Bio-Concrete with Natural Fibres

Optimizing concrete mixture containing Miscanthus fibres for insulation bricks

Study year 2021/2022, Semester 2

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Research Report

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Abstract

The focus of this research is to optimize the bio-concrete mixture design containing natural plant-based fibres as well as to investigate and describe the properties of the developed materials. The main goal of the project is to produce a bio-concrete design that is sufficient to be used as an insulation material, for which the required minimum compressive strength is 2,5 MPa. The aggregates used for the bio-concrete are sand (0-4 mm) and gravel (4-16 mm), the cement is type CEM I 52.5 R and the natural fibres are Miscanthus of size 0,5-2 mm. The Miscanthus fibres are pre-treated with a slurry of cement and water with a 1:1 ratio. In addition to enhancing the bonding between the fibres and the concrete mixture, the purpose of the pre-treatment is to improve the hydrophobic properties of the natural fibres. In this paper, five different bio-concrete mixtures with increasing Miscanthus content are created, tested, evaluated and compared in order to achieve the set goals. The tests carried out assist in understanding the properties of the developed materials. The investigated properties are the workability, the density, the compressive and tensile strength and the thermal conductivity. An additional test regarding the importance of pre-treating the fibres is conducted as well. In general, the outcome of the tests prove, that the compressive strength of the bio-concrete is influenced by the Miscanthus fibre content and it is concluded, that it is necessary to conduct the fibre pre-treatment. However, the thermal conductivity of the different bio-concrete mixtures was significantly affected by the roughness and thickness of the produced samples. Afterwards, a Multi-Criteria Analysis (MCA) was implemented to assess and evaluate the five different mixtures based on the test results and the requirements of the client. The investigated criteria were the Miscanthus fibre content, thermal conductivity, cement content, density, compressive strength and workability of the bio-concrete. The mixture with the 2nd highest fibre content (21,4% of the overall volume), the highest average compressive strength (34 MPa) and the lowest cement content (13% of the overall volume) appeared to be the most preferred bio-concrete design based on the evaluation after the MCA.

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1. Introduction

The aggregates of conventional concrete are gravel, usually sized between 4-20 mm, and sand of 0-4 mm of particle size. These materials are produced by mining or are taken from quarries, however, the availability of the sources is limited as they are non-renewable. The idea of plant-based fibres in concrete has been applied in earlier days and has been a topic for research regarding sustainability in construction. The project of making bio-concrete with natural fibres described in this report is related to a previous research, Viberscrete, carried out by Adebiyi (2021). Miscanthus was chosen as the plant-based fibre to be mixed into the mortar. The focus of the work was mainly to find the most feasible method of fibre pre-treatment, as well as to maximise the amount of Miscanthus fibres in the concrete mixture and to optimize the consistency of the mixture for production in the future. The research to learn more about the possible applications of bio-concrete continues based on the results.

The current project is a joint effort between the research group Centre of Expertise Biobased Economy (CoEBBE), the companies De Hoop and Vibers. The intention of a bio-based economy is to utilize biomass instead of fossil fuels to manufacture not edible products, such as materials, chemicals or transport fuel. The organisation Centre of Expertise Biobased Economy is a collaboration between HZ University of Applied Sciences and Avans University, which was established by the Ministry of Education in the Netherlands. The goal of CoEBBE is to link higher education to the economic priorities of the region by helping companies achieving their bio-based ambitions while offering students the opportunity to be involved in designing the transition to a bio-based society. CoEBBE is referred to as the client in this project. De Hoop is a family-owned company that produces and provides building materials, structural products to contractors for both residential and non-residential constructions. The company aims to meet the sustainability requirements of the future by testing innovative ideas, such as bio-concrete. Furthermore, De Hoop have the ambition to normalise standardised homes by creating prefabricated three-dimensional frames, meaning that the floors and the walls are made in one step. The units may be joined together, put on top of each other with the possibility of adding further extensions later, if necessary or desired. The other company, Vibers, has already collaborated with the research group CoEBBE for the previous project, Viberscrete, about bio-concrete with Miscanthus fibres. One of the latest goals of the company is realise a bicycle path made of bio-concrete containing Miscanthus.

