



# DEVELOPMENT OF “GREEN” POLYURETHANE BIO-COMPOSITES



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## ABSTRACT

Polyurethane (PU) is based on two main components: isocyanate and polyol. The two most important isocyanates are methylene diphenyl diisocyanate (MDI) and toluene diisocyanate (TDI). Generally, MDI is easier to handle and has fewer safety requirements due to its higher evaporation point. Polyols can be divided into two groups: polyether and polyester polyols. In addition to the two main components, additives such as foaming agents, catalysts, surfactants, and colorants are also inevitable to achieve the required quality and aesthetic properties of the product. Due to the increasing environmental concerns, the development of “green” polyurethanes is currently an important topic, because the industry is seeking to replace conventional base materials and additives with bio-alternatives. Several different bio-resources (*e.g.* agrowaste) were tested before to apply as bio-alternatives in polyurethane production. One special example is the application of algae-based materials. Algae is a large group of aquatic plants which are relatively easy to grow and thus, to produce biomass.

In this research, polyurethane bio-composites will be developed by using algae powders as additives. The algae powders are applied as colorants to replace the particularly expensive synthetic pigments. In order to finetune the recipe and check the materials’ quality, so-called “cup experiments” are carried out by using the FOAMAT 285 foam qualification system. The algae powders were mixed into the formulated polyol and then isocyanate was added. The colour change was observed with the help of colour measuring equipment. The examination of the microstructure of the foams was carried out, and the size distribution of the algae powder was also measured. Mechanical tests were conducted on the algae/PU systems and compared with algae-free standard foams. The physical and chemical properties of the algae/PU bio-composites were assessed, and potential applications were proposed.

## 1. INTRODUCTION

Polyurethane is a plastic material, which used in various forms. It has a wide range of applications in the furniture, automotive and construction industries in the form of adhesives and sealing foams, coatings, elastomers, rigid foams, moulded foams, flexible foams, cushion covers, and many more. Algae are photosynthetic organisms with many health benefits. It is also an excellent colouring agent, a property that is exploited in this work. Two types are used in the current research: spirulina and chlorella. The green colour of algae is due to chlorophyll, phycocyanin and other natural pigments.

A literature search was conducted on coloured polyurethane foams. Although coloured foams are very often used in industry, it was found that algae had not really been used to colour polyurethane foams, but a number of other colouring agents had, such as red pigment [1]. Furthermore, composites/nanocomposites were produced by replacing some of the conventional materials in PU with natural substances (e.g. vegetable oils) to reduce the polymer's environmental impact [2]–[8].

### 1.1 Research Objectives

The goal of this research is to produce green polyurethane foam in terms of colour and environment impact. The aim is to add algae powders to the polyol side and prepare a composite material. The algae powder is expected to provide a nice green colour to the polymeric composite material. However, the amount of the applied algae powder will be determined in a way to preserve the quality of the conventional polymer. Increasing amounts of algae powder are added to the polyol side, 1%, 2%, and 5% wt. These algae/PU bio-composite foams are compared to a standard foam which does not contain algae powder to determine any changes in the properties of the polymeric material.

## 2. LITERATURE REVIEW

### 2.1 Polyurethane foams

In 1937, Otto Bayer and his team produced polymeric fibres from aliphatic diisocyanates and aliphatic diols (glycols) and established polyurethane chemistry.

One of the most significant reactions in the synthesis of polyurethanes is the reaction between isocyanates and alcohols (polyols) (Figure 1), which is an exothermic process.[9]

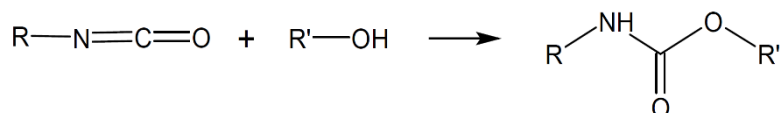


Figure 1: General urethane formation reaction[10]

The term polyurethane is a generic term, all macromolecules with multiple urethane bonds belong to this group. The transformation reaction can be stopped at any desired state, so that end products with different properties can be produced. If diisocyanate reacts with a polyol compound containing two or more hydroxyl groups, long polymer chains are formed.

