper sheets to adhere to one another during storage or handling. By applying a silicone-based anti-blocking agent to the paper surface, manufacturers can ensure that paper sheets remain separated and easy to handle. Silicone can be formulated to provide both lubricating and anti-blocking properties, making it an effective solution for paper manufacturers.

Water resistance is a crucial property for many paper products, particularly those used in packaging applications (Zhang, 2024). Silicone elastomers can be used to improve the water resistance of paper by forming a hydrophobic barrier on the paper surface (Rajendra et al., 2014). This barrier prevents water from penetrating the paper, thereby helping to protect the contents of the package and maintain the integrity of the paper product. Silicone-based water-repellent agents can be applied to paper using various methods, such as coating, spraying, or dipping. Depending on the formulation and coating conditions, silicone-based coatings can also influence the mechanical and durability properties of paper. (Zhang, 2024).

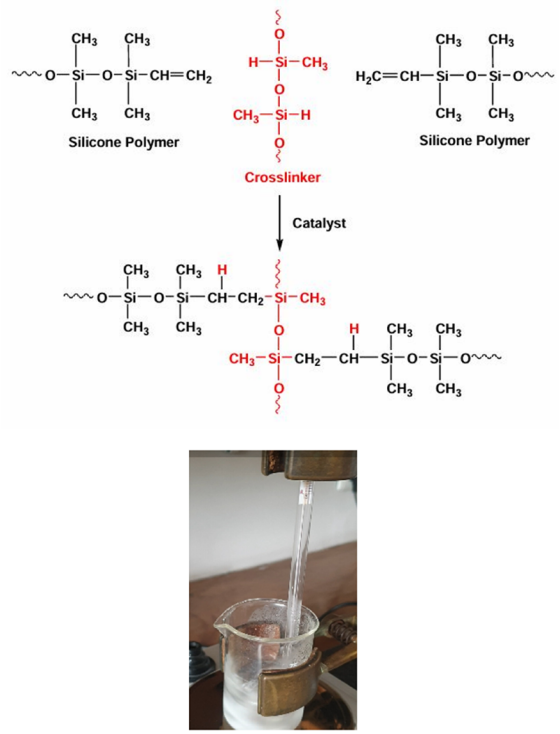
In some paper applications, such as tissues and sanitary products, softness and flexibility are important properties (Pawlak, 2022). Silicone elastomers can be used to enhance these properties by reducing the stiffness of the paper fibers and improving the overall hand feel of the paper. The application of silicone elastomers can therefore produce a paper product that is gentle on the skin and has a pleasant texture.

In this paper, silicone elastomer-based emulsions were formulated and characterized. The investigation comprised the structural characterization of the initial silicone elastomers by Fourier transform infrared (FTIR) spectroscopy. The obtained emulsions were evaluated in terms of dispersed-phase properties, emulsion type, and surface interactions with a solid substrate using dispersion analysis, conductometric measurements, and contact angle measurements, respectively. The results provide a basis for assessing the relationship between the structural properties of the starting silicone elastomers and the properties of the resulting emulsions, which is essential for their further optimization and application.

2. Experimental part

2.1. Materials and Methods

Precursors for the siloxane elastomer were Vinyl-functionalised siloxane with terminal group (SFA 42102, vinyl content 0.15 mmol g^{-1}, Viscosity 1000 mPa s) and Hydrogen siloxane with lateral groups (SFA 11430, hydrogen content 3.3 mmol g^{-1}, Viscosity 1000 mPa s) both provided from CHT GMBH BEZEMA, Germany. As a catalyst in PDMS was used platinum complex containing vinyl groups (KAT-A, GMBH BEZEMA, Germany). Surface modified hydrophilic SiO_2 nanofillers were provided from Evonik Resource Efficiency GmbH, Germany. In the synthesis of silicone composites, active fillers with a high specific surface were used hydrophilic (AEROSIL 300) of 300 m^2 g^{-1}, particle size d50 = 10 nm. Lutensol nonionic surfactant based on C10-rich iso-fatty alcohol ethoxylates. It has a cloud point of approximately 60 °C and density of around 0.98 g cm^{-3} provided from BASF Germany and linear alkylbenzene sulfonic acid (LABSA/DDBSA). The method of preparing the emulsion system is shown in Figure 1.