1.1 Background

The construction industry is one of the largest industries in the world, and due to the constant need of restoration and new structures, it is still growing. As the most common conventional construction material, concrete has often been used in structures of extensive range from residential homes to monumental buildings to bridges. It is a relatively strong and durable material, as an example, the Pantheon in Rome has been standing since ancient Roman times. Versatility adds to the advantages of concrete, as it may be produced on construction sites or be pre-fabricated in a factory and it is suitable for constructing walls, floors, staircases. The possibilities of the application of concrete in construction are nearly limitless.

A well-known disadvantage of concrete besides its large self-weight is that the production of the cement has a high carbon footprint. According to the World Business Council for Sustainable Development (2018) the production of cement is accountable for consuming 7% of energy in the industrial sector and qualifies as the second largest carbon-dioxide emitter in the world, also with 7%. According to Hasanbeigi et al. (2012), the process of calcination produces approximately half of the total CO_2 emitted, while the remaining amount is released due to the burning of fuel that provide the thermal energy for the manufacturing of cement. With the growth of population, the demand of the expansion of existing towns and cities is rising, which results in the increase of the global cement production. The emission of CO_2 contributes to the greenhouse effect and therefore to the accelerated changing of the climate. As described by Hasanbeigi et al. (2012), there are technologies that are aiming to reduce CO_2 emissions and the energy consumption in the construction sector by, for example, using alternative raw materials or capturing carbon.

Another factor that may further contribute to energy consumption concerning concrete is its ability to retain heat. When a material has a relatively high thermal conductivity, it allows heat to be transferred through it. Therefore, if a building is constructed only using materials that perform poorly in this regard, it results in an increased demand of energy to keep a certain temperature inside the building. According to findings of different researches, Kim et al. (2003) and Kodur en Khaliq (2011), the thermal conductivity of concrete ranges between 1,7-3,3 W/(m K), depending on the composition of the concrete matrix. These are considered as higher values, therefore the application of insulation materials is essential for concrete buildings to prevent wasting energy. In comparison, the thermal conductivity of traditionally used insulation materials according to review by Schiavoni et al. (2016) is 0,03-0,05 W/(m K) for different types of wool, 0,04 W/(m K) for cellulose, 0,031-0,037 for polystyrene. The same review by Schiavoni et al. (2016) includes information about the thermal conductivity of some unconventional insulation materials, such as date palm with ~0,08 W/(m K), pineapple leaves with ~0,04 W/(m K), recycled cotton with ~0,04 W/(m K) and several types of recycled textiles ranging between 0,036-0,053 W/(m K).

Sustainability is present in most aspects of the lives of people and it is becoming more and more important in order to be able to provide a liveable future for the coming generations. The use of bio-based materials and limiting the consumption of fossil fuels and materials produced from non-renewable resources is more commonly promoted. Recycled concrete from previously demolished structures may also be put to use again by crushing and adding it into a new mixture as coarse aggregates. This method may require less newly extracted gravel and sand and therefore results in decreased consumption and construction waste production as well as contributes to circularity. Furthermore, reusing materials made of non-renewable resources, such as plastic, is rapidly increasing. For instance, Hamdi et al. (2020) elaborates on reusing shredded tyres as concrete aggregates. The findings include that some properties of the concrete, such as the resistance to erosion, freeze and cracking, were enhanced. One of the disadvantages is that the workability of the mortar decreases as more rubber is added, however it can be improved by the pre-treatment of the rubber or by the addition of plasticizers. The compressive strength of the concrete also decreases with the increase of rubber content, which seems to be the tendency with alternative aggregates in general.