Although some polyurethane grades are also available in thermoplastic forms, PUs are classified as thermosetting polymers since they do not melt when heated. [11]

Isocyanate demand is rising as a result of growing polyurethane usage. Additionally, it supports the industrialization and subsequent economic and scientific advancement of nations like China, Japan, and India. It should be highlighted, nonetheless, that this product also has disadvantages, such as stringent governmental restrictions and environmental worries about its management. These issues have increased demand for bio-based isocyanates, which are anticipated to see significant application in the upcoming years. [12]

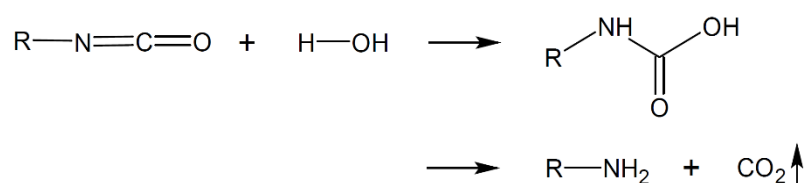
The three primary categories of polyurethane foams are rigid, semi-rigid, and flexible foams. Based on cross-linking densities, Saunders and Frisch divided foams into the following three categories:

- rigid, stiff foams: 400-700 cross-link per M
- semi-rigid foams: 700-2500 cross-link per M
- soft foams: 2 500-20 000 cross-link per M [13], [14]

Some polyurethane foam characteristics serve as critical gauges of the material's comfort, support, and longevity. Foam density ( $\text{kg/m}^3$ ) is one of these variables. Foam hardness is another such metric, and it is determined by the foam's surface imprint [15]. The element may not necessarily be more robust if the foam has a larger density. Density and durability have been demonstrated to be independent characteristics [16], despite the fact that a higher foam density implies the presence of more solids. Within the polyurethane structure, the various

monomer configurations make up segments with various characteristics [17]. Understanding this problem, nevertheless, has proven difficult in a number of earlier investigations.

Due to their structure, isocyanates react readily with active nucleophilic molecules. As a result, they interact with a wide variety of substances, the most significant from an industrial standpoint being their interactions with alcohols, amines, thiols, and water. Additionally, isocyanates frequently engage in dimerization and trimerization processes with one another [9]. In a series of steps, the reaction between isocyanate and water produces the end products urea and carbon dioxide. Carboxylic acid is only created in the first stage as an unstable intermediate that quickly breaks down into carbon dioxide and amine (Figure 2). Urea is formed when the amine interacts with an additional isocyanate group. Since the reaction produces carbon dioxide, which causes foaming (cellular structure), water is frequently utilized as a foaming agent in polyurethane foam production.[9]



*Figure 2: Reaction of isocyanate and water*[10]

Methylene diphenyl diisocyanate (MDI) and toluene diisocyanate are the two most significant isocyanates from an industrial perspective (TDI). Pure MDI, in contrast to the majority of isocyanates, has a melting point of roughly 40 °C and is a solid at ambient temperature. Melting can lead to dimerization and trimerization, thus, caution is advised. Due to their simplicity of handling, their employment in liquid form is more popular in industry; consequently, so-called polymer MDIs or isomer blends are typically used. Different purities of TDIs are employed primarily in the manufacture of flexible foams and other polyurethane goods. Due to its low evaporation point, TDI is substantially more dangerous than the MDI stated above, making it harder to handle and significantly more expensive to establish a facility with TDI due to the greater safety system requirements (extraction system, personal safety sensors) [17].

The two types of polyols which are most frequently used are polyester and polyether polyols. Polyether polyols can be made by copolymerizing propylene oxide with a polyol precursor that is compatible with ethylene oxide or by reacting an epoxide with an active hydrocarbon molecule. Epoxy monomers can also be used to create polyether polyols by using ring-opening



polymerization process. Polyester polyols fall into the second group and are produced by polycondensing hydroxyl compounds and multifunctional carboxylic acids [18].

In addition to the two main components, various additives are used to produce polyurethane foams. Examples include catalyst, surfactant, water, and dyes.

## 2.2 About algae

Algae are photosynthetic organisms. One of the best known species is blue-green algae. Its most popular species is spirulina, which is rich in minerals, high in protein, and has immune-boosting, detoxifying and antioxidant properties. For this reason, it is known as a nutritional supplement. Spirulina is very diverse in its composition. Phycocyanin is a bluish pigment present in spirulina in concentrations of about 7-14%. Spirulina algae also contain a number of vitamins, including B vitamins, vitamin C, vitamin E and the provitamin of vitamin A, carotenoids. Spirulina creates an alkaline environment around itself, which allows it to incorporate large amounts of minerals into its cells. In addition, the minerals absorbed are chelated organically with the amino acids in spirulina, so they are in the form that is most usable by the body. It contains a relatively long list of organic minerals: iron, zinc, calcium, magnesium, potassium, selenium, phosphorus and manganese. Another important component is chlorophyll, which has two main properties: detoxification and alkalinisation. Its mechanism of action is highly complex. Chlorophyll is very rich in oxygen and therefore provides favourable conditions for beneficial bacteria. Spirulina also contains nucleic acids, DNA and RNA, which play a crucial role in the transfer and storage of genetic information. Nucleic acids increase the energy of cells and improve the efficiency of communication between cells, but also slow down the ageing process in the body. Spirulina contains an outstanding amount and quality of protein, with a protein content of around 65-72%. Moreover, its proteins contain all 8 essential amino acids, namely lysine, leucine, isoleucine, methionine, phenylalanine, tryptophan, threonine, and valine. It also contains 10 other non-essential amino acids that are also important for us. Finally,  $\gamma$ -linolenic acid is also part of the composition and is also known to have many health benefits.

