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Optimizing the properties of molded silicone foams

Master´s Thesis (30 EAP)

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Optimizing the properties of molded silicone foams

This master´s thesis investigates the impact of various additives on the structure and properties of silicone foams as well as their effect on the thermochemistry of the formation reaction. The silicone foam’s tensile strength was evaluated as a proxy for mechanical properties. Foam structure and density were determined. The goal of the study was to improve and optimize the foam production process by determining which parameters affect foam properties. The analysis considered the balance between producing foams with a density below 120 kg/m^3 and a specific strength over 0.4 N·m/kg with a uniform structure. The foam must have also been suitable for cushioning materials in seating and had to be producible by injection-molding technology.

Keywords: Polymer foam, silicone foam, PDMS, silicone, polysiloxane, diols, mechanical properties, tensile strength

CERCS codes: T150, Material Technology; T152, Composite materials.

Vormitud silikoonvahu omaduste optimeerimine

Käesolevas magistritöös uuritakse erinevate lisandite mõju silikoonvahu omadustele ja nende mõju tekkiva silikoonvahu temperatuurile reaktsiooniprotsessi käigus. Hinnati silikoonvahu tõmbetugevust asendusnäitajana teistele mehaanilistele omadustele ning samuti määrati kindlaks vahu struktuur ja tihedus. Eesmärk oli vahu tootmisprotsessi täiustamine ja optimeerimine, määrates kindlaks, millised parameetrid mõjutavad vahu omadusi. Analüüsis hinnati ühtlase struktuuriga silikoonvahtude tihedusi, mis pidid jääma alla 120 kg/m^3 ja eritugevusi üle 0,4 N·m/kg. Vaht pidi sobima ka istmete pehmendamiseks ja olema valmistatav madal-survevalu tehnoloogiaga.

Võtmesõnad: polümeervaht, silikoonvaht, PDMS, silikoon, polüsiloksaan, dioolid, mehaanilised omadused, tõmbetugevus

CERCS koodid: T150, Materjalitehnoloogia; T152, Komposiitmaterjalid.

Table of contents

Abbreviations used in the thesis

SIF- Polysiloxane foam

PDMS- Polydimethylsiloxane

PUR- Polyurethane

PUF- Polyurethane foam

FS- Fumed silica

1 Introduction

In the transportation industry, seat paddings are a common application for polyurethane foams. These foams have been widely used because they are affordable, simple to make, and have easily tunable characteristics. The drawbacks of PUR foams include their easy flammability, quick burning, production of hazardous gases, short lifespan, and combustion-related release of poisonous and carcinogenic compounds. Therefore, to increase the safety of padding foams, tight regulations and production standards have been implemented [1].

Polysiloxane foams are emerging as an alternative to PUR foams due to their relatively high fire and heat resistance, and the ability to decompose without giving off harmful vapors. The drawback of polysiloxane foams has been their somewhat higher cost and underdeveloped production technology, which would allow them to be a serious competitor to PUF. SIFs are currently employed, for instance, as seals and fire barriers. They are also used in medicine, for wound dressings, prosthetics and implants. SIFs are often extruded as sheet material for bigger goods, which are then cut into the necessary shape. This manufacturing process generates a lot of waste and is generally more difficult than inflating it into a mold [2].

This master's thesis is closely related to a project that aims to create an injection-molding technology for reproducible polysiloxane foams of low density and mechanical qualities that are usable in upholstery. The objective is to link the obtained foam properties to the fabrication conditions. This master's thesis has two goals:

1) To achieve SIFs that are reproducible using injection-molding technology and usable in cushioning's. The foam also must have a density below 120 kg/m^3 and specific strength over 0.4 N·m/kg. The research began with SIF densities of 240 kg/m^3 and specific strengths of 0.01 N·m/kg and we picked out a favorable compromise between providing sufficient cushioning properties in seating and maintaining a reasonable weight-to-strength ratio. The selection of these figures were picked after careful consideration.
2) Investigate which types of blowing agents, crosslinkers, and fillers yield optimal results for SIF density and specific strength.

2 Author’s contribution

The experimental part of the master´s thesis involved setting up a lab-prototype for the industrial manufacture of SIFs and establish methods for the reproducible fabrication and characterization of the SIFs. The author adjusted the physical parameters and the chemical composition to investigate the characteristics of SIFs and the factors affecting them. The author handled the prototype-machine and created the polymer premixes from base materials. Additionally, the author monitored temperatures, tested tensile strength, measured densities, examined SIFs with a scanning electron microscope, and evaluated the mechanical properties of the produced SIFs. Through these experiments, the author was able to establish methods for the reproducible fabrication of SIFs and gain insight into the factors that influence their properties.

3 Literature review

Cellular plastics, also known as polymeric foams, have been widely used in industrial and consumer applications since their invention in the 1930s. Particularly appealing features are their inexpensive cost of materials, high strength-to-weight ratios, variety of characteristics, and simplicity of processing. The typical cell diameters of these materials might range from a few microns to hundreds of microns. Bulk foam densities are sometimes less than one-hundredth of that of the underlying polymer, which is relatively low [3].

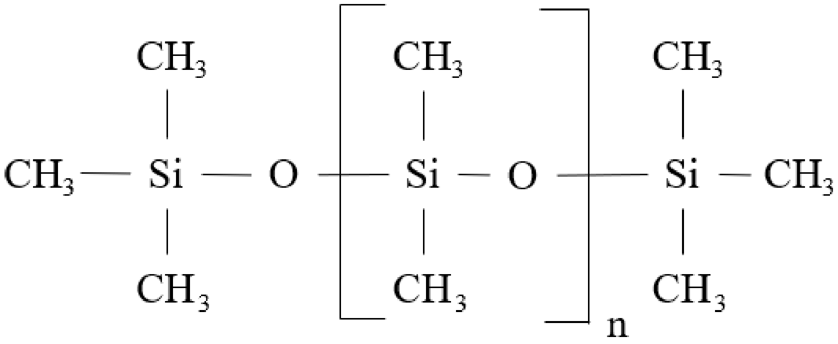
Foam is created when a significant amount of gas is pumped into a solid or liquid object, forming gas-filled pockets in a solid or liquid matrix. Gas can also be mechanically combined with liquids to create foam. When gas dissolves in a liquid under pressure, the liquid becomes supersaturated with gas. Upon reducing the pressure, the gas is expelled as bubbles. Common examples of foams in daily life include shaving foam and foam rubber. Different applications require specific foam qualities, such as furniture upholstery that can tolerate repetitive compression with properties that persist over time. For products like shaving foam, persistence is essential to ensure the user has enough time to effectively remove all hair. Additionally, solid foams are produced by solidifying the liquid phase of a foamed mixture, and their structure is comparable to that of liquid foams [4].

SIFs are versatile materials and have a variety of applications in the medical field, including wound dressings, prosthetics, and implants. This is because of the biocompatibility [5], [6]. Another useful property that SIFs have, is resistance against fire hazards. In most cases, SIF is self-extinguishing, which means it can help prevent the spread of fire. This makes it ideal for use in construction and insulation where fire resistance is much needed. The self-extinguishing property is also very useful in the field of seating materials, especially in public transport, because it can make traveling a much safer option [7].

Silicone foams

Foam materials constructed of cross-linked polysiloxanes are known as polysiloxane foams or SIFs. These foam components usually include fillers and additives in addition to the structural backbone of cross-linked PDMS [8], [9].

Polysiloxane formulations consist of alternate covalent bonds between silicon and oxygen atoms in the main chain. The length of the main chain and the functional groups affect how viscous a particular polysiloxane is. The functional groups determine the reactivity and characteristics of the polymer [10], [11].



$$CH_3-Si(CH_3)_2-O-\left[Si(CH_3)_2-O\right]_n-Si(CH_3)_2-CH_3$$

Figure 1. The most common base material in the silicone industry. Polydimethylsiloxane is also known as PDMS.

Crosslinked polysiloxane chains support the fundamental structure of SIF. The gas produced during the chemical reaction and different physical processes are used to create the porous structure. During the reaction, gas is produced which creates bubbles in the mixture, The bubbles grow until they converge or the reaction ends. The prepolymers and crosslinkers involved in the reaction are also supplemented with various additives and strengthening fillers. SIF´s often have fumed silica added as a reinforcing filler to increase stiffness, strength, and durability. However, other mineral or polymeric fillers may also be employed. Cross-linkers in the substance bind polysiloxane molecules to form an elastic three-dimensional network [12], [13].

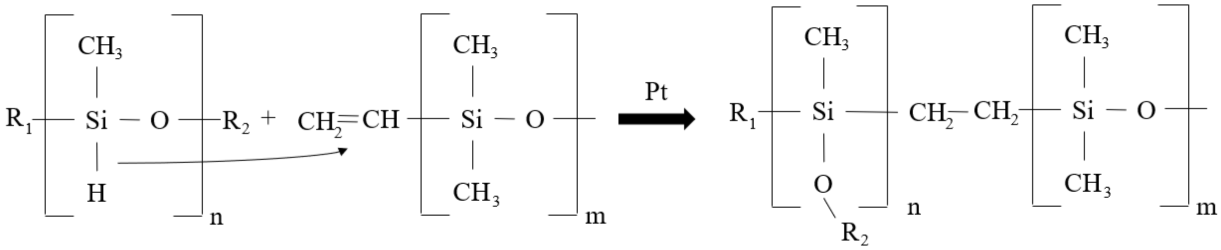


Figure 2. Hydrosilylation process between vinyl and hydrosilane group. This creates the backbone of the silicone rubber foam.

Blowing agents for silicone foams

Blowing agents are substances that give polymeric foam materials their cellular structure. Most blowing agents work during the crosslinking reactions in polymers. Gases that expand when pressure is released, liquids that develop cells when they turn into gases, and chemical substances that break down or react under the influence of heat or a catalyst to generate a gas are examples of blowing agents[14].

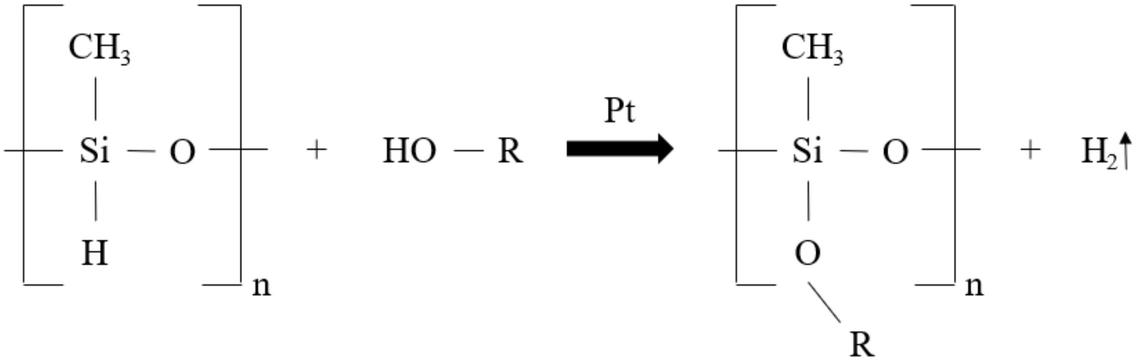


Figure 3. Formation of crosslinks and hydrogen gas between hydrosilane group and hydroxyl group.

Physical and chemical foaming are the two foaming processes in the polymeric foam business. The latter depends on chemical reaction, while the former incorporates physical fluctuation in polymer states. To benefit from gas vaporization while reducing pressure, the two approaches can also be explained as follows: blowing an agent into the polymer by mixing within a chamber; or blending reactants to reactive conditions for gas evolution within a dense medium. The same three steps: gas application, gas expansion, and foam stabilization, are included in both techniques. Over the past fifty years, various intriguing ways have been created around each concept [3].

When preparing to create a SIF, physical blowing agents can be introduced into the prepolymer mixture by applying pressurized gas like air. During the mixing process, the crosslinking reaction occurs simultaneously with the formation of gas bubbles. This allows for more precise and safer production by eliminating the need for high pressure. If the blowing agent has poor solubility, a higher pressure will force the blowing agent into the solution. As a result, the cellular structure may become inhomogeneous and more unpredictable, blowing efficiency may decrease, the surface may develop imperfections, etc. When preparing to create a SIF, various physical blowing agents can be introduced into the prepolymer mixture through pressurization.

The choice of blowing agent can significantly affect the resulting foam's properties, including density, cell size, and mechanical strength. Henry's Law states that the amount of gas dissolved is directly proportionate to the gas pressure, which is the rule by which physical blowing agents are soluble in most regularly used liquid polymers. Physical blowing agents can be air, CO_2, N_2, etc. [14], [15].