It is possible to use more natural materials in concrete production, such as plant-based fibres. Research by Pacheco-Torgal and Jalali (2011) reviews the possibilities of using several different vegetable fibres, including banana leaf, coconut coir, eucalyptus, etc., to reinforce building materials. In general, beyond being environmentally friendly, the natural fibres appear to be cost-effective and perform similarly regarding tensile strength compared to synthetic materials, such as polypropylene or PVA. However, the idea of infusing concrete with different natural materials, such as plant-based fibres has been around and has been implemented long before the modern days.

Originally, the optimization of bio-concrete containing bamboo fibres was to be the topic of the project. A company called BambooLogic showed interest in collaborating for the research by providing natural bamboo fibres. The company has several growing fields in Portugal, France and Belgium, therefore they are able to provide an option to manufacture products made out of bamboo, that is grown in Europe. The main hindering factor that prevented the realisation of the collaboration is that although the company already harvested their first crops and was able to fabricate prototypes of some products, the production of bamboo fibres is out of their expertise. Therefore, due to the lack of material, the topic of the research was changed to be about bio-concrete with Miscanthus fibres based on the findings of the Viberscrete project. However, the focus of the current project is different, the aim is to further increase the Miscanthus fibre content of the concrete and inspect its thermal insulation properties.

1.2 Problem statement

As the production of cement has a negative impact on the environment, the possibilities of lowering the cement content of concrete by using natural fibres is crucial to consider. The conventional aggregates are taken from limited resources that are continuously diminishing, because the rate of reproduction is much slower than that of extraction due to the high demand. For this reason, the plant-based fibres can be a sustainable alternative to gravel and sand as aggregates in the concrete mixture.

Advantages of the application of natural plant-based fibres include that they come from renewable sources. Plants not only produce oxygen while growing, but also retain carbon instead of releasing it back into the environment. Furthermore, it is possible to reduce the self-weight of concrete without losing strength by partially replacing aggregates with plant-based fibres, because the fibres are lighter than sand and gravel. The tensile strength of concrete may also improve due to the flexibility of the natural fibres.

A variety of organic and inorganic materials are used for insulating buildings. The performance of thermal conductivity differs depending on the materials. Based on comparison made by Schiavoni et al. (2016), regarding thermal conductivity and fire resistance, plant-based fibres perform similarly to synthetic materials while having lower density. However, concrete in general has higher fire resistance, therefore bio-concrete with Miscanthus fibres could provide a potentially less combustible alternative as insulation.

1.2.1 Research questions

The main research question is as follows:

What is the most optimal ratio of components in concrete mixture with natural Miscanthus fibres to achieve sufficient thermal insulation properties?

Sub-questions:

- What are the possible pre-treatment methods for Miscanthus fibres intended to be mixed into concrete?
- Which pre-treatment method is the most feasible for this project?
- What are the requirements for the final product as insulation material regarding thermal conductivity?
- What are suitable testing methods to find out the insulation performance of the bio-concrete?
- In which scenarios may the final product be used as thermal insulation?
- What could be potential forms of application of the final product?

1.2.2 Objective

The objective of this project is to conduct desk research as well as laboratory tests to develop the most optimal ratio of natural Miscanthus fibres in concrete mixture so that the final product is sufficient as a material for the production of insulation bricks. As it is meant to serve the purpose of heat retention or protection rather than to act as a structural element, the final product should have the minimal compressive strength of at least 2,5 MPa. The produced bio-concrete cubes are going to be tested for compressive strength, tensile strength and insulation performance (thermal conductivity).

1.3 Boundary conditions

The starting points are provided based on previous research carried out by Adebiyi (2021). In order to be able to compare the results, the same method of fibre pre-treatment with cement is going to be applied. Furthermore, the control mixture for this project is going to be the mixture with the previously maximized amount of Miscanthus fibres within the concrete matrix. The ratio of fibres in that mixture was stated as 50,5% in volume and the achieved compressive strength was 35,13 MPa. Therefore, the amount of fibres added into the mixture is going to be increased in this project for a higher percentage of fibres and a lower strength. Further tests of durability and fire resistance are to be conducted, however said tests are outside of the scope of this report.