Another algae with a high protein content is chlorella, which is a green algae with a high chlorophyll content. It has beneficial effects on the intestinal tract, promotes wound healing and strengthens the body's resistance to stress. Chlorella is a complete food, feeding all the cells in your body. Its main constituents are protein, which makes up 50-60% of its diet, non-essential

amino acids, active vitamin B12, iron and vitamin C, other vitamins and minerals, essential fatty acids, omega-6 fatty acids, antioxidants and chlorophyll, of which chlorella contains 10 times more than spirulina. According to some sources, chlorella has the highest chlorophyll content. The deep colour of chlorella is linked to its high chlorophyll content, but it also contains natural pigments such as lutein.

In addition to their many health benefits, they are also excellent colouring agents. Their colouring property will be exploited in this research. These naturally occurring algae will be applied to colour the synthesized polyurethane foams.

### 2.3 Comparison of natural and traditional colouring pigments

Acrylic, latex, silicone and mosaic are the most commonly used dyes for polyurethane in the industry. As polyurethane is a flammable material, it is usually coated with flame retardant acrylic paints. Natural options include powdered herbs and vegetables. Unfortunately, the colouring of polyurethane foams in this way is not yet widespread. It has the advantage of having a more positive impact on the environment than artificial colourings. In addition, algae is also a good natural colouring agent. Their disadvantage is perhaps that they can change the structure and mechanical properties of the foam. In addition, algae is a much more economical product than artificial colourants. This is illustrated in the table below .

*Table 1: Price comparison of used algae with two artificial pigments*

| Dyes                                | Packaging               | Price      | Price per gram |
|-------------------------------------|-------------------------|------------|----------------|
| Bio Spirulina powder                | 250 g                   | 3 690 HUF  | 14.76 HUF      |
| Bio Chlorella powder                | 250 g                   | 4 990 HUF  | 19.96 HUF      |
| Imunex algae complex                | 122 g<br>(180 capsules) | 11 700 HUF | 95.90 HUF      |
| Pigment orange 5<br>(Sigma-Aldrich) | 1 g                     | 22 900 HUF | 22 900 HUF     |
| Brilliant Yellow<br>(Sigma-Aldrich) | 25 g                    | 55 200 HUF | 2 208 HUF      |

### 3. MATERIALS AND METHODS

#### 3.1 Materials used for polyurethane foams coloured with algae

Ongronat TR4040, a methylene diphenyl diisocyanate isomer mixture (Wanhua-BorsodChem) and Ongropur FFP-303, a polyether type polyol premix (Wanhua-BorsodChem) were used to prepare the foams. The polyol system contains catalysts and other additives such as propellants and surfactants mixed in a base polyol (Alcupol F2831, Repsol). The material ratio (isocyanate index, NCO) is 1.0 isocyanate to 1.0 polyol. Bio Spirulina powder (GymBeam), Bio Chlorella powder (GymBeam) and Imunex algae complex were used as a colouring agent. Two types of methods are used to prepare the foams. The chosen algae were added two different ways: in-situ and premixed one week prior to the foam preparation. The composition of the foams in the case of non-premixed foams is as follows: polyol, algae (1 % by weight) and isocyanate, measured according to the recipe. For the premixed foams, the algae were added in 1, 2 and 5 % by weight one week prior to the experiments and mixed well several times. The isocyanate ratio was the same with all of the tests carried out.

#### 3.2 Polyurethane foam production with FOAMAT 285

Polyurethane flexible foam samples with different algae powders as colorants were made using FOAMAT 285 foam qualification system. This system, Figure 3 measures physical parameters during foam formation. It measures rise height, start time, curing, weight loss and density. A high-resolution pressure sensor within the Advanced Test Container ATC's upgraded technology displays precise cell formation data. The FOAM V4.0 program include density and particular volume curves. By monitoring the foaming process' creation parameters, consistent product quality is achieved. When foam parts with special properties are being developed, measuring the foam formation parameters gives an insight into how the reaction is proceeding and how foam formation can be affected by additives, blowing agents, stabilizers, and the mixing ratio. By offering different types of test containers, the Foam Qualification System FOAMAT combines versatility and high measuring accuracy. Measuring the rise height or rise profile is a common way to describe foams. It is possible to gauge a foam sample's expansion in a cup, box, or cylinder. The increase rate is used to calculate the critical start time. After the reactive components have been mixed, it denotes the beginning of the reaction between them. Another essential foam element is the rise time. It is referred to as the interval between the beginning of mixing and the foam's greatest expansion. The FOAMAT system's proprietary

ultrasonic fan sensor LR4 is specifically made to measure the distance to the foam surface with great accuracy. It has a thermometer, an ultrasonic sound transducer, and an integrated fan to homogenize the air. All kinds of foams, including semi-rigid and stiff foams with potent heat release, flexible moulded and slabstock foams, and rigid foams, can be measured. The expansion containers may be heated to both the necessary reaction temperature and repeatable starting conditions. The rise profile, which serves as the foam's unique fingerprint, is compared to predetermined master curves during quality assurance testing. The borders of a "good" foam sample are shown by a tolerance band known as a master curve.