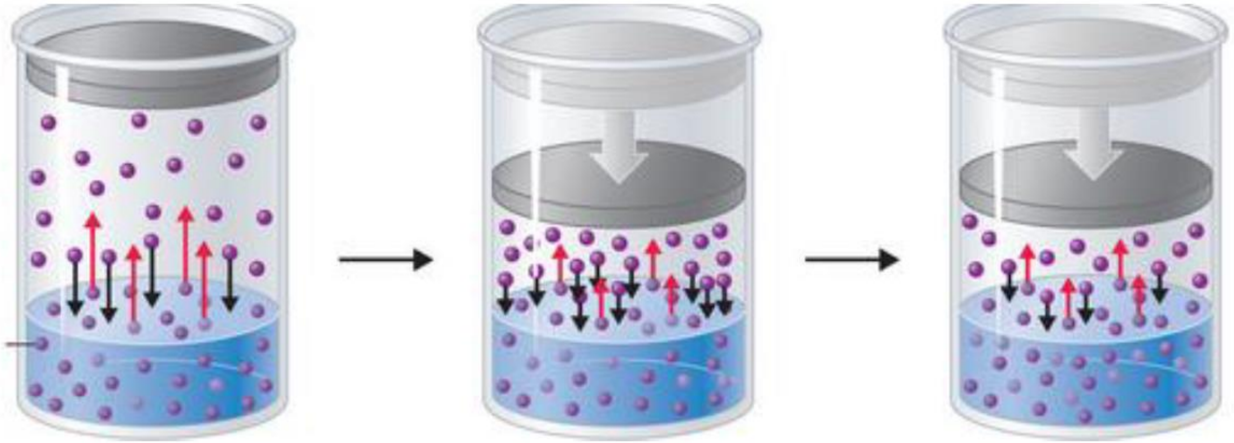


Figure 4. Dissolution of gas into a liquid under increased pressure [16].

Chemical blowing agents release gases due to thermal decomposition or chemical reactions when used to produce the foam. The most common chemical blowing agent for SIFs is polymethylhydrosiloxane which will react with hydroxy-terminated polysiloxane, water, etc. These reactions give off hydrogen gas and simultaneously create the basic structure of SIFs [15].

Crosslinkers in silicone foams

Crosslinkers are molecules or compounds added to SIF components to help the polymer chains in the foam bond together and form a network of interconnected molecules. Crosslinking is not limited only to SIF but is also utilized in thermosets and elastomers so that they can have enhanced mechanical properties and dimensional stability. Crosslinking is crucial because it endows SIF with its distinctive qualities, such as strength, durability, and resistance to heat and chemicals. Several types of crosslinkers can be used in SIFs, including water and diols.

Water is used as a crosslinker frequently in the manufacturing of SIFs. The resulting foam usually has effective thermal and acoustic insulation quality. When water reacts with hydrosilane(-Si-H) groups on silicone polymer chains, siloxane (-Si-O-Si-) bonds are created. Diols react similarly, but the crosslinking fragment is the hydrocarbon piece between the hydroxyl groups

[17]. The crosslinking reaction is typically catalyzed by a platinum compound, such as a Karstedt´s catalyst, and the reaction can occur at room temperature [18], [19]. The resulting foams can have higher mechanical strength or other needed characteristics [20].

The choice of crosslinker will depend on several factors, including the desired properties of the foam, the processing conditions, and the cost of the crosslinker. It is important to choose a crosslinker that is compatible with the other components of the foam, and that will produce the desired crosslinking density and structure.

Mechanical properties of silicone foams

Composites with reinforcing fillers generally exhibit greater mechanical strength than the polymer matrix alone. This reinforcement effect is primarily due to the unique interactions between the reinforcing additives and the polymer matrix at the interphase region. This interfacial region differs from the bulk polymer in terms of polymer structure and mobility [21], [22]. Polysiloxanes, with their excellent dielectric properties, high thermal stability, and extensive industrial use, have found numerous applications in electronic devices, coatings and medicine [23]. However, when used alone, polysiloxanes tend to have low mechanical strength and the addition of reinforcing fillers is needed [24].

Increasing the filler's surface area usually results in higher reinforcement since it increases the contact area and, as a result, the interaction between the filler and the polymer. Increasing the contact area enhances the effectiveness of stress transmission from the matrix to the filler, and improved interaction improves the wetting and adherence of the polymer to the filler. As a result, nanocomposites and fillers with small particle sizes and high surface areas are preferred in particulate-reinforced polymers. Due to the significant increase in viscosity and the low dispersibility of small particles, the incorporation of nanoparticles into a polymer matrix has certain constraints. Blending PDMS with isometric fumed silica particles significantly improves the material's mechanical characteristics [25].

A polymer foam's structural response to mechanical stimuli is greatly influenced by its density and foam porosity, including the pores size, shape, type (open or closed), and solid polymer characteristics [26]. The majority of applications necessitate the use of particle fillers to reinforce PDMS for these and other reasons. Fumed silica and carbon black are the most frequently used fillers in polysiloxanes. But acicular fillers, like fibers, have also been used. Composites made of fibrous fillers typically have poorer mechanical characteristics in the opposite direction from the fiber orientation [27], [28].

When talking about upholstery materials, there are other mechanical properties that we should consider, like stiffness, tear resistance, fatigue and wear resistance [29]. Achieving the right balance of these properties can be challenging. For example, in a seating application, the stiffness of the SIF should be balanced to provide sufficient support and comfort for the user. Usually higher stiffness means using more fillers or getting more cross-linking and that may result in higher densities and insufficient wear and tear resistance [30], [31].

Silicone foam rise and molding

Controlling the process of bubble formation and growth is important for achieving desirable properties in SIFs during molding. By gaining a better understanding of the foam formation process, we can optimize the resulting mechanical and physical properties of the foam. The primary justification for low density foam concerns the advantageous economics of producing novel products with less weight. Bubble nucleation and bubble development during foam expansion are crucial phenomena that must be regulated to control the foaming process properly. A straightforward chemical reaction creates bubbles within a liquid, which are then used to create thermosetting foams like SIF. Various systems have different foam nucleation processes. Since it is difficult to initially observe cell development in polymers and liquids, foaming mechanisms are highly complicated. Potential nuclei have extremely small sizes, on the order of nanometers or angstroms [32].

Soon after the components are mixed in a closed system such as a mix head, typically found in an injection molding system, cell development starts as gas diffuses from the liquid and fills the bubble nuclei. Since the mix head pressure is substantially higher than the ambient external pressure, the bubbles can easily expand. Bubbles comprise a small portion of the mixture's volume in the early stages. They continue to be spherical and are far apart. The cells must deform as they collide and pack in three dimensions as they develop. At some point, gas will eventually fill up to 99% of the space. Because the produced gases are trapped inside closed cells, foam rises. The internal pressure of the cells is equal to the external pressure plus any additional pressure required to keep the cells alive and able to develop in the face of forces like gravity, friction, surface tension, viscosity, and elasticity. As the liquid exits the pressurized mix head, the pressure inside the cells decreases dramatically. This pressure will slightly exceed atmospheric pressure during the reaction's free-rise phase. When the foam is molded, the pressure increases once more when it is filled, and the foam loses its ability to expand. The pressure inside the cells of a free-rise slab stock foam stays just above atmospheric until the cell membranes rupture and the gas vents to the atmosphere. If the stress of the expansion is sufficiently considerable, a significant tear inside the block, known as a split, may form [33], [34].

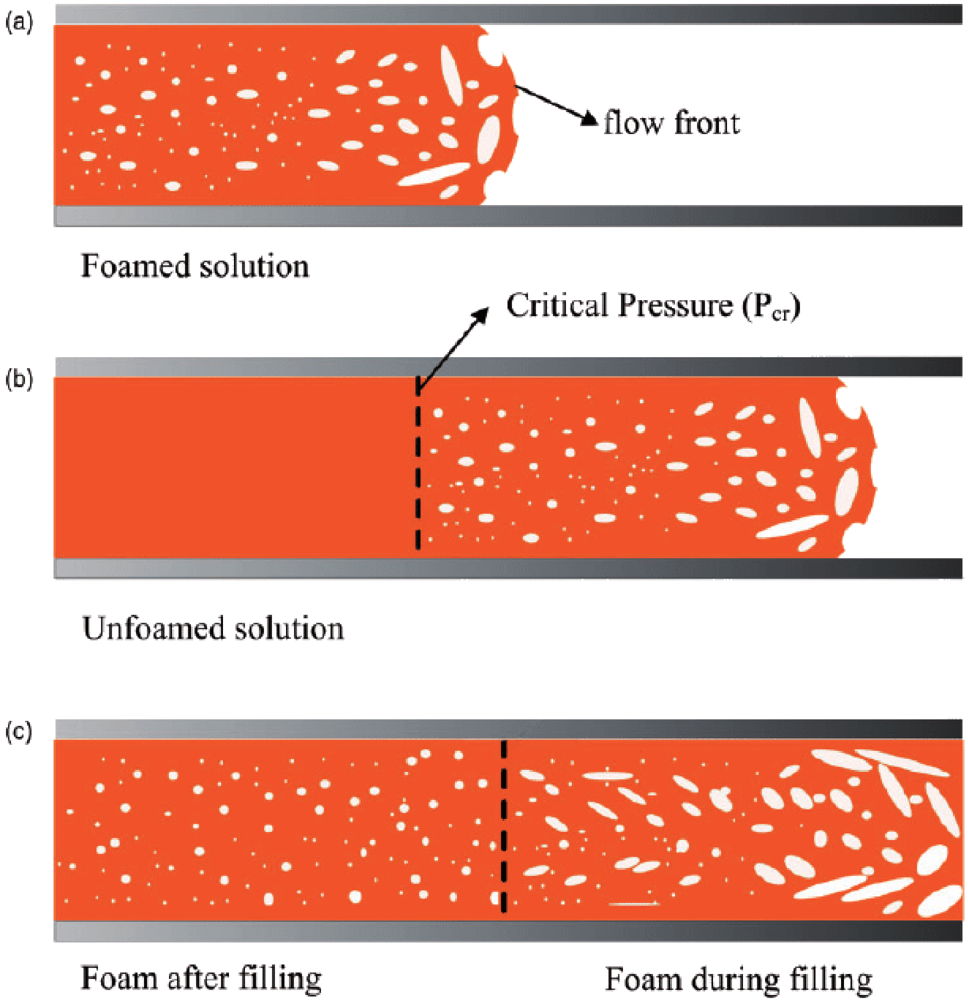


Figure 5. Cell forming process in injection molding: (a) beginning of the filling; (b) middle of the filling stage; (c) end of the filling stage [35].

The mold's shape will impact the growth of the foam. Molds that are tall and slender increase surface friction at the sidewalls, which slows the expansion. Because of the increased backpressure produced when closing the mold, closed molds may require 20–50% more foam than the anticipated free-rise density, requiring overpacking to achieve the desired foam density. In these molding procedures, the venting of the mold is essential. Vents are preferable at the mold's sharp corners and highest point. If fewer vents exist, more backpressures can build up, and the foam will emerge without trapped air or irregular cell structures [33].

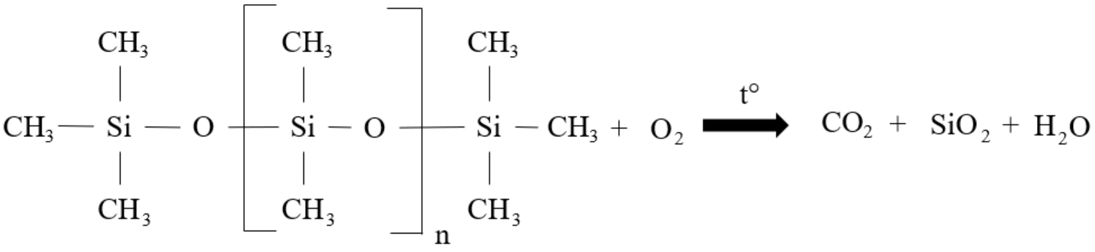
Combustion of silicone foams

Silicone is a material that is known for its ability to meet the most stringent standards for smoke toxicity tests across a range of industries, making it a popular choice as a flame retardant.

When fires start, the resulting vapors and smoke frequently cause the greatest damage rather than the burns themselves. More people have died from the smoke and toxic vapors that follows devastating flames than from the fire itself in many cases. The risks of smoke and toxic vapors are well known, and several businesses have established tight rules to reduce the number of poisonous vapors produced in large quantities when there is a fire.

Utilizing materials with increased fire resistance may help lessen the fatal and financially damaging effects of flames on property and people. Compared to traditional organic polymers, silicones emit less smoke, hazardous gases, and heat than those materials. Numerous methods have been postulated, depending on the end groups connected to the siloxane backbone, to explain the thermal breakdown of silicones. Silicones break down through a succession of thermal depolymerization and oxidation reactions when exposed to high temperatures and oxygen, leaving behind a silica residue, and releasing relatively non-volatile chemicals. The layer of silica that develops and accumulates first on the silicone polymer's surface gives silicones their fire-retardant properties [36].