Particle size of materials to be used:

- Gravel: 4-16 mm;
- Sand: 0-4 mm;
- Miscanthus: 0,5-2 mm.

The produced bio-concrete block should:

- have minimum 2,5 MPa compressive strength;
- be sufficient for thermal insulation purposes;
- comply with the applicable regulations.

2. Theoretical Framework

2.1 Miscanthus

Miscanthus (x Giganteus), also called elephant grass, is a perennial grass that grows up to a height of 4 m. As described by Lewandowski et al. (2000), Miscanthus is originally from tropical regions of the world, however the plant has a high tolerance of different weather conditions, which made it possible to start the cultivation of the crop in Europe as well. For instance, the company Vibers create their products using Miscanthus that is grown in the Netherlands, which makes it possible to reduce the carbon-footprint of the production as well as the transportation. Furthermore, research by Dias and Waldmann (2020) states some ecological and economical benefits of Miscanthus, which are its low necessity of application of pesticides and fertilisation, as well as it contributes to the decrease of groundwater pollution.

Research by Dias and Waldmann (2020) explains that the cross-section of Miscanthus is constituted of four different types of tissue in three layers:

- the epidermis (Ep), which is the protective layer on the outside;
- the sclerenchyma (Sc), which provides support for the structure of the plant;
- the vascular bundles (Vb), which supportive and protective tissues;
- and the parenchyma tissues (Pa) on the inside section, which are accountable for photosynthesis and the commutation of gases.

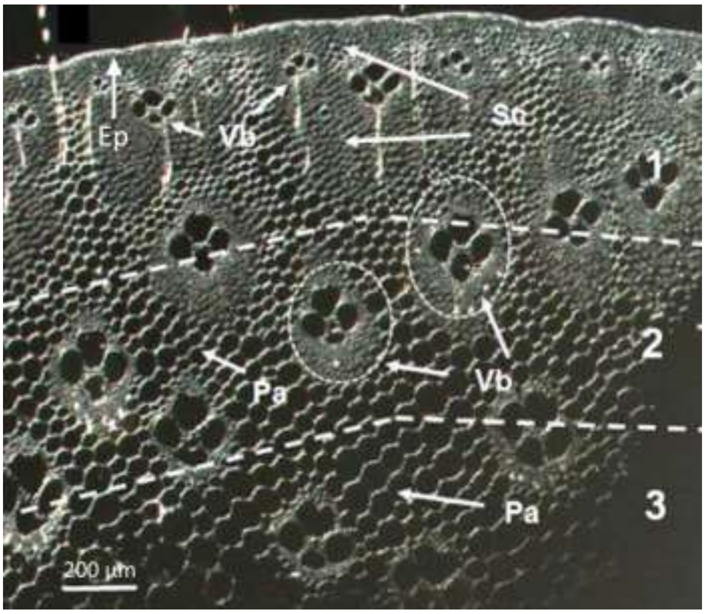

Figure 1. Miscanthus cross-section (Chabbert et al., 2017)

The natural Miscanthus fibres are typically used to produce energy and bio-fuel or they are applied for their high water absorption capacity. In addition, the fibres are suitable to be used as aggregates for production of lightweight bio-concrete, however conducting further research is required to learn more in detail about the properties of mentioned bio-concrete as well as the possible applications.

2.2 Pre-treatment methods

In most cases plant-based fibres undergo a sort of pre-treatment before added into the concrete mixture. The purpose of pre-treatment is to increase the performance of fibres regarding strength or adhesion between the fibres and cement. There are various methods, such as the use of alkali, water glass or cement pre-treatment, which assist in achieving the desired effect.

2.2.1 Alkali pre-treatment

The method of plant-based fibre pre-treatment with alkali, such as NaOH (sodium hydroxide) or $Ca(OH)_2$ (calcium hydroxide) which are often used, removes the pollution from the fibres. According to research on sisal fibres by Toledo Filho et al. (2009), the treatment with alkali decomposes the fibre which increases the overall surface area of the fibres in the mortar as well as creates a coarser surface for an enhanced adhering performance.