» **Figure 1:** *Silicone emulsification and chemical structure of siloxanes*

2.2. Emulsification and modification of liquid silicone rubbers

Siloxane elastomers were prepared by a conventional method, with the hydrogen- and vinyl-siloxane ratios 50/50 (wt:wt). Formulation of prepared materials

based on different contents of vinyl siloxane and the composites with SiO_2 nanofillers is shown in Table 1. For syntheses was used 0.1 wt% platinum catalyst (KAT-A, corresponding to approximately 1000 ppm Pt relative to the total siloxane mass). All components were added to a laboratory vacuum mixer and homogenized for 1 h. The high shear made the good mixing of all components in high viscosity material, with good dispersion and distribution of fillers, which was of great importance for samples with a high percentage of nanofillers. The preparation of the emulsion was started by the prior dissolution and incorporation of the emulsifier into the silicone phase to ensure optimal system stability. During the process, the aqueous phase was gradually added to the prepared silicone phase under high-speed propeller mixing. The mixing speed was continuously and proportionally increased from 200 to 4000 rpm as the aqueous phase was added. The alternating increase in rotational speed ensured efficient homogenization and the formation of a fine and stable emulsion. During emulsion preparation, hydrophilic silicon dioxide acted as a highly effective stabilizer through the Pickering stabilization mechanism. Under the influence of strong shear forces generated at mixing speeds of up to 3000 rpm, the particles became preferentially positioned at the silicone-water interface. The hydrophilic silanol groups (Si-OH) present on the particle surfaces established strong interactions with water molecules, thereby forming a protective, rigid layer around the dispersed droplets. Simultaneously, the silicon dioxide particles formed a three-dimensional structure within the system, which further immobilized the droplets and contributed to the long-term stability and homogeneity of the emulsion.

Table 1

Formulations of prepared materials based on different contents of vinyl siloxane and the composites hydrophilic nanofillers*
- all siloxane ratios contained the same amount of filler

Sample	Siloxane ratio		Content of SiO_2, wt%	Amount of emulsifier
	By weight	By mol	Hydrophilic	3-5% of the silicone phase, depending on the mixing conditions –
Hydrogen-vinyl 50/50	1-1	10-1	1	

2.3. Characterization of synthesized materials

Chemical structure of obtained siloxane materials was analyzed by Fourier-transform infrared FTIR spectrophotometer Thermo-Nicolet Nexus 670 (ThermoFischer Scientific, USA). Attenuated total reflection, ATR, with one reflection on the crystals of germanium was used for the recording. 100 scans were recorded per sample at a resolution of 4 cm^{-1}. As a detector was used deuterated triglycerin sulphate, DTGS. To process the spectra, the Thermo-Nicolet Omnic 6.0 software was used.

The specific electrical conductivity of the aqueous solutions was measured conductometrically using a laboratory conductivity meter, InoLab Level 1 (WTW, Germany), equipped with a standard measuring cell with an integrated temperature sensor. The measurement principle is based on recording the electrical current passing through the solution according to Ohm's law, based on which the instrument primarily determines the electrical conductance, expressed in siemens (S). Taking into account the cell constant of the measuring cell, the instrument software converts the measured conductance into specific electrical conductivity, expressed in µS cm-1. The instrument was calibrated using a standard 0.01 mol L^{-1} KCl solution. All measurements were performed with automatic temperature compensation (ATC), with the measured values normalized to the reference temperature of 25 °C.

Dispersion analysis of the silicone emulsion was performed using the dynamic light scattering (DLS) method on a Zetasizer Nano ZS instrument (Malvern Instruments, UK). The method is based on monitoring the Brownian motion of the dispersed-phase droplets as a function of time by analyzing fluctuations in the intensity of laser light scattered at a defined detection angle. A helium-neon laser with a wavelength of λ = 633 nm was used as the light source. All measurements were performed at a constant temperature of 25 °C, following appropriate dilution of the sample with distilled water to avoid multiple-scattering effects and minimize interparticle interactions. The hydrodynamic diameter of the droplets and the estimated polydispersity index (PDI) were determined as the main parameters, with PDI serving as an indicator of the homogeneity of the size distribution within the system.