Silica is a solid substance that settles on the surface of the substance. Also, silicone compounds take quite high temperatures (>400°C) to ignite. At this temperature, carbon oxides are typically clear and do not affect visibility. Since silicones don't include any hazardous halogens or sulfur, the byproducts of their decomposition are mainly non-toxic. Using flame retardant silicone can improve fire resistance, including smoke mitigation [37], [38]. Figure 6 and Figure 7 demonstrates a clear difference in the burning behavior of PUR and PDMS, with PUR producing more toxic compounds than PDMS.



$$CH_3-\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{Si}}-O-\left[\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{Si}}-O\right]_n-\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{Si}}-CH_3+O_2\xrightarrow{t^\circ}CO_2+SiO_2+H_2O$$

Figure 6. Combustion of PDMS and the resulting products.

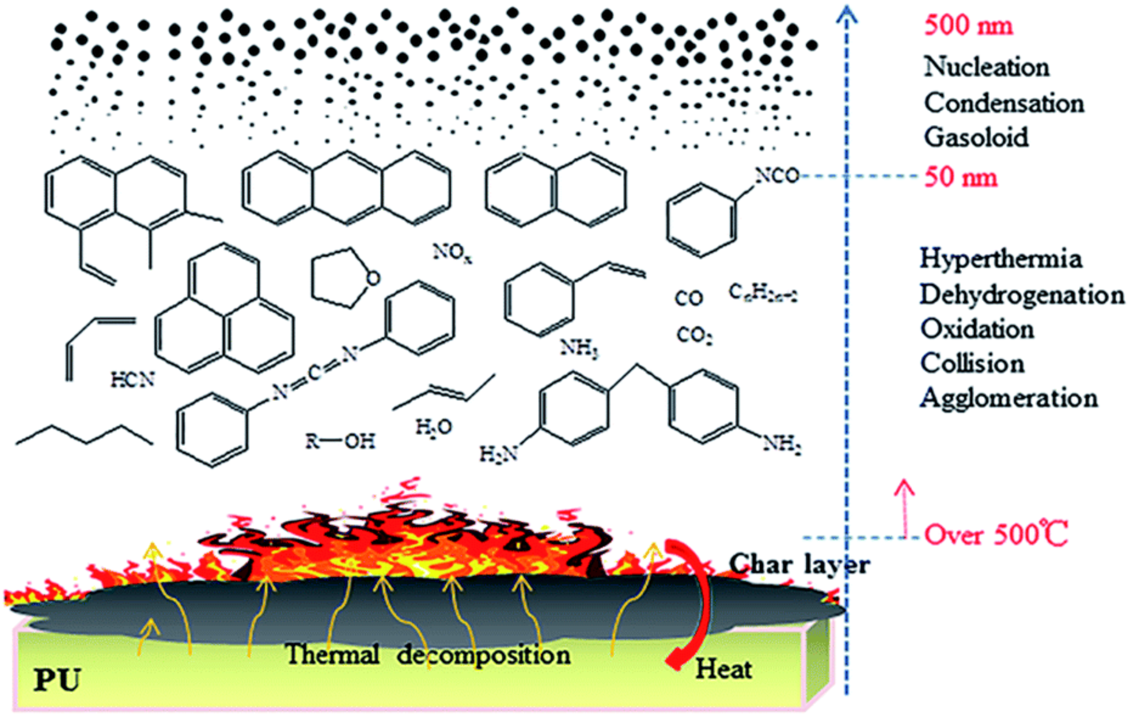


Figure 7. smoke and vapours products generated by combustion PUR [39]. Shown in contrast with the combustion of silicone foams.

Common fillers and their effect on the properties of silicone foams

The flame resistance of PDMS composites can be significantly increased with the addition of carefully chosen additives. Various variables influence the additives' function and mode of operation, but morphology, the presence of functional groups, and thermal resistance play a key role [40].

The majority of additives used in plastics technology are mineral fillers. Fillers enhance the qualities of such composites and minimize the cost of raw materials used in polymer composites. Numerous factors, including fillers' chemical composition, particle size and shape, surface characteristics, and the presence of functional groups, affect how fillers affect the properties of polymer composites [41].

Fumed silica

FS is a type of silica that is produced by pyrolyzing $SiCl_4$ with oxygen and hydrogen at a high temperature. The resulting FS particles have diameters typically on the order of 10-100 nanometers, and have a high surface area per unit mass. This makes FS an excellent reinforcing filler for polymers and elastomers, as well as a thickening agent and flow aid in a wide range of applications. FS can also be surface modified with a variety of functional groups to enhance its compatibility with different matrices and to impart specific properties such as hydrophobicity [42].

Adding FS to SIF compounds increases the materials ability to withstand high mechanical loads, by forming hydrogen bonds between the silanol groups on the surface of the FS particles and the Si-O-Si chains. However, the creation of hydrogen bonds between FS silanol groups and oxygen from the organosilicon polymer chain can also result in unwanted phenomena that impede the processing of the polymer composite. The use of hydrophobized fillers with blocked hydroxyl groups on their surface is advised to avoid the issues above [43].

The method used to incorporate FS into the composite and the FS particle size and type has the biggest influence on flame retardancy. It has been established that the addition of FS increased flame retardancy through physical processes in the solid phase, not through chemical interactions. Therefore, effective FS dispersion in the polymer matrix is crucial to achieving the desired qualities, such as flame retardancy [44].

Mica

The mica group includes approximately 30 groups of minerals, with only a few being commonly found. Some of the most significant mica representatives are muscovite, phlogopite, and biotite. Muscovite is highly prevalent due to its stability, and is found in a wide range of geological environments. A high aspect ratio and flaky structure is crucial for enhancing the strength of polymers and enables the production of polymers with a high filler content. Therefore, the aspect ratio and flakiness are the most significant property that determines the quality of micas. To prepare mica fillers, surface treatment with silanes may be employed as a part of the manufacturing process [42].

It was discovered that the effect of mica on the PDMS composite's thermal characteristics and the creation of the sintered layer heavily depends on the particle size and quantity of filler used. It was discovered that mica with a large aspect ratio accelerated the PDMS composite's thermal degradation, while mica with a small aspect ratio boosted its thermal stability [25].

4 Experimental

Objectives

The objectives of the laboratory experiments of this master´s thesis were to:

1) Analyze how different fillers and blowing agents and their combinations affect the formation of SIF and its density, and to optimize the choice and content of fillers and blowing agents for optimal foam formation;
2) Analyze the effect of fillers and blowing agents, and their combinations on the mechanical properties of the foam. This also includes the optimization process.

The general aim was to find a composition for injection molding SIFs, yielding a foam with :

a) a porosity that is as uniform as possible;
b) a density that is less than 120 kg/m^3;
c) specific strength higher than 0.4 N·m/kg, so it is sufficient for a cushioning material;
d) uniform expansion in all directions.

Chemicals and materials used in silicone foams

Component	Origin	What was it used for	Description
Functional PDMS (OH-PDMS, V-PDMS)	Hubei	Basic structure, crosslinking	Viscosity 5- 80 Pa·s
SiO_2	Evonik	Enforcing filler	Fumed silica
Water	Institute of Technology	Blowing agent, crosslinking	Milli Q
Methanol	Lach-ner	Blowing agent	Reagant grade methanol
Diols	Lach-ner	Blowing agent, crosslinking	Reagant grade diols
MICA	Omya, technical	Enforcing filler	*Muscovite*
Platinum catalyst	Hubei	Activation of hydrosilylation and dehydrocondensation	*Karstedt* catalyst

Functional PDMS (PMHS- HMS-992)	Hubei	Blowing agent, the basic structure	Polymethylhydrosiloxane
Moderator	Gelest	Moderating hydrosilylation process	1,3,5,7-Tetramethyl-1,3,5,7-tetravinylcyclotetrasiloxane

The prepolymer mix is created by mixing specific combinations of silicone polymers, fillers, blowing agents and other additives. The A and B compounds are thoroughly mixed before added into the device. The ratios of different blowing agents are calculated based on the use of polymethylhydrosiloxane in the reaction.

The crosslinking and foaming processes were carried out concurrently while the SIFs were created. The dehydrocondensation of hydroxyl-terminated PDMS and water with the crosslinking agent's Si-H groups served as the crosslinking's basis. Water has been deliberately substituted with various diols, methanol, or glycerol for specific purposes. A Karstedt catalyst was used to catalyze this reaction.

1,3,5,7-tetramethyl-1,3,5,7-tetravinylcyclotetrasiloxane was added to the SIF mixtures at varying concentrations. We observed that the addition of the moderator improved the homogeneity of the curing process, particularly in tall molds, resulting in more uniform foams. This effect is likely due to the mediator's ability to facilitate the hydrosilylation process, leading to a more efficient and even cross-linking of the silicone polymer chains.

Construction and use of the prototype device

The purpose of the device that was used in the experiments was to allow controlled and repeatable fabrication of two-component SIFs. The device was made as a prototype for a future industrial device that would produce SIF in industrial quantities by injection molding. The device was assembled from two vessels designed to saturate the components with air. The vessels could maintain high pressure over a long timeframe. The vessels also had mixers of their own that evened out the composition of the components. At the bottom of the vessels were taps through which the components were discharged from the vessels. A controller that runs both gear pumps at equal speed maintains an equal flow rate of the components. The mixtures were mixed with the help of a screw mixer, and the homogenized reaction mixture was discharged into a bowl or a mold. It should be noted that the purpose of the device was to facilitate the SIF fabrication process. The machine was designed to be able to process the two-component SIFs in a controlled and repeatable manner, with the goal of producing SIF in industrial quantities via injection molding.

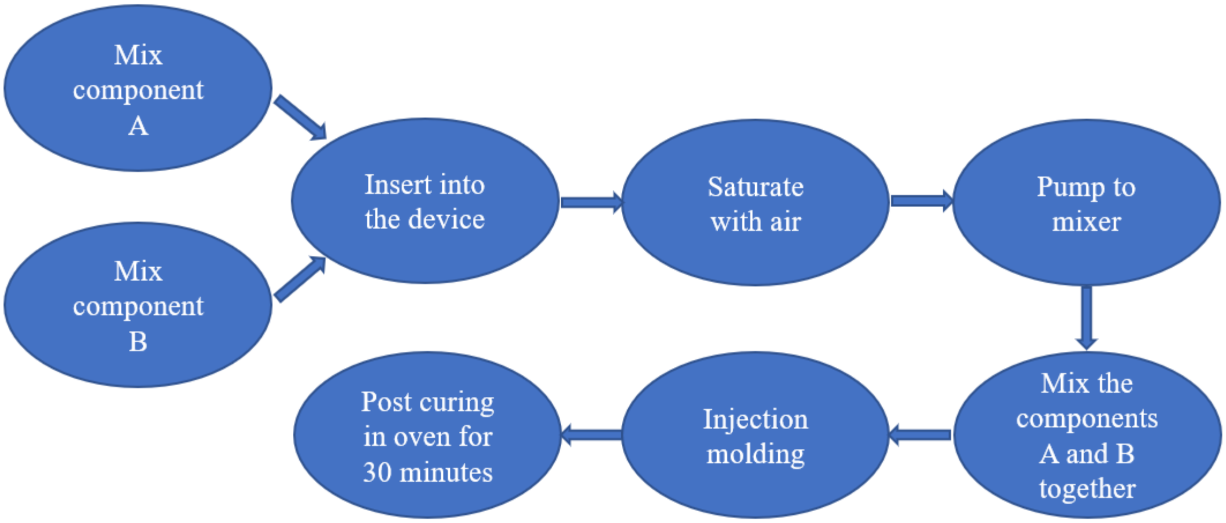


Figure 8. Fabrication of two component SIF with the prototype machine.