Adebiyi (2021) conducted the testing of alkali pre-treatment of Mischanthus fibres. Two different sizes of fibres were used for the treatment, one being 0,5-2 mm and the other 2-10 mm. The fibres were soaked in 5%wt solution of NaOH for an hour and were rinsed and left to dry for 7 days before mixing into concrete. According to the results of the strength tests, the concrete with the smaller fibres performed stronger both in compression and tension compared to the mixture with the 2-10 mm fibres.

As observed and described by Adebiyi (2021), the downside of alkali pre-treatment is that the solution has to be rinsed off completely, otherwise the alkali deteriorates the fibres in the mixture. The reaction hinders the setting process of the concrete, as well as causes a reduction of strength.

2.2.2 Water glass pre-treatment

Sodium silicate, also referred to as water glass, acts as a water repelling agent by filling the pores of the coated materials. It is applied in a number of scenarios, for example as an alternative food preserving agent, as a flocculant in wastewater treatment or as a fireproofing layer of surfaces. In research by Martínez Suárez et al. (2021) the mechanical properties of two types of treated and untreated natural fibres, hemp and fique, are compared. First the fibres to be treated were immersed in different concentrations of NaOH for various time periods after which the samples were dried for 42 hours. The dry samples were then submerged in water glass solution of 68% for 24 hours and added to the cement mortar. After testing the compressive and tensile strength of both types of treated and untreated fibres Martínez Suárez et al. (2021) found that the tensile strength of the treated fibres was favourable compared to the untreated fibres in both cases. However the results of the compressive strength tests show that the sample with treated hemp fibres performed better, while the concrete with untreated fique fibres achieved higher strength.

2.2.3 Cement pre-treatment

Based on research by Ezechiels (2017), the cement creates a water resistant coating on the surface of the natural fibres, therefore reduces water absorption by the fibres. The layer of cement also creates a rough surface which enhances the bond between the fibre and the concrete mixture. The method was tested by Adebiyi (2021) using two types of Miscanthus fibres of larger (2-10 mm) and smaller (0,5-2 mm) sizes. According to the results presented in the research of Adebiyi (2021), the concrete mixture containing smaller fibres achieved a higher compressive strength compared to the concrete with larger fibres, however the tensile strength was found to be less for the 0,5-2 mm fibres. In the same research, the cement pre-treatment was compared with alkali pre-treatment. Considering the strength of the concrete produced with the treated fibres as well as the method of treatment, it was concluded that the cement pre-treatment is the overall more preferred method. The Figures 2 and 3 below represent the comparison of the strength of concrete made with both types of pre-treated fibres of both sizes.