The rise curve reflects the generation of the blowing agent and the rise pressure reflects the properties of the cell, which are influenced by the polymerisation reaction. The integration of the laboratory balance into the FOAMAT system automatically records the mass of each component in the batch documentation. In addition, the foaming agents and volatile components released during the foaming process and the weight loss due to buoyancy can be continuously recorded. Another advantage of scale integration is the determination of foam density from the mass of the finished foam sample and the final rise height. Typically, FOAMAT experiments are used to measure the physical formation parameters of reactive foam products.[19]



Figure 3: Foam Qualification System FOAMAT 285

### 3.2 Colour measurements

Colour measurement was carried out with a Konica Minolta CM 2600d handheld portable spectrophotometer on the coloured polyurethane foams. Based on the colour space we can characterise colours with three coordinates [20]:

$$a \times b \times L$$

(1)

The different points of colour represent different shades of colour. The „a” indicates the degree of redness or greenness, „b” is the degree of blueness or yellowishness, and „L” indicates the lightness or darkness of the colour.

### 3.3 Mechanical measurements

During the mechanical measurements, Test Method C of ASTM D3574 [21] (complex test standard for flexible polyurethanes) was followed with a modifications in the sample parameters. Cylinders with a 30 mm diameter were cut, which were then divided into equal sections ( $35 \pm 4$  mm) along their height. The samples were subjected to compression tests across their full surface to 50% of their height, and for one minute the force change was measured. The results obtained is the compression force deflection at 50% of the sample height ( $F_{50\%}$ ), which is a well known way at the industries to measure the strength of polyurethane foam samples and other polymeric materials.

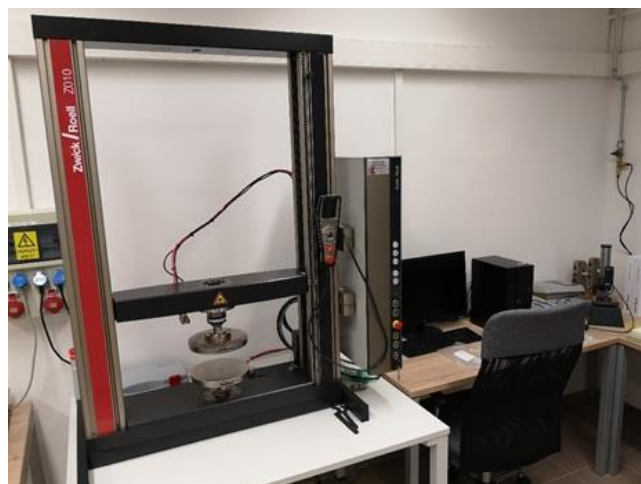


Figure 4: Zwick Roell Z010 Universal Material Testing Machine

### 3.4 Acoustic measurements

The foams produced were tested by mechanical and acoustic measurements to determine their different properties. For the acoustic measurements, an AED 1000 AcoustiTube® impedance tube was used. If necessary, the impedance tube can be upgraded with a module that enables the measurement of the sound transmission coefficient ( $\alpha$ ) of open porous materials and the determination of additional acoustic parameters of the sound-absorbing material in accordance with ASTM E2611 (standard test method for the determination of the acoustic properties of porous materials by the normal incidence transfer matrix method).[23]

The geometry of the impedance tube and the spacing between the microphones place a restriction on the measurement's frequency range. The following are the prerequisites as per EN ISO 10534-2:

Lower frequency limit  $f_1$ :

$$f_1 = 0.05 \frac{c}{s} \quad (2)$$

Upper frequency limit  $f_u$ :

$$f_{u,1} \times d < 0.58 \times c \quad (3)$$

$$f_{u,2} \times s < 0.45 \times c \quad (4)$$

$$f_u = \min(f_{u,1}; f_{u,2}) \quad (5)$$

In all instances, „d” is the impedance tube's diameter (in m), „c” is sound speed (in m/s), and „s” is the separation between the microphones (in m). The measuring tubes employed in this investigation had an internal diameter of 30 mm, hence the useful frequency range was 150-6600 Hz. The aforementioned extension can also be used to calculate the sound transmission factor. At least two microphones are required to carry out the measurements in accordance with the specification. In this instance, three microphones were employed, allowing lower- and upper-frequency readings to be made in one measurement. With the help of the microphones, the sound pressures were measured, and the transfer functions between them were calculated as follows:

$$r = \frac{H_{12} - H_1}{H_R - H_{12}} e^{2jk_0 x_1}$$

(6)

where  $H_{12}$  is the transfer function between microphone 1 and microphone 2,  $H_R$  is the transfer function of the reflected wave,  $H_1$  is the transfer function of the incident wave,  $k_0$  is the wave number, and  $x_1$  is the distance between the sample and the farthest microphone (in use). On the basis of this equation, the normal incidence sound absorption coefficient ( $\alpha$ ) can be calculated as follows:

$$\alpha = 1 - |r|^2$$

(7)

A total of three equal sections of cylinders with a 30 mm diameter were cut out along the 95 mm height of the entire sample. In order to assess the impact of the samples' prolonged use as sound insulation, acoustic measurements were taken both before and after aging.[22]

## 4. RESULTS AND DISCUSSION

### 4.1 Polyurethane foams with different amounts of alga



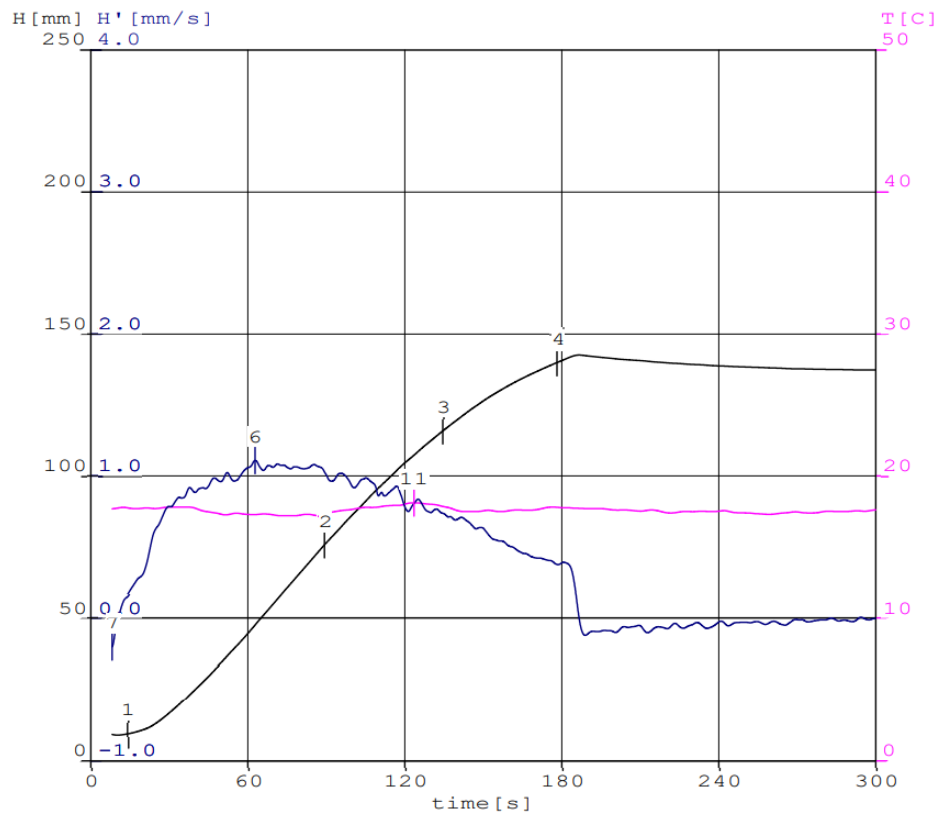
Figure 5: Spirulina premixes



Figure 6: Chlorella premixes



Figure 7: Freshly made polyurethane foams with algae



*Figure 8: 5% spirulina premixed foam Foamat test results*

The FOAMAT results of the 5% spirulina premixed foam is highlighted in the Figure 8. This foam was found to have the highest density (67.2 g/l). The black curve in the graph illustrates that the foam did not decrease much after reaching its maximum height. The pink line shows the temperature of the foam, but the temperature sensor was not used in this case, and the blue curve shows the rate of foaming, which starts abruptly and then levels off. Overall, it can be said that the foams obtained with different amounts of algae were all stable and of adequate quality.

#### 4.2 Colour measurement results

Samples were measured with a Konica Minolta CM 2600d handheld portable spectrophotometer. The colorimetric results were compared with the results measured on standard foam. The results are summarised in Table 2: Colour measurement results compared on reference sample and foams.