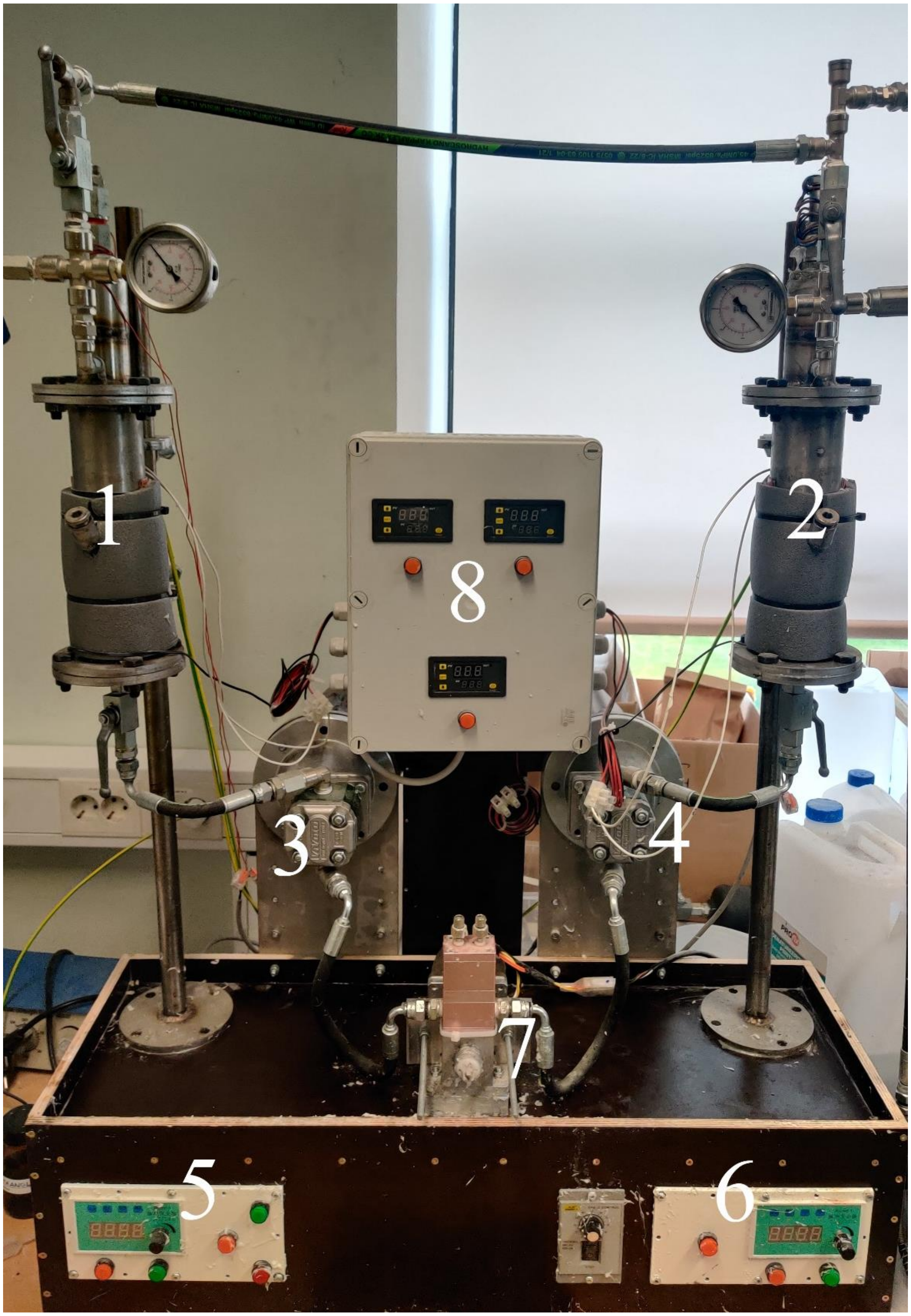


Figure 9. Fourth generation prototype device. 1, 2- pressurized vessels, 3, 4- pumps, 5, 6- controllers, 7- exit hole, 8- temperature controller.

After 5 minutes of expansion and cross-linking at room temperature, the formed foam was placed in the oven for the post-curing procedure at 70°C for 30 minutes. The foam was then allowed to cool for ten minutes, and to determine the density, a cube with sides of about centimeter was cut from the middle of the sample with a band saw.

Characterization of SIFs

Measurement of the density of silicone foams

To measure the foam's density, a small cuboidal piece was cut from the center of the sample and weighed. The piece was cut from the center because the measured piece needs to be free of skins, densification lines, voids, and defects. The measured density only refers to the immediate area where the specimen was taken. It may or may not be related to the overall foam piece's bulk density.

The density of the solid foam was also determined using glass bead pycnometry. To calculate the density of the SIF, a piece of foam was weighed and placed in a container filled with glass beads. Additional glass beads were added to the container up to a certain limit, and the mass of the added glass was weighed. Based on the density of the glass beads and the weight of the added glass, the volume of the foam was calculated. The densities obtained from measuring and dividing mass and volume of a cuboidal piece and glass bead pycnometry were found to be consistent.

Measurement of the tensile strength of silicone foam

Tensile strength is a mechanical property of materials that measures their ability to resist deformation and breaking under tension. By measuring the tensile strength of SIFs used in seating, we can determine whether it is strong enough to withstand someone sitting on it by determining the material´s ability to resist tearing or stretching under tension.

The tensile strength and elongation of SIFs were assessed by the tension test. The measured peak was divided by the sample's cross-sectional area to determine the tensile strength. This specific SIF tensile strength test is similar to testing other polymers. However, gripping and measuring the extension requires more care because foam pieces must be relatively thick compared to other polymer tensile tests. Because of the low tensile strength of SIFs, low-force grips need to be used.

Tensile strength was measured because it allows comparing foams with specific chemical composition and conditions used during the injection molding. The standards ISO 1798 and ASTM D 3574 were used as a reference for tensile strength measurements.

The specimens for the tensile test were stamped out with a die of the shape and dimensions shown in Figure 10. The test specimens were cut from a flat sheet of material with the foam rise in the thickness direction. The test specimens were free of ragged edges, and the cut edges were perpendicular.

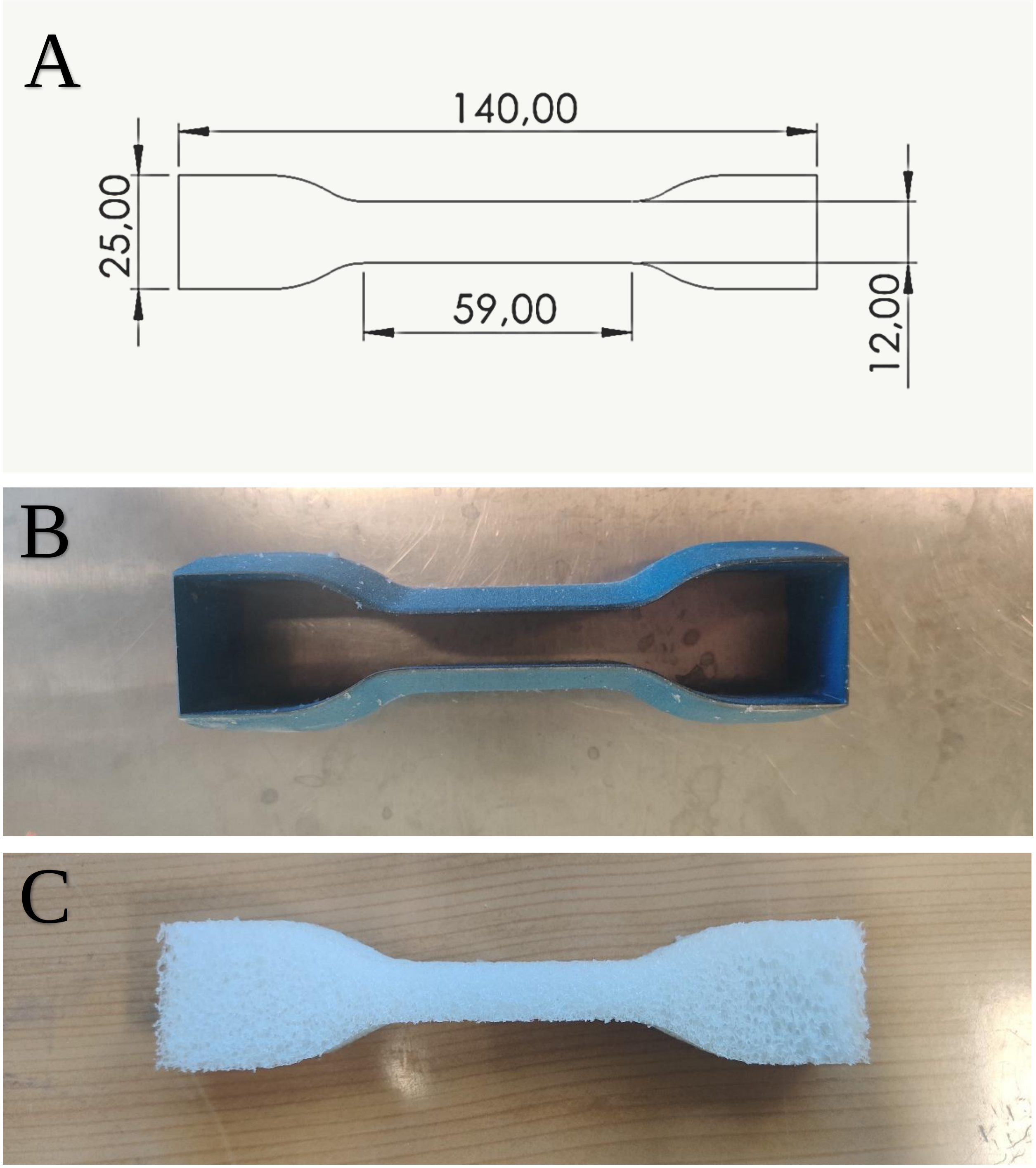


Figure 10. Die for stamping the foam specimens. A- Dimensions and shape of the die. B- The die itself. C- Foam stamped out with the die and ready for the tensile strength test.

The machine used was a Motorized Test Stand model AEL-A-1000 (**Annex 1**. AEL-A-1000) by Hefei Vetus Electronic Technology. The test speed of the machine was 300 mm/min and was uniform during the whole test. The slipping of the foam specimens was prevented by using a screw-type jagged plate grip that exerted uniform pressure across the gripping surface.

Figure 11. Dumbbell specimen in the grips of the Motorized Test Stand model AEL-A-1000.

The tensile strength was calculated by dividing the maximum breaking force by the cross-sectional area of the specimen. The specific strength of the SIFs was also calculated by dividing the tensile strength by the density.

Using scanning electron microscope to characterize the structure of silicone foam.

The characterization of SIF structure is important to understand its properties and behavior in various applications. In particular, the size and distribution of pores within the foam can affect its mechanical properties. By characterizing the foam structure, we can optimize its properties for specific use cases and improve its overall performance.

To examine the foam structure in more detail, a scanning electron microscope (SEM) was used. The SEM (Hitachi TM3000) allowed for high-resolution imaging of the foam surface, revealing the size, shape, and distribution of its pores. The SEM used has a highly sensitive backscattered electron detector, with detects precise surface structures. It is possible to magnify up to 30000 times at excitation voltages of 5 or 15 (kv) [45]. To perform the analysis, the sample surface was made conductive by coating it with a 10 nm thick gold layer using a sputtering device (Leica EM ACE600). This ensured that the sample remained stable under the SEM's high-energy electron beam and this also gave better contrast. The examined samples were about 20x15x10 mm.

To estimate the pore size of the SIF, ImageJ [46] software was used to analyze the SEM micrographs, that were done with the SEMs software. The software utilized contrast differences in the large SEM micrographs to measure and estimate the size of the pores within the foam structure. By analyzing the size and distribution of pores, we can gain insights into the foam's properties and performance.

Measuring reaction temperatures of silicone foams

Measuring reaction temperatures is an important aspect of characterizing chemical reactions, as it provides valuable insights into the reaction kinetics, mechanisms, and stability. By monitoring the temperature rise and fall during a reaction, we can determine the rate of reaction and the heat of the reaction.

For this master’s thesis, Elitech GSP-6G data logger device was used to measure the temperature rise and fall during the reaction. The device had a detachable electronic thermometer with a 1.5-meter cord that could be inserted into the reacting mixture. The device had a 10-second interval and measured the temperature changes over a 30-minute window. By measuring the temperature changes over time, we were able to understand how the reaction progressed and how fast does the SIF cool down in the mold and in open air.

This information is essential for optimizing the reaction conditions and ensuring that the reaction proceeds in a safe and efficient manner. By monitoring the reaction temperature, we can adjust the reaction parameters such as the temperature, pressure, and catalyst concentration to optimize the reaction kinetics and yield.

Dynamic fatigue test by constant force pounding

Dynamic fatigue test by constant force pounding is a method used to determine the fatigue life of materials under repeated loading conditions. In this test, a deformation of 33 mm was used in the program and the machine measured the force needed to create this deformation. This force was applied 200000 times. Thickness and structural breakdown was assessed within that set range. Dynamic fatigue testing was performed on the SIF samples to evaluate their resistance to repeated loading (**Annex 2.** Dynamic fatigue test by constant force pounding).

The dynamic fatigue testing machine used in this study was in-house built by the engineers and scientists of our research group. It consisted of an electromagnetic actuator, and a load cell that allowed for the application of a constant force to the foam specimens. The machine was designed to apply the force in a repetitive manner at a controlled frequency, simulating the repeated loading conditions that materials may experience in real-world applications. The machine was equipped with sensors to measure the force applied, displacement, and frequency; software provided data acquisition and analysis.