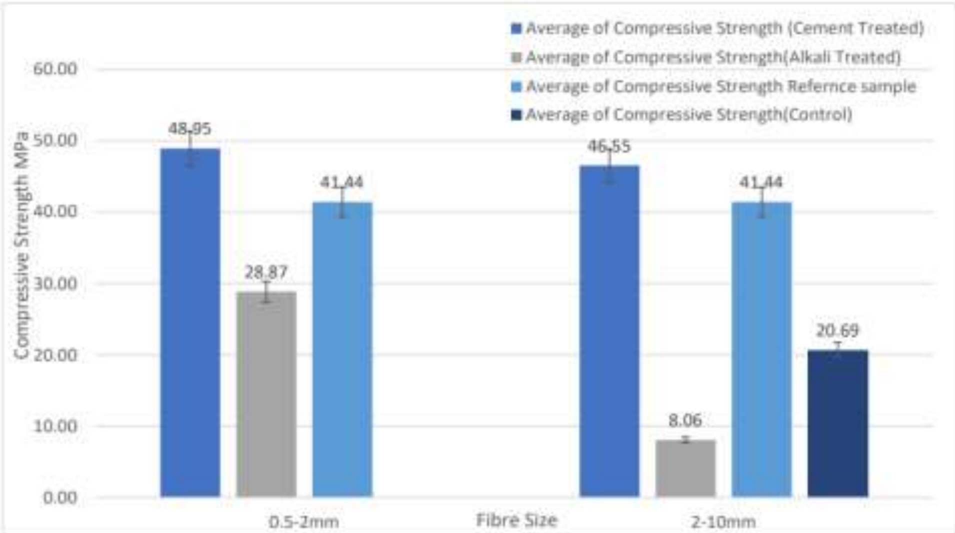

Figure 2. „Compressive strength of tested samples" (Adebiyi, 2021)

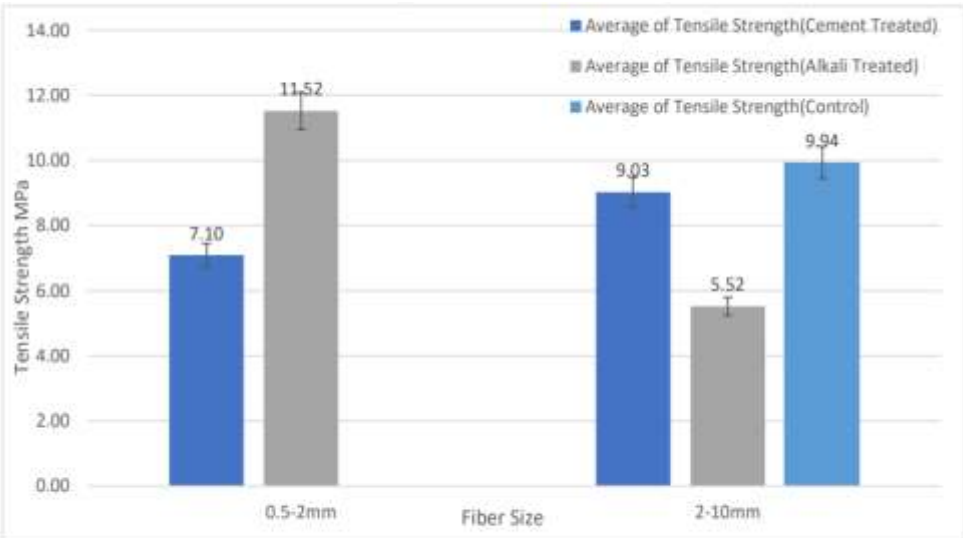

Figure 3. „Tensile strength of tested samples" (Adebiyi, 2021)

2.3 Insulation

The energy consumption of a building is highly affected by the thermal properties of the material that was used to construct the walls, the floors as well as the roof. Therefore, the purpose of the application of insulation is to retain heat or a certain temperature and sound inside or outside of a structure. Insulation increases the energy conservation of a building which is beneficial both in the aspect of expenses, as less energy is required to maintain a constant temperature inside, and sustainability, due to the decreased energy consumption and therefore minimized wasting of energy.

2.3.1 Acoustic insulation

In general, the waves of sound are transmitted through air and when the wave reaches a surface, it may be reflected or absorbed, which depends on the material that the surface is made of. Installing acoustic insulation is beneficial for decreasing the noise pollution inside or outside of a structure or room. For instance, soundproofing is often used for sound recording rooms, where the purpose is to keep any disturbing noises outside and to prevent the formation of echo.

The acoustic insulation performance of a material is determined based on its ability to absorb and/or to resist the transmission of sound waves. As described by Schiavoni et al. (2016), sound absorption is dependent on the movement of the air inside the pores of a material, therefore porous materials are preferred sound absorbers and often perform well as thermal insulators. According to comparison by Aditya et al. (2017), the conventional thermal insulators with the highest sound absorption are polyurethane, rock wool and fibreglass. However, the transmission of sound is dependent on the mass of the material, and as a consequence a higher mass usually results in a higher acoustic insulation.