*Table 2: Colour measurement results compared on reference sample and foams*

| Reference foam | SCI   | SCE   |  | Algae mix    | SCI   | SCE   |
|----------------|-------|-------|--|--------------|-------|-------|
| L              | 80.37 | 80.32 |  | $\Delta L$   | -3.44 | -3.38 |
| a              | -1.05 | -1.00 |  | $\Delta a$   | -0.08 | -0.09 |
| b              | 7.08  | 6.94  |  | $\Delta b$   | -0.52 | -0.53 |
|                |       |       |  | $\Delta E$   | 3.47  | 3.42  |
|                |       |       |  |              |       |       |
| Spirulina 1%   | SCI   | SCE   |  | Chlorella 1% | SCI   | SCE   |
| $\Delta L$     | -4.91 | -4.89 |  | $\Delta L$   | -7.57 | -8.1  |
| $\Delta a$     | -0.03 | -0.03 |  | $\Delta a$   | -0.73 | -0.77 |
| $\Delta b$     | 1.03  | 1.05  |  | $\Delta b$   | 2.51  | 2.84  |
| $\Delta E$     | 5.02  | 5.00  |  | $\Delta E$   | 8.01  | 8.62  |
|                |       |       |  |              |       |       |
| Sp.premix 1%   | SCI   | SCE   |  | Ch.premix 1% | SCI   | SCE   |
| $\Delta L$     | -5.35 | -5.38 |  | $\Delta L$   | -11.9 | -12.2 |
| $\Delta a$     | -0.64 | -0.65 |  | $\Delta a$   | -1.13 | -0.95 |
| $\Delta b$     | -0.75 | -0.77 |  | $\Delta b$   | 9.61  | 9.5   |
| $\Delta E$     | 5.44  | 5.47  |  | $\Delta E$   | 15.3  | 15.5  |
|                |       |       |  |              |       |       |
| Sp.premix 2%   | SCI   | SCE   |  | Ch.premix 2% | SCI   | SCE   |
| $\Delta L$     | -16.4 | -16.7 |  | $\Delta L$   | -18.7 | -17.4 |
| $\Delta a$     | -1.16 | -1.12 |  | $\Delta a$   | -1.27 | -1.22 |
| $\Delta b$     | -0.89 | -0.88 |  | $\Delta b$   | 11.3  | 11.8  |
| $\Delta E$     | 16.47 | 16.76 |  | $\Delta E$   | 21.9  | 21.1  |
|                |       |       |  |              |       |       |
| Sp.premix 5%   | SCI   | SCE   |  | Ch.premix 5% | SCI   | SCE   |
| $\Delta L$     | -21.1 | -21.3 |  | $\Delta L$   | -26.1 | -26.1 |
| $\Delta a$     | -1.33 | -1.34 |  | $\Delta a$   | -1.80 | -1.73 |
| $\Delta b$     | -1.34 | -1.39 |  | $\Delta b$   | 9.49  | 9.38  |
| $\Delta E$     | 21.18 | 21.39 |  | $\Delta E$   | 27.8  | 27.7  |

The SCI column shows the value with reflection, the true colour of the material, and the SCE column shows the value without reflection, the apparent colour. The "L" indicates the colour saturation, as mentioned above, and can vary between 0 and 100 (towards 100 indicates light, white colour, towards 0 indicates dark, black colour). The "a" represents greenish (-) or reddish (+), and the "b" describes blueness (-) or yellowish (+).

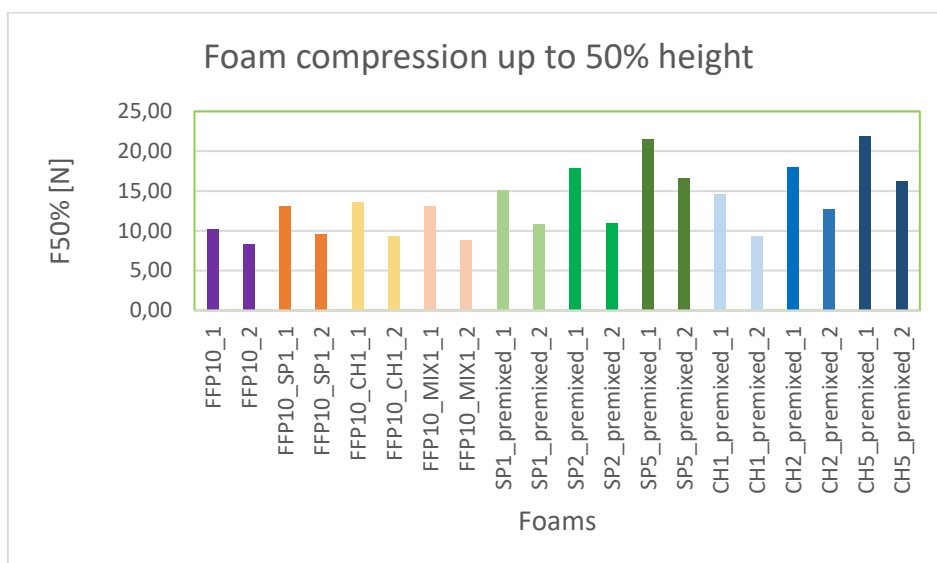
The "E" indicates the relationship of the colour difference, if the value reaches 6, there is a significant colour change. In our case, the colour of the premixed foams is very different from