Fumed silicas and their use in silicone foams

Due to its mechanical and thermal characteristics, FS is frequently used as a reinforcement filler in polymeric foams. However, because of its hydrophilicity, it can cause problems with foam stability and moisture absorption. Hydrophobic FS can be used in place of this material to get around these restrictions.

Numerous combinations with various FS loadings were created to examine the impact of FS on the viscosity of SIFs. Both commercially sourced FS-s and hydrophobized on-site using chlorotrimethylsilane FS were tested. We used a rotational viscometer to measure each mixture's viscosity in order to establish the ideal FS addition amount.

5 Results and discussion

The silicones used as pre-polymers and main components have a density of 0.97 g/cm^3. As most additives have a higher density than silicone, the foams density tends to increase as well. On the other hand, the dissolved air allows for achieving foams less dense than the silicones we used as our main components.

SIF was produced by forming a network of siloxane connections via the use of gaseous hydrogen as a blowing agent. The resulting foams had densities ranging from 75 to 205 kg/m^3 and specific tensile strengths between 0.29 and 0.54 N·m/kg. To ensure accuracy, each test was conducted at least three times to determine the true value and uncertainty.

This work aimed to create a SIF that has a density less than 120 kg/m^3 and a specific strength higher than 0.4 N·m/kg. The SIF also had to be usable as cushioning's in seating and they had to be created by injection-molding technology. The selection of these figures were picked after careful consideration. The research began with SIF densities of 240 kg/m^3 and specific strengths of 0.01 N·m/kg and we picked out a favorable compromise between providing sufficient cushioning properties in seating and maintaining a reasonable weight-to-strength ratio. These figures were selected to align with the requirements and expectations of cushioning application.

The choice of chemicals used in this master's thesis was based on extensive experimentation to identify these chemicals that produced SIFs with desirable properties. Methanol was chosen for its stiffness-enhancing properties and reactivity [47], while 1,4-butanediol was chosen for its reported success as a suitable crosslinker in other polymers, resulting in lower densities and desirable mechanical properties [10]. Other diols were selected because of their ability to crosslink polymer chains and affect the properties of resulting SIFs. All choices were made through a logical and systematic process, considering various factors such as the desired properties and reactivity of the chemicals.

Tensile stress-strain measurements were selected as the proxy for assessing the mechanical strength and elasticity of the foams. The test specimens were simple to fabricate, and the specimen size allowed carrying out measurements in triplicates from each batch. By measuring the tensile strength of SIF used in seating, we can determine whether it is strong enough to withstand someone sitting on it. It is also worth noting that the base polymer mixture has a significant effect on the foam's mechanical properties. While optimization of the base polymer mixture is an important aspect of SIF research, this was not the focus of this thesis.

Effects of different fumed silicas on the mechanical properties of silicone foams and prepolymers

The addition of different FS to the foam formulation resulted in varying levels of mechanical properties and foam density. We found that FS with differently modified and hydrophobized surfaces have different effects on viscosities of the silicone mixtures. These variations in rheological properties of silicone mixtures can have a significant impact on the properties of the resulting SIF, such as its density and mechanical strength. Therefore, the choice of FS used in the SIF formulation should be carefully considered and optimized to achieve the desired properties. The hydrophobic FS exhibited increased compatibility with the SIF, resulting in improved mechanical properties such as increased tensile strength and elongation at break. The use of hydrophilic FS is not feasible as it significantly increases the viscosity of the mixture, making it difficult to handle and process.

The main FS used was R8200 by Evonik because of its low rheological effect and its effectiveness to increase the strength of SIF. It has been noted that less structured and hydrophobized FS give longer lasting elastomers because the highly structured fillers tend to break apart under stress [48]. We also tried to recreate the same effect with other FS. We had tried different commercial hydrophobized fumed silicas like Fusil 132, Fusil 135, Fusil 620, Fusil 630 and Evonik R 972. The FS did not meet our requirements, so we prepared our own FS by modifying its hydrophobicity. We tried to modify the Fusil 132 FS by grinding and reacting in 1 part of chlorotrimethylsilane and 25 parts of FS. The cholotrimethylsilane was dissolved in toluene. The reaction was carried out at room temperature with continuous stirring for two days. The hydrophobic FS thus obtained was thoroughly dried before being added to the foam mixture. The use of this modified FS improved the FS rheological effect on silicone polymers, and higher concentrations could be added to the silicone prepolymer mix without making it too viscous.

The rheological effect of different FS through viscosity and using a rotational viscometer was determined. 120 grams of hydroxy-functionalized PDMS, with a base viscosity of 5000 mPa·s was mixed with 4 grams of FS and were compared.

Table I

Hydrophobic fumed silica rheological effect in hydroxy-terminated PDMS

Manufacturer	Density (g/L)	Viscosity in OH-PDMS (mPa·s)
Evonik R8200	140	6400
FUSIL 132	40	8400
Self-modified FUSIL 132	170	6600

After testing different FS, we observed that FUSIL 132 had a significant impact on the viscosity of the silicone polymer. By further hydrophobizing it, we were able to reduce its rheological effects. This allowed us to increase the amount of FS used in the foam, resulting in an improvement in the foam's tensile strength. These findings highlight the importance of selecting the appropriate FS for the prepolymer mix to achieve desired mechanical properties in the final product.

Effect of methanol on foam density and mechanical properties

The choice of chemical additives can significantly impact the properties of SIFs. Previous research has shown that water is a crucial component for producing these foams, but investigations have also been conducted to explore the role of methanol [47]. Methanol is known to be a fast-reacting alcohol in this type of reaction and its addition can lead to variations in the foam mechanical properties, including density, tensile strength, and elongation. Moreover, if the pore size is too small, the foam will behave like memory foam, which may not be desirable for seating applications. The addition of methanol can increase the pore size, thus losing the unwanted memory foam property.

Investigations were done into how different mol% ratios of water and methanol affected the density, tensile strength, elongation, and other properties of the manufactured SIFs.

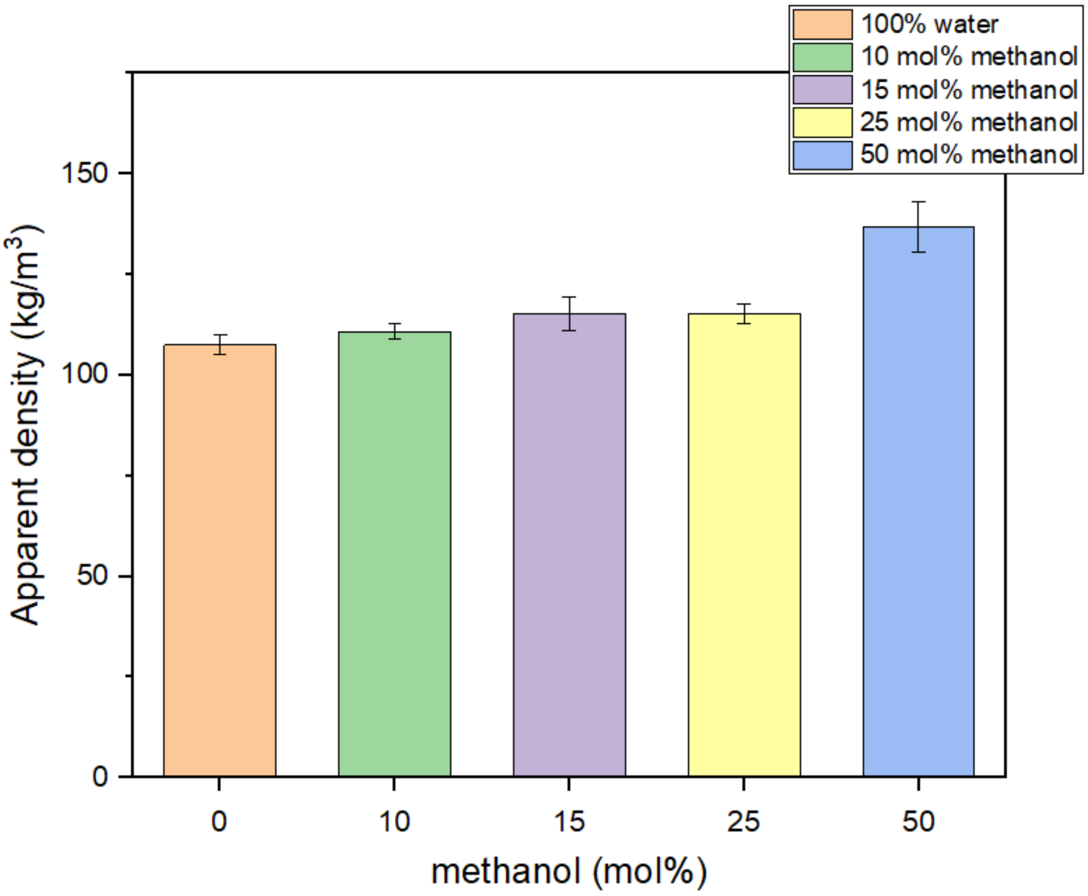


Figure 12. The apparent density of SIFs increases with the increasing mol% ratio of methanol.

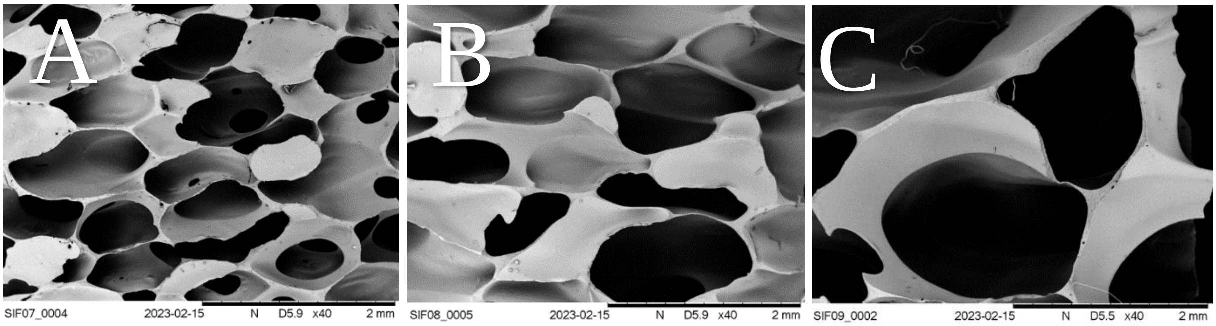


Figure 13. SEM micrographs of SIFs with methanol:water molar ratios. A) 10%, B) 15%, C) 25%.

The graph (Figure 12) shows that the average density rose with increasing methanol-to-water mol% ratio. As shown in Figure 13, with increase in the methanol/water mol% ratio, the average pore size grew from small (pore diameter less than 1 mm) to large (pore diameter greater than 2 mm). The average homogeneity also decreased.

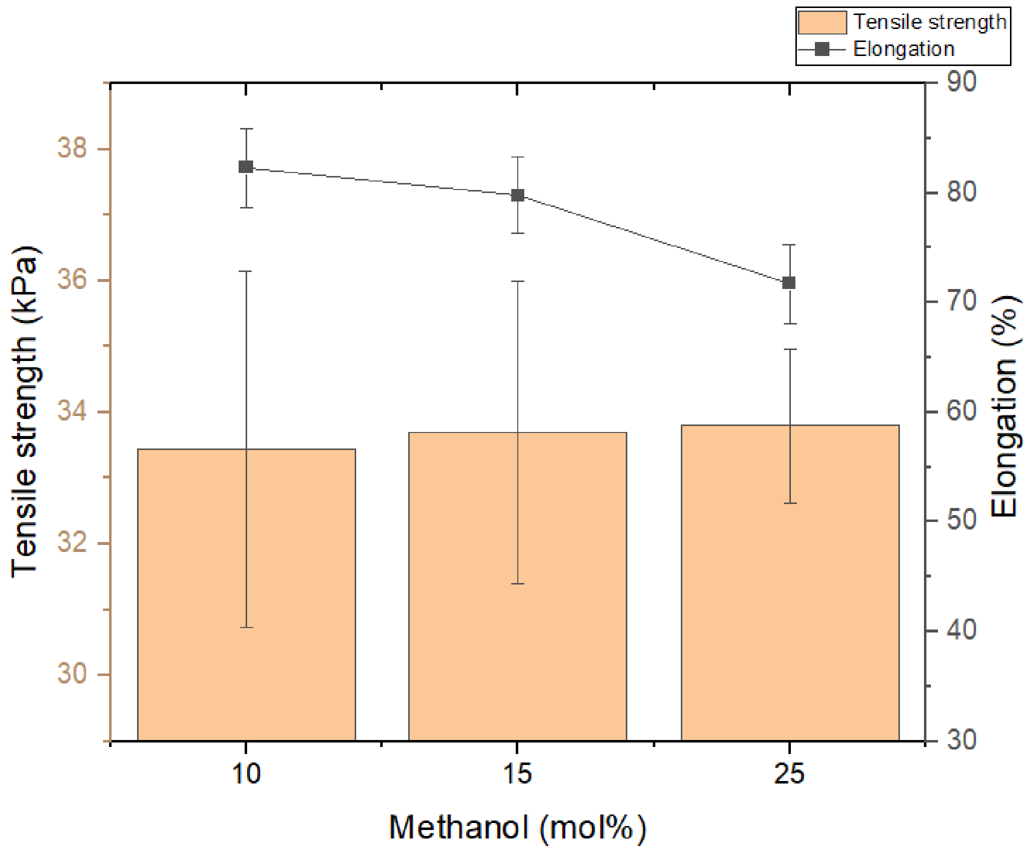


Figure 14. Higher mol% of methanol exhibited greater tensile strength but lower elongation at break, indicating that the change in methanol-to-water mol% affects the mechanical properties of SIFs.