The contact angle of the silicone emulsion was determined using an indirect method with a laboratory goniometer. The method is based on analysis of the profile of an emulsion droplet deposited on a standardized solid substrate, with the geometrical parameters of the droplet used for software-based calculation of the contact angle (θ) at the three-phase contact line (solid-liquid-vapor). All measurements were performed under controlled conditions at room temperature. The obtained contact angle values were used as indicators of the surface properties and the hydrophilic-lipophilic balance (HLB) of the investigated emulsion system.

3. Results and discussion

Figure 2 and Table 2 show the results of the FTIR analysis of the synthesized materials molecular structure. Sharp bands at 2961 cm^{-1} and 2905 cm^{-1} originated from the asymmetric and symmetric C-H stretching vibrations of Si-CH3. Also, clearly observed are characteristic peaks of siloxane matrix that originated from the functional groups $Si-CH_3$, Si-O-Si, and Si-C. Hydrophilic silica was attached to the silicone matrix because reactive OH groups react secondary interactions (of the hydrogen bond type) with the silicone chain, and the absence of hydroxyl vibrations (3200-4000 cm^{-1}) was confirmed on FTIR analysis. The ratios of silicone in which vinyl siloxane is present in a smaller proportion show the quantitative reaction of the double bond C=C in vinyl siloxanes, which confirms the absence of peaks at wavelengths greater than 3000 cm^{-1}. The FTIR spectrum of the investigated sample (Figure 2c) shows characteristic bands confirming the structure of silicon dioxide. The intense peak at 1080 cm^{-1} is attributed to the asymmetric stretching vibration of Si-O-Si bonds.

Table 2

Characteristic bands in the FTIR spectrum of obtained materials

Wavelength, cm^{-1}	Functional group
3000 – 2800	CH_3 and CH_2 group
1450	Asymmetric stretching CH_3
~1290	C-Si-CH_3
~1250	$(CH_3)_3$, Si
1130 – 1000	Si-O-Si
1155	Si-O
790	$SiCH_3$ twisting

The specific electrical conductivity of the aqueous solutions was measured conductometrically. The final values were recorded after stabilization of the measurement signal using the integrated AutoRead function. Measurements were performed on five emulsion samples.

Note: The samples were diluted with water having an electrical conductivity of 2 µS cm^{-1} to obtain a 5% (v/v) emulsion solution. Electrical conductivity was measured at room temperature (25 °C ± 1).

Table 3

Results of electrical conductivity measurements of the 5% emulsion sample

Measurement No.	1	2	3	Average value
Electrical conductivity (µS cm^{-1})	98.2	98.3	98.2	98.26

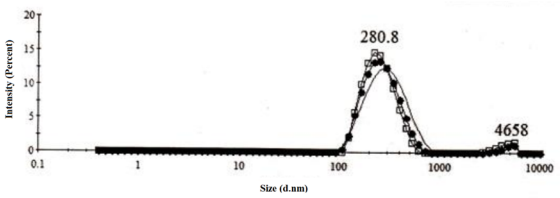
The measured specific electrical conductivity of the diluted sample at room temperature was 98.2 µS cm^{-1}. Since the oil phase acts as an electrical insulator, the ability of the system to conduct electric current depends directly on the nature of the external (continuous) phase. The measured conductivity value, being of a significant magnitude, clearly indicates that the continuous phase consists of water containing mobile ions, thereby identifying the investigated system as an oil-in-water (O/W) emulsion.

Dispersion analysis of the silicone emulsion was performed using the dynamic light scattering (DLS) method on a Zetasizer instrument in three consecutive replicates at a temperature of 25 ± 1 °C, following dilution of the sample with distilled water at a 1:100 (v/v) ratio. Table 4 presents the mean hydrodynamic diameter values of the droplets in the silicone emulsion sample, while Figure 3 illustrates the droplet size distribution within the system.