2.3.1.1 Testing

Research review by Schiavoni et al. (2016) states that the acoustic testing of materials may be conducted both on small or real-sized samples. It is possible to conduct tests on site, in laboratories, in a reverberation room or in an impedance tube. Several standardised methods are available for the assessment of sound absorption as well as of acoustic insulation.

2.3.2 Thermal insulation

A barrier preventing heat transfer is created by installing thermal insulation in structures. Thermal insulation may be applied for residential buildings as well as for commercial or industrial structures to reduce energy consumption. According to a report for the EU Reference Scenario 2016 about predicting trends of energy, transport and greenhouse gas emissions until 2050, more than half of the energy demand in the residential sector is a result of heating, illustrated on Figure 4. The demand is expected to decrease, however it remains a significant portion of the overall energy consumption. The application of thermal insulation is therefore advantageous for energy efficiency and financial savings on the long term.

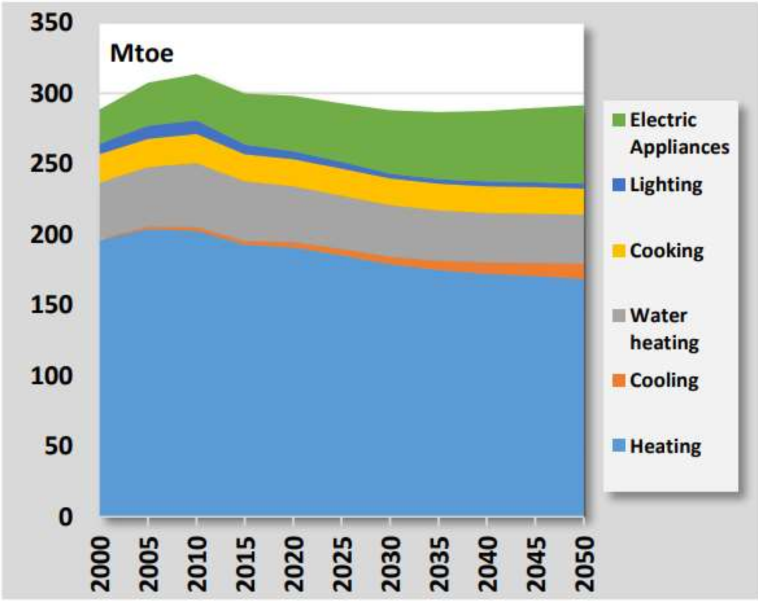

Figure 4. Expected trend of residential energy demand in Europe (EU Reference Scenario 2016)

Several materials are frequently used for thermal insulation, which are referred to as commercial or conventional insulation materials. Examples are stone wool, glass wool, polystyrene, phenolic foam, cellulose, wood and hemp fibres or sheep wool. Unconventional or alternative materials often include different natural fibres such as hemp, oil palm or date palm; other natural materials such as cotton, bagasse or rice. Recycled materials for unconventional thermal insulation are usually textiles, glass and plastic. The thermal properties of materials that are considered for insulation are the thermal conductivity, the thermal diffusivity and the specific heat.

2.3.2.1 Thermal conductivity

The performance of a material as a thermal insulator is defined by its thermal conductivity coefficient (λ) in steady state. The materials with the lowest values of the thermal conductivity coefficient are considered the most optimal for thermal insulation. Colour-coded table in research by Asdrubali et al. (2015) provides a range for good, intermediate and poor thermal insulation performances based on the thermal conductivity of unconventional insulation materials:

- good: 0–0,056 W/(m K);
- intermediate: 0,056–0,1 W/(m K);
- poor: > 0,1 W/(m K),

however, the ranges are applicable to any other material to determine its performance as thermal insulation.

The thermal conductivity highly depends on the type of material, however the tendency is that it is influenced more by the density of the material rather than its origin, whether it is organic or synthetic. As a consequence, a higher density commonly results in a higher thermal conductivity coefficient and a less favourable insulation efficiency. For instance, the density of polystyrene is 15-40 kg/m