Modifying the blowing agents in the silicone prepolymer mixes by changing the methanol-to-water mol% ratio did not significantly influence tensile strength. But the elongation of these flexible SIFs is lower when more methanol is added. The elongation decreased from 82 ± 4% to 72 ± 4%. The 50 mol% methanol foam tensile strength was not measurable because the dumbbell specimen for the tensile strength test was narrower than the pore size of the foam.

Table II

Characteristics of silicone foams created with different mol% ratios of methanol and water

mol % of methanol	Density (kg/m^3)	Tensile strength (kPa)	Elongation (%)	Pore size
0 mol %	108 ± 2	56 ± 5	97 ± 7	small
10 mol %	127 ± 4	42 ± 2	82 ± 4	small
15 mol %	115 ± 4	34 ± 5	80 ± 4	medium
25 mol %	115 ± 3	34 ± 2	72 ± 4	medium
50 mol %	137 ± 10	-	-	large

These results show that the methanol affected the foaming process by increasing the foam's pore size. This could be due to various factors, such as changes in the nucleation and growth of gas bubbles during the foaming process. With an increased porosity in the foam structure, methanol can also affect the efficiency of other blowing agents used in the process. This can lead to changes in the amount of gas released during the foaming process, which in turn, can affect the resulting density of the foam. The amount of gas released is influenced by the reaction speeds of water and the silicone prepolymers, as well as the reaction speed of the alcohol component.

The use of methanol in our recipe allows us to mold the SIF. Because the density of the foam object stays the same throughout the piece when injected into a tall mold. It may be because methanol slows down the curing of the SIF and starts rising after the end of the pour. To optimize the use of methanol careful consideration should be taken when creating the prepolymers. The appropriate ratio of methanol with other components should be determined to get a balance between foam density, tensile strength, processing ease and desired end results.

Effect of different diols on foam density and mechanical properties

When various diols were combined with water in a 10-mole percent ratio, the effects on density, tensile strength, elongation, and other properties of the resulting SIFs were investigated and compared to each other. The diols used were: ethylene glycol, 1,2- propanediol, 1,3-propanediol, 1,4- butanediol, 1,5-pentanediol, 1,6- hexanediol, and 1,7- heptanediol.

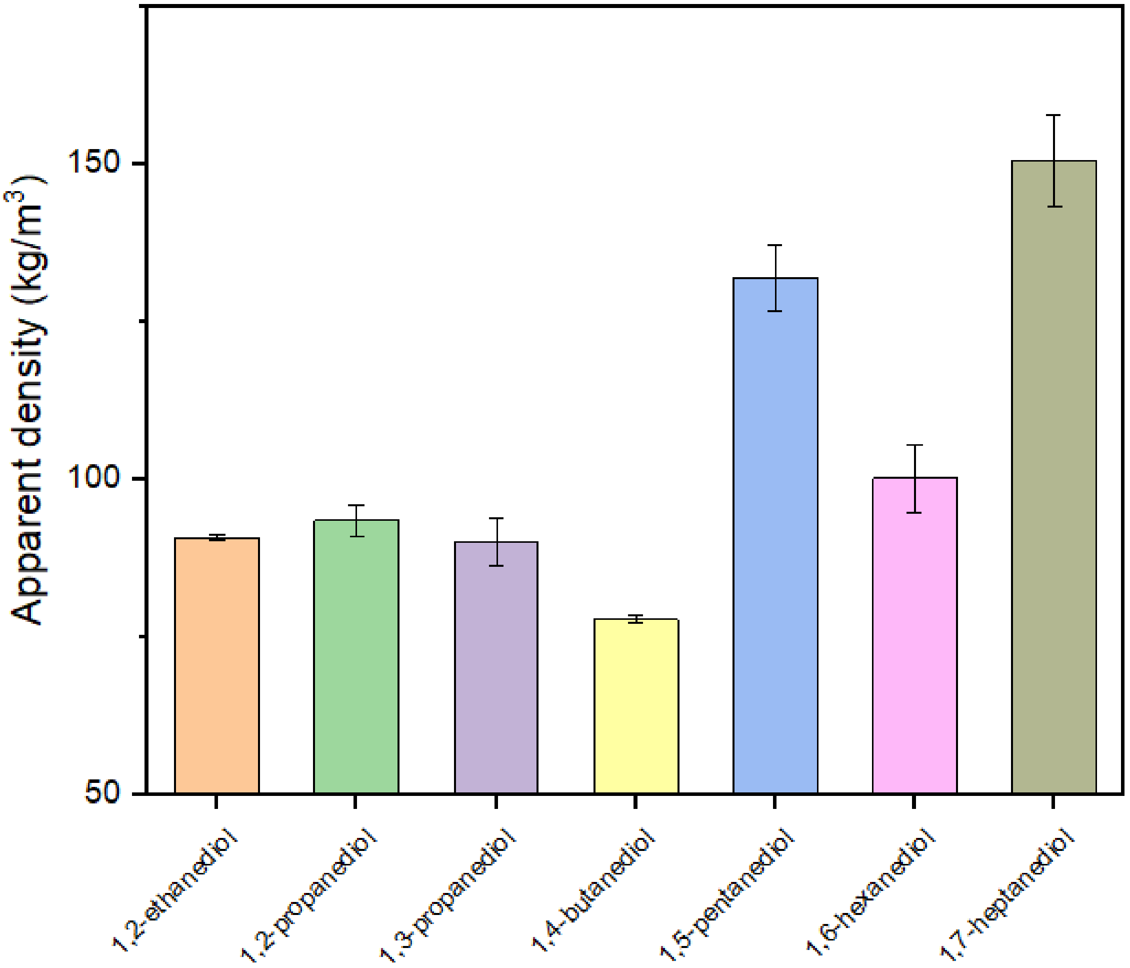


Figure 15. Apparent density of SIFs related to the different diols used. Indicating that diol selection has a significant impact on foam density.

The results showed that the apparent density of SIFs varied depending on the diol used. As shown in Figure 15, smaller diols like ethanediol and propanediols result about the same value in foam density. A density drop happens when we use 1,4- butanediol, significantly increasing again when we use other medium-sized diols like 1,5- pentanediol and 1,7- heptanediol.

Table III

Characteristics of silicone foams created with 10 mol% concentration of different diols and water

Diols	Density (kg/m^3)	Tensile strength (kPa)	Elongation (%)	Specific strength (N·m/kg)
1,2- ethanediol	91 ± 1	32 ± 5	65 ± 5	0.35 ± 0.05
1,2- propanediol	94 ± 2	38 ± 6	74 ± 3	0.41 ± 0.07
1,3- propanediol	90 ± 4	46 ± 2	76 ± 1	0.51 ± 0.02
1,4- butanediol	78 ± 1	41 ± 4	86 ± 7	0.52 ± 0.05
1,5- pentanediol	132 ± 5	41 ± 3	74 ± 7	0.31 ± 0.02
1,6- hexanediol	100 ± 5	40 ± 7	54 ± 7	0.34 ± 0.07
1,7- heptanediol	150 ± 7	49 ± 11	55 ± 10	0.32 ± 0.07

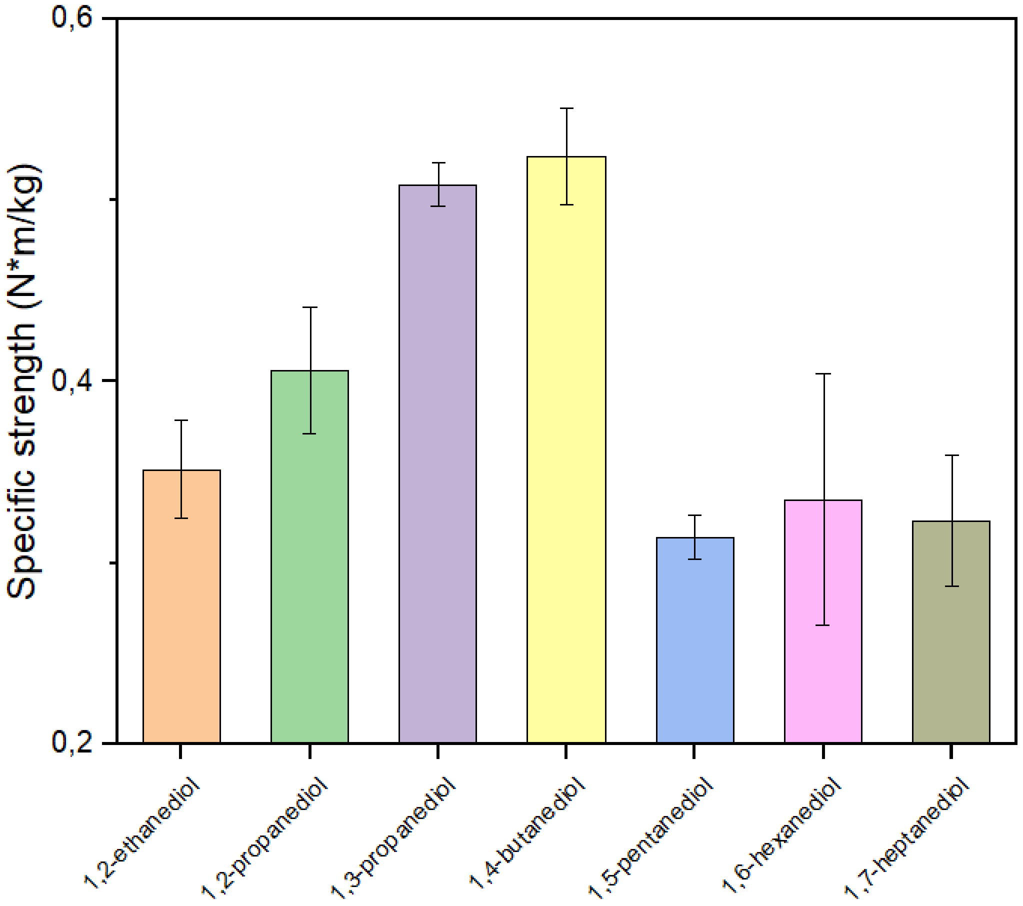


Figure 16. Specific strength of SIFs related to the different diols used. It shows variation in specific strength across different diols tested, highlighting the importance of diol selection.

As shown in Figure 16 and in table III, 1,4-butanediol resulted in the highest average specific strength (0.52 N·m/kg), while 1,5- pentanediol and 1,7- heptanediol gave the lowest values. We can also see in Figure 16 that with the growing molecular mass of the diols, the average specific strength rises with it till it drops suddenly.

The results of this study suggest that the choice of diol can significantly impact the apparent density and specific strength of SIFs. After examining the properties of different diols used in the synthesis of SIFs, it was observed that 1,4- butanediol resulted in the lowest apparent density and highest specific strength. On the other hand, 1,5- pentanediol exhibited high density and low specific strength, making it less suitable for creating materials with properties we needed.

The reactivity of various diols with other foam ingredients may be the cause of the variations in how well they work in the formation of SIF. It's likely that 1,4-butanediol and the other ingredients work better together, resulting in a more uniform distribution of tension throughout the foam. As a result, the foam may become stronger, lighter, and more resilient to tearing and deformation under load. In contrast, other diols could result in foam that is denser and more crosslinked, which is more prone to breaking under pressure because of unequal stress distribution. Another explanation can be the odd-even effect that is seen in alkanes [49]. Because diols have also a carbon chain, this effect could be brought over to explain the phenomenon on why 1,5-pentanediol and 1,7-heptanediol give the highest densities. Further research is required to confirm these hypotheses and to explore other potential factors affecting the performance of different diols in SIF production, such as phase separation and interfacial tension.

By selecting the appropriate diol, we can affect the specific strength and density of the material. Optimizing the specific strength of SIFs for a wide range of applications with different diols may be possible.

Effect of 1,4- butanediol content on foam density and mechanical properties

Having established that 1,4- butanediol was the best performing diol, it remains to determine the optimal concentration that would give a foam that would have the needed density, specific strength and qualities that could be used in cushioning materials. Investigations were done into how 1,4- butanediol affected the density, tensile strength, elongation, and other characteristics of the manufactured SIFs. I employed various 1,4-butanediol-to-water mol% ratios in our silicone components. The choice of 1,4- butanediol as a component in SIF was based on its potential to enhance the foams mechanical properties, such as density and specific strength.