Table 4

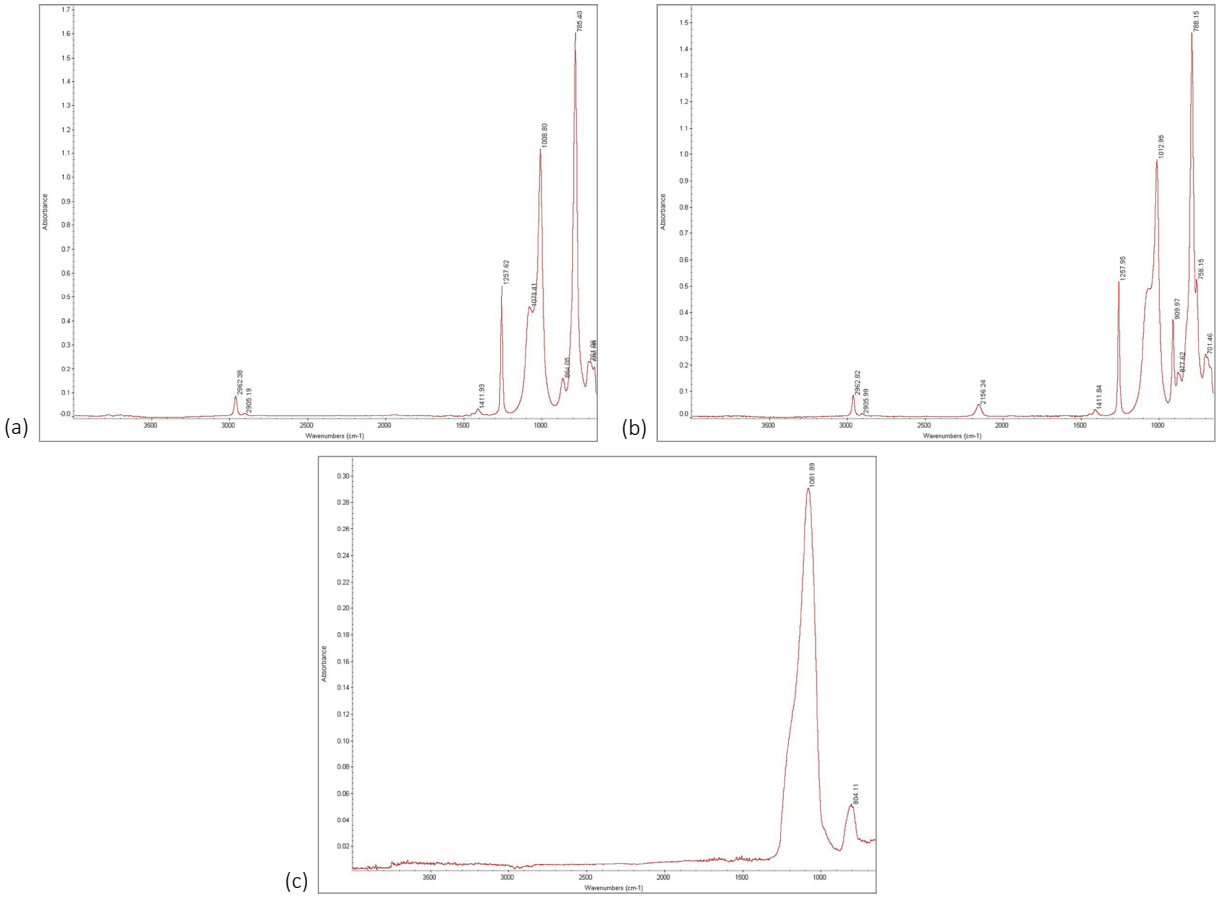
Mean droplet diameter of the silicone emulsion sample

Measurement No.	Peak 1	%	Peak 2	%
1	310.8	100	-	0
2	257.3	94.6	4528	5.4
3	274.3	96.8	4787	3.2
dsr ±σ (nm)	280.8 ± 27.34		4658 ± 183.1	



» **Figure 3:** *Results of the determination of the mean droplet diameter of the emulsion sample*

The results of the dispersion analysis clearly indicate that the investigated system is an emulsion with droplet sizes predominantly in the nanometer range. Analysis of the results presented in Table 3 and Figure 3 indicates a bimodal droplet size distribution, with two distinct maxima being observed. The first maximum occurs at 280.8 ± 27.34 nm and represents the mean diameter of more than 95% of the droplets present in the emulsion sample. The second maximum occurs at 4658.16 ± 116.1 nm and represents the mean diameter of a smaller droplet fraction, accounting for approximately 5% of the total number of droplets present in the emulsion. The presence of two distinct droplet fractions and the resulting bimodal distribution indicates a relatively high polydispersity index (PDI), estimated to be approximately 0.4-0.7. Such a high PDI value indicates pronounced heterogeneity and a broad droplet size distribution, confirming that the system is not monodisperse but consists of two distinct droplet populations.



» **Figure 2:** *FTIR spectra of: a) silicon elastomers vinil, b) silicon elastomers hidrogen and c) hydroplic fillers*

The measured contact angle of the silicone emulsion on the solid paper substrate was θ = 38.08°. A contact angle substantially below 90° indicates high wettability and a pronounced affinity of the liquid system for the investigated solid substrate. The low contact angle may be attributed to the effective reduction of interfacial tension at the liquid-solid interface, which is properties of emulsion systems containing surface-active agents capable of modifying the interactions between the liquid phase and hydrophobic substrates.

4. Conclusions

Considering the potential of silicone-based materials to modify the surface and properties of paper, the development of stable silicone emulsions represents an important theme. In this research a silicone-based oil-in-water (O/W) emulsion was successfully formulated and characterized using FTIR spectroscopy, conductometric measurements, dynamic light scattering (DLS), and contact angle analysis. FTIR analysis confirmed the characteristic structures of the silicone matrix and silicon dioxide, while conductivity measurements confirmed the O/W character of the obtained emulsion. DLS analysis showed a predominantly nanoscale droplet population, with more than 95% of the droplets having a mean hydrodynamic diameter of approximately 280.8 nm. However, the presence of a smaller fraction of larger droplets resulted in a bimodal size distribution and relatively high polydispersity. The measured contact angle of 38.08° indicated good wettability of the emulsion on the investigated paper substrate.

The advantage of the formulated silicone system manifests through the use of a lower catalyst content in combination with a higher-molar-mass vinyl siloxane, providing a basis for the preparation of crosslinked elastomers with improved mechanical properties.
In addition, the obtained silicone elastomers exhibit good homogeneity within the emulsion system, which directly contributes to the stability and quality of the material and, consequently, to the performance of the final products, resulting in improved paper properties.

5. Acknowledgments

This study was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, and these results are parts of the Grant No. 451-03-33/2026-03/ 200132.

6. References

Abenghal, L. and Brouillette, F. (2024) 'Phosphate Esters: New Coating Materials for a Sustainable Release Paper', ChemistrySelect, 9(19), e202400134. DOI: 10.1002/slct.202400134

Clarson, S.J. (2003) 'Silicones and Silicone-Modified Materials: A Concise Overview'. In: Clarson, S.J., Fitzgerald, J.J., Owen, M.J., Smith, S.D. and Van Dyke, M.E. (eds.) *Synthesis and Properties of Silicones and Silicone-Modified Materials*. Washington, DC: American Chemical Society, pp. 1–10.

Gu, L. (2022) 'Silicone Applications in Pulp and Paper'. In: *2022 PEERS/IBBC Conference*.

Kelar Tučeková, Z., Galmiz, O., Kelar, J., Kováčik, D., Stupavská, M., Šrámková, P., Zemánek, M., Vallade, J. and Černák, M. (2020) 'Adhesive Properties of Silicone-Coated Release Liner Paper Enhanced by Atmospheric Pressure Plasma Pre- and Post-Treatment', *Coatings*, 10(11), 1102. DOI: 10.3390/coatings10111102

Pawlak, J.J., Frazier, R., Vera, R.E., Wang, Y. and Gonzalez, R. (2022) 'Review: The softness of hygiene tissue', *BioResources*, 17(2), pp. 3509–3550. DOI: 10.15376/biores.17.2.Pawlak

Rajendra, V., Sicard, C., Brennan, J.D. and Brook, M.A. (2014) 'Printing silicone-based hydrophobic barriers on paper for microfluidic assays using low-cost ink jet printers', *Analyst*, 139(24), pp. 6361–6365. DOI: 10.1039/c4an01626b

Zhang, R., Tan, J., Ma, T., Xu, M., Chen, W., Zhu, F. and Cao, Y. (2024) 'Developing Waste Fatty Acid-Grafted-Silicone Oil as Repulpable, Enhanced Gas and Water Resistant Coating for the Paper Industry', *ACS Applied Polymer Materials*, 6(19), pp. 11964–11973. DOI: 10.1021/acsapm.4c02086



© 2026 Authors. Published by the University of Novi Sad, Faculty of Technical Sciences, Department of Graphic Engineering and Design. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license 4.0 Serbia (http://creativecommons.org/licenses/by/4.0/rs/).