the standard foams, this is clearly visible to the human eye and is also shown by the value of "E". As can be seen, except for two cases (Spirulina 1% non-premixed and premixed), the colour change is considered significant as the value of delta  $\Delta E$  is above 5. In both cases, the degree of colour change also increased with the amount of algae. Greening and yellowing can be seen when Chlorella is added, whereas blueing and greening can be seen when Spirulina is added. This is clearly visible to the human eye, but the present measurement supported our observations.

#### 4.3 Mechanical test results

According to ASTM D3574 C, ten samples with different compositions were subjected to compression tests. The force was measured at 50% of the original height of the sample after 1 minute. All of the samples are stoichiometric mixtures of 1 isocyanate:1 polyol reactive functional groups (NCO-index=1.0). The tests are performed on two types of test specimens: samples containing the skin surface and samples from the foam volume (without skin). Figure 9 contains the results of the measurements. At the end of the names, \_1 stands for samples with skin surface and \_2 is for measurements on the inside. For comparability, a standard foam was also measured with a skin surface and inside. Samples were prepared with the addition of spirulina and chlorella algae powder (FFP10\_SP1\_1, FFP10\_SP1\_2, FFP10\_CH1\_1 and FFP10\_CH1\_2), and a foam containing algae mix complex (FFP10\_MIX1\_1, FFP10\_MIX1\_2). The polyol system contains 1 % by weight of algae powder. There is no significant change in these foams compared to standard foams.

There are also prepared foams that are made from premixes ("\_premixed" added in their name). Polyol premixes containing algae powder were stored for a week, and then cup experiments were performed with these premixed foams. In this case, 1%, 2% and 5% of the polyol system is algae powder. The test results show that there is a significant difference between standard foam and premixed foam. Especially for the foam with 5% algae content, when a sample with the skin surface is tested. This is due to the fact that the skin on the foam surface is much more dense (and thus harder) than the skin inside the foam. This means that the algae powder is probably compacted on the structure of the foam.



*Figure 9: Results of the compression set test according to ASTM D3574 C. Outstanding values are observed for the skin surface of premixed foams with the highest algae content (SP5\_premixed\_1 and CH5\_premixed\_1).*

Spirulina and chlorella behave in a similar way. However there is a significant difference in the inside quality, since the foam prepared with 5% chlorella algae premix is poorer. As the Figure 10 shows, it is deficient. This failure may be due to the fact that the cup experiment was not the most successful.