Figure 17 shows that using 1,4- butanediol with water can significantly decrease our average apparent density. The average pore size did not change and was very small, and the homogeneity of our foams also stayed the same. It was noteworthy that adding 1,4- butanediol into our premixed components raised the viscosity of that said component.

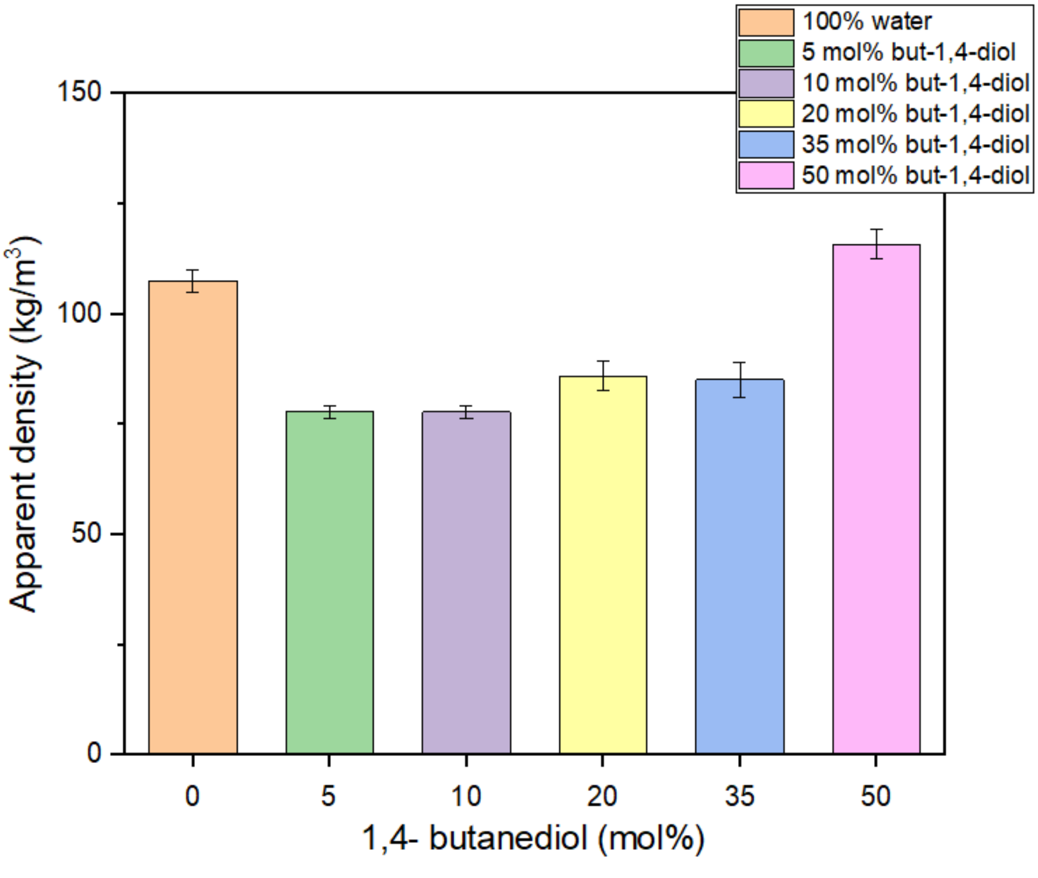


Figure 17. Apparent density of SIFs as a graph of 1,4- butanediol content. The data shows a clearly that smaller quantities decrease the apparent density significantly.

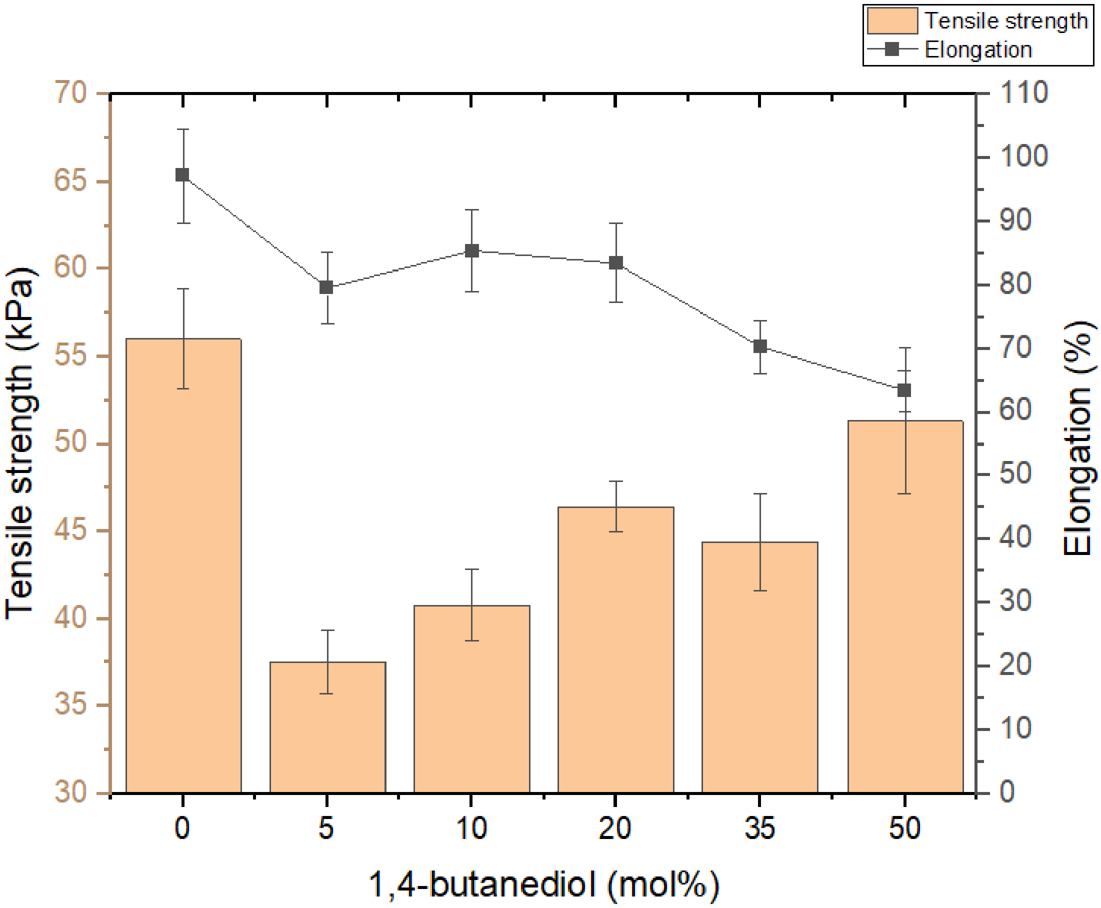


Figure 18. Tensile strength and elongation at break of foams with different mol% ratios of 1,4- butanediol and water. The data reveals clear relationship between the diol/water mol% ratio and mechanical properties, with higher diol percentages resulting in decreased elongation at break.

The use of 1,4- butanediol also significantly influenced our SIFs´ tensile strength and elongation (Figure 18). When adding smaller quantities of 1,4- butanediol, the tensile strength dropped but grew with larger quantities. With these kinds of results, it is necessary to evaluate our findings by calculating the specific strength of our SIFs.

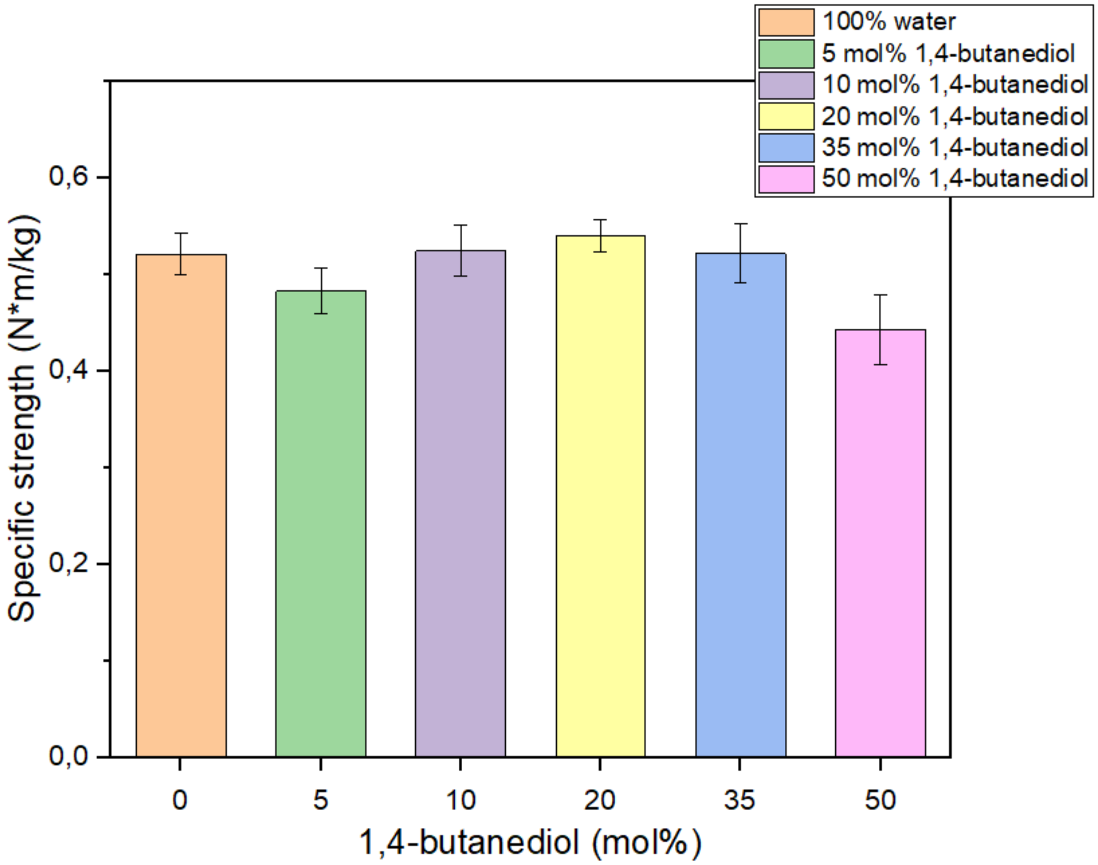


Figure 19. Specific strength of SIFs related to the mol% ratio of 1,4- butanediol used. Specific strength stays relatively similar, but the highest specific strength is with 20 mol% 1,4-butanediol / 80 mol% water.

We can see that the highest specific strength was with 20 mol% of 1,4- butanediol and 80 mol% of water. This gave us a specific strength of 0.54 ± 0.03 N·m/kg.

With these results, adding 1,4- butanediol can make our SIF lighter and with a higher specific strength in some cases rather than using 100 mol % of water.

The most plausible explanation is that 1,4- butanediol acts as a crosslinker, and connecting larger polymers with the four carbon atoms gives us a more flexible structure. This, in combination with the higher reactivity, gives us a decreased density and higher specific strength at around 20 mol% of 1,4- butanediol. It can be assumed that using larger quantities of butanediol increases the foams density and lowers specific strength because it has led to excessive crosslinking of the SIF, resulting in a more tightly packed foam structure. The increase in crosslink density can lead to decreased flexibility and increased brittleness of the foam, resulting in lower specific strengths. We can also see that with 50 mol% of 1,4- butanediol that the elongation is also the lowest.

Table IV

Characteristics of silicone foams created with different mol% ratios of 1,4-butanediol and water

mol % of 1,4-butanediol	Density (kg/m^3)	Tensile strength (kPa)	Elongation (%)	Specific strength (N·m/kg)
0 mol %	108 ± 2	56 ± 5	97 ± 7	0.52 ± 0.02
5 mol %	78 ± 1	38 ± 4	80 ± 6	0.48 ± 0.05
10 mol %	78 ± 1	41 ± 4	86 ± 6	0.52 ± 0.05
20 mol %	86 ± 3	46 ± 3	83 ± 6	0.54 ± 0.03
35 mol %	85 ± 4	44 ± 5	70 ± 4	0.52 ± 0.06
50 mol %	116 ± 3	51 ± 8	63 ± 3	0.44 ± 0.07

It is also important to note that the optimal amount of 1,4-butanediol for a specific application will depend on various factors, including the desired properties of the foam, the formulation, and the processing conditions. It is also noteworthy that using 1,4-butanediol in a mixture with water resulted in an unusually high temperature of the reaction (look at **Annex 3.** Comparison of temperatures). This indicates a more exothermic reaction and potentially leading to a faster reaction rate relative to other diols or only water. Also, the underlying mechanisms can be very complex when using 1,4- butanediol and water together to form SIF.