*Figure 10: 5% chlorella algae premixed foam inside*

#### 4.4 Acoustic measurements results

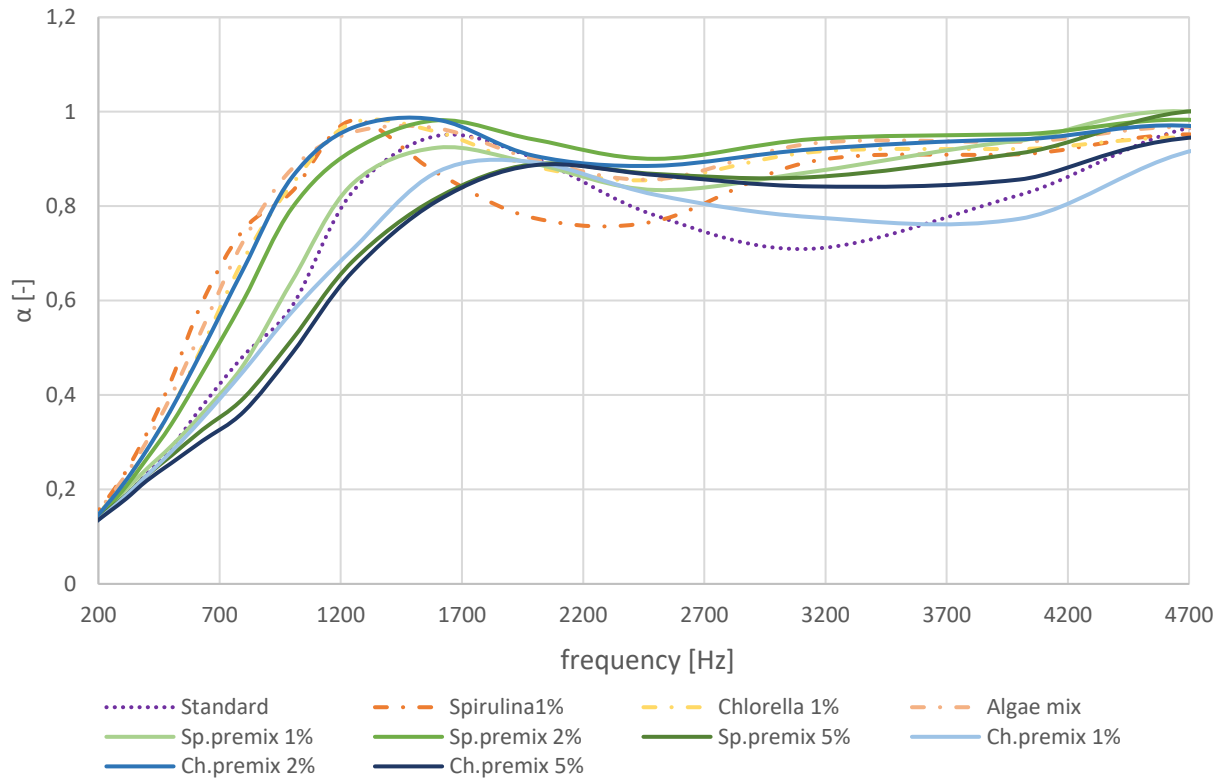


Figure 11: Average curves of the sound absorption coefficient ( $\alpha$ ) over the frequency range 200-4700 Hz. The purple dotted line indicates the sound absorption of the standard foam.

A standard foam was first tested to compare the sound absorption of the foam. The algae foams were measured on the skin surface and then inside. After evaluation, it was observed that the foam with a skin surface absorbed less sound. This is due to the fact that the skin surface is much harder and denser than the foam inside. At higher frequencies, the relatively dense skin has a high flow resistance, so sound waves can penetrate it less and the foam underneath cannot have the same sound absorbing effect as without the skin.

The measurements are shown in the picture, demonstrates that the 2% premixed foams approached  $\alpha=1$  the fastest, then decreased a little, but stayed around 1. This means that the sound absorption of the 2% premixed foams is the best of the algal foams, even better than the sound absorption of the standard foam. The local maximum of the 2% chlorella premix is 1250 Hz, after which the absorption coefficient value decreases, but at higher frequencies it increases again to 1. For the 2% spirulina premix foam,  $\alpha=1$  was most closely approached at 1600 Hz,

then the coefficient value also decreased, and finally an increase was observed at higher frequencies.

## 5. SUMMARY

In summary, during the tests, the algae foams behaved in surprising ways depending on their preparation. A standard foam was always available for comparison. The colour change in premixed foams can be seen with the human eye, most obviously with the 5% premixes, especially the chlorella algae and the colour measurements confirmed this observation. It is found that the chlorella algae is the best colouring agent for the foam. Mechanical tests were also conducted to measure the strength of the foams with the help of standardized compression tests, summarised in the Table 3. The algae powders made the foam considerably harder, the most significant change in hardness was achieved with the 5% premixes, for an example the 5% spirulina premix foam was twice as hard as the standard foam. For this reason, 5% premixes can be used when the aim is to increase the load-bearing capacity of the foams.

*Table 3: Compression force deviation from standard foam expressed as a percentage*

|               | <b>Spirulina 1%</b> | <b>Chlorella 1%</b> | <b>Algae mix</b>    |
|---------------|---------------------|---------------------|---------------------|
| Skin surface  | 1.27%               | 1.32%               | 1.28%               |
| On the inside | 1.15%               | 1.13%               | 1.06%               |
|               | <b>Sp.premix 1%</b> | <b>Sp.premix 2%</b> | <b>Sp.premix 5%</b> |
| Skin surface  | 1.47%               | 1.74%               | 2.10%               |
| On the inside | 1.31%               | 1.33%               | 2.00%               |
|               | <b>Ch.premix 1%</b> | <b>Ch.premix 2%</b> | <b>Ch.premix 5%</b> |
| Skin surface  | 1.42%               | 1.76%               | 2.14%               |
| On the inside | 1.13%               | 1.54%               | 1.97%               |

Acoustic tests have shown that 2% premixed foams absorb sound the best, while 5% premixed foams absorb less sound. The sound absorption of the non-premixed foams reflects the lack of proper homogenisation. Therefore, for acoustic applications, 2% premixed foams are recommended.

### 5.1 Future plans

My goal is to work with other types of dyeing, mainly natural dyes will be tested. Turmeric powder, beet powder and carotene sound promising. Artificial dyes are also interesting, but it



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has to be studied to what extent they change the structure of polyurethane foams. Another interesting topic is making bio-composites from ceramic rubble thought to be rubbish.

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