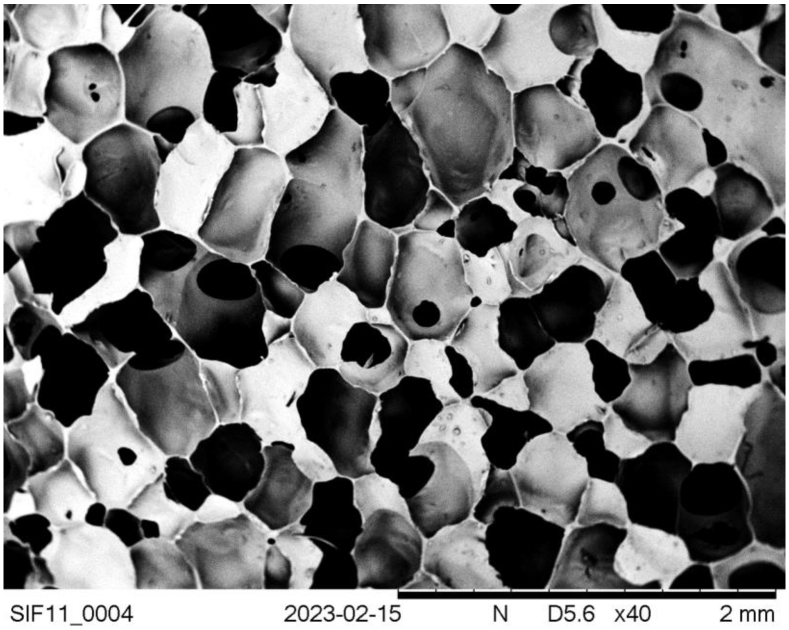


Figure 20. 20 mol% 1,4-butanediol. The uniform porosity and small pore size give the foam its high tensie strength and low density.

Optimal composition of silicone foam

The complexity of these SIF materials means that every compositional change and addition can have multifaceted effects. A small alteration can have a significant impact on the resulting properties, and the challenge lies in balancing these different factors. For instance, increasing the density may lead to closed small pores, which can make the foam break under a smaller load than anticipated. On the other hand, trying to increase the strength may result in a denser foam, which could negatively affect other desirable properties. Furthermore, some additives may have unintended consequences, such as compromising the catalyst or losing the fire-retardant effect. Thus, working with these materials requires careful consideration and testing to optimize the properties while avoiding any potential negative effects.

It was found that the addition of 25 mol% methanol, 20 mol% 1,4-butanediol and 55 mol% water resulted in the best combination of structure, strength, and density. This optimized mixture produced a uniform and strong foam that can resist deformation and tearing under load. The foam was also reproducable using injection molding technology. It was also used in the dynamic fatigue test and gave promising results with fitting in the test range of suitable seating materials. The suitable range was 20-170 N with a deformation of 33,8 mm after 200000 iterations. The foam held 50 N during the whole test. Our findings show that careful selection and optimization of the prepolymer mixture can lead to significant improvements in the properties of SIFs, with potential applications in cushioning materials for public transport.

Summary

This thesis researched the physical properties of SIF´s with two goals in mind:

1) To achieve SIFs that are reproducibly fabricated using injection-molding technology and usable in cushioning's. Such foams should have a density below 120 kg/m^3 and a specific strength over 0.4 N·m/kg.
2) Investigate which types of blowing agents and fillers yield optimal results for SIF density and specific strength.

Utilizing equipment created specifically for the consistent and repeatable low-pressure injection molding method of producing SIF, the factors influencing the characteristics of silicone were examined.

The goal of creating SIF that could match the desired parameters was achieved. The highest specific strength obtained for a SIF was 0.54 N·m/kg. The lowest density SIF was 76 kg/m^3. The 20 mol% 1,4-butanediol and 80 mol% water foam had a density of 86 kg/m^3 and a specific strength of 0.54 N·m/kg. The foam was also usable for cushionings.

The tensile strength test showed that adding 1,4-butanediol results in higher specifics strengths. It was also found that adding methanol increased moldability of SIF, and hydrophobizing FS lowered the rheological effect it had on the prepolymer mix, allowing higher concentrations of FS.

It was also established that:

a) Using a mediator greatly improved the SIF's moldability.
b) Using diols in our premixed components increased their viscosity significantly.
c) Methanol creates bigger pore sizes, and more methanol means bigger pores.

Kokkuvõte

Käesolevas lõputöös uuriti silikoonvahtude füüsikalisi omadusi pidades silmas kahte eesmärki:

1) Valmistada SIF-e, mis on reprodutseeritavad ja valmistatud madal-survevalu tehnoloogia abil. SIF-de tihedus peaks olema väiksem kui 120 kg/m^3 ning eritugevus kõrgem kui 0,4 N·m/kg, et nad oleksid kasutatavad istmepehmendustes.
2) Uurida erinevaid gaasitekitajaid, ristsidujaid ja täiteaineid, mis annaksid SIF-le soovitud tiheduse ja eritugevuse.

Silikoonvahtusid valmistati madal-survevalu seadet kasutates, et tulemused oleksid kindlad ja korratavad. Nii sai uurida erinevaid faktoreid, mis mõjutavad SIF-i tekkimist.

Püstitatud eesmärgid said täidetud. Kõrgeima eritugevusega SIF oli 0,54 N·m/kg ja madalaima tihedusega SIF oli 76 kg/m^3. 20 mol% 1,4- butaandiooli ja 80 mol% vee segu andis vahu mille tihedus oli 86 kg/m^3 ja eritugevusega 0,54 N·m/kg. See vaht oli ka sobilik istmepehmenduseks.

Tõmbetugevuse katsed näitasid, et 1,4-butaandiooli lisamine suurendab eritugevust. Leiti ka, et metanooli lisamine parandas SIF-de kasutamist vormides. Samuti leiti, et hüdrofobiseeritud pürogenne ränidioksiid vähendas silikoonkomponentidel reoloogilist mõju ja võimaldas seda kasutatada suuremates kogustes.

Vahtude valmistamisel veel selgus:

a) SIF-i reaktsioonikiiruse muutmisega sai parandada SIF-i kasutamist vormides.
b) Dioolide kasutamine tõstis silikoonkomponentide viskoossust.
c) Metanooli kasutamisega kasvab pooride suurus ja mida rohkem metanooli, seda suuremad poorid.

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Annex 1. AEL-A-1000

Figure 21. Motorized Test Stand model AEL-A-1000

Annex 2. Dynamic fatigue test by constant force pounding

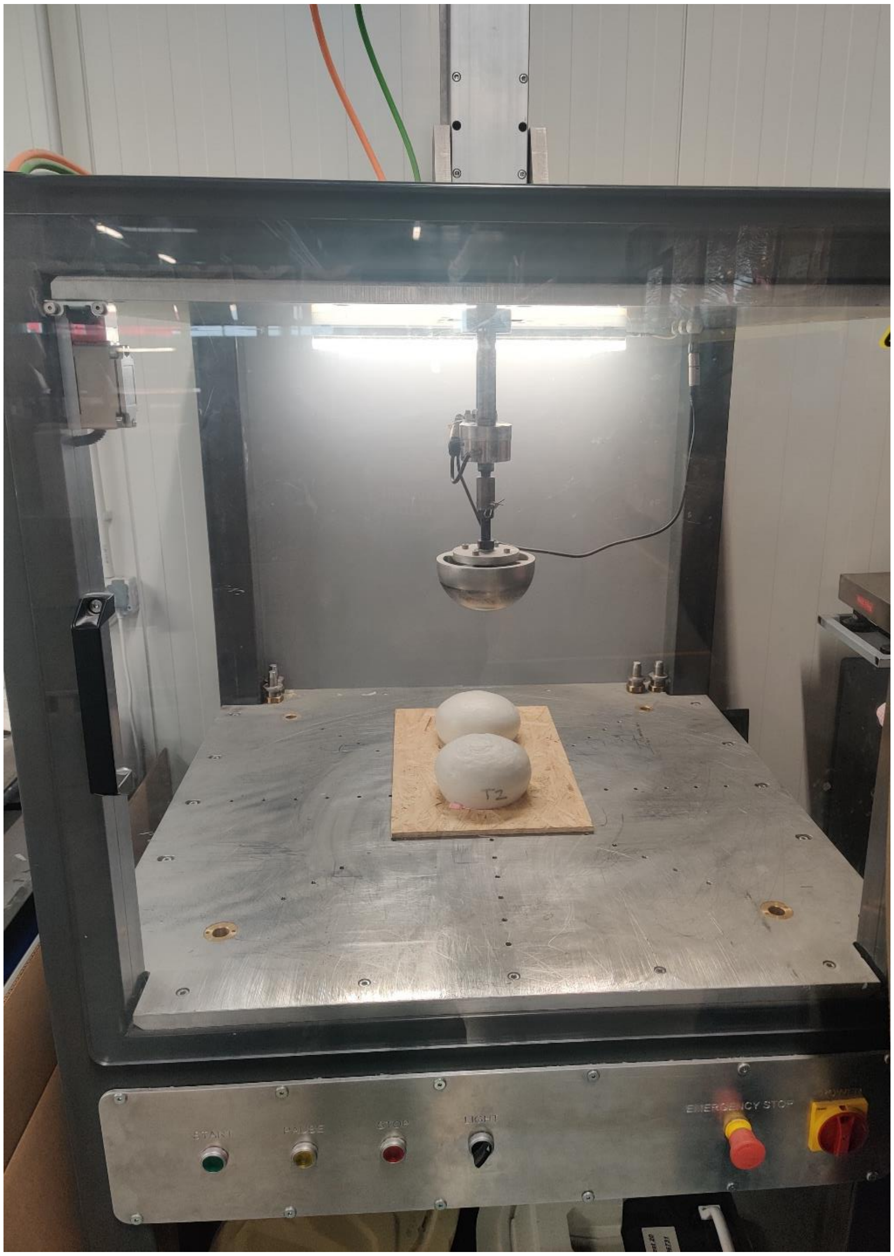

Figure 22. Test stand for dynamic fatigue test by constant force pounding

Annex 3. Comparison of silicone foam reaction temperatures

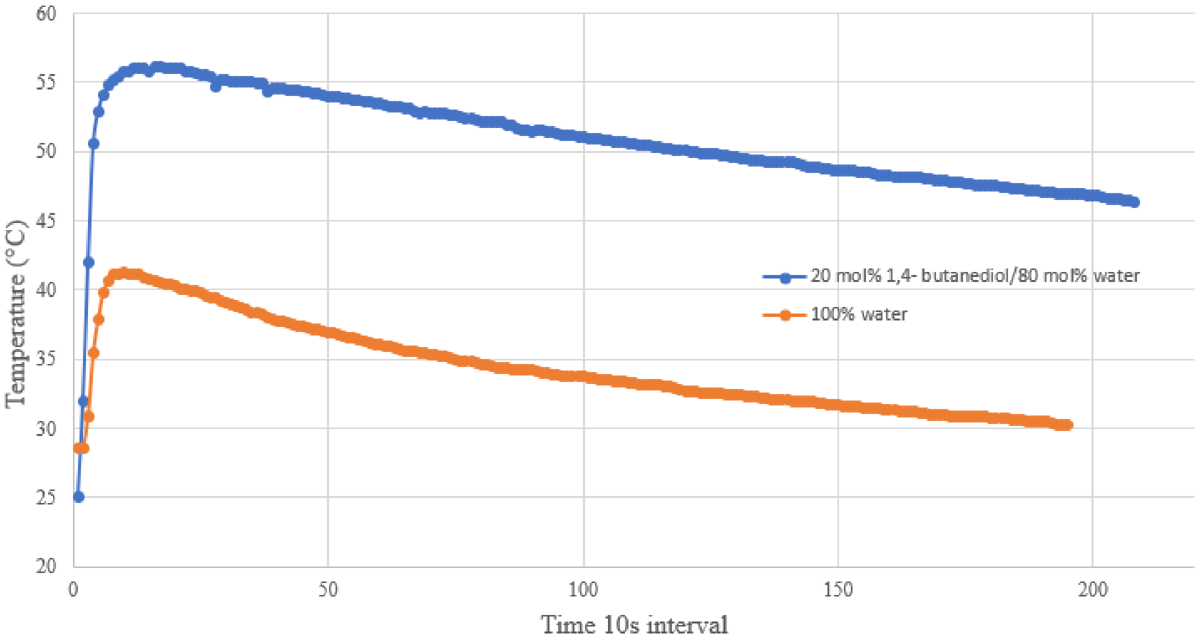

Figure 23. Temperature comparison of silicone foam reactions. 20 mol% 1,4-butanediol and 80 mol% water compared to a foam that had no 1,4- butanediol and the only blowing agent was water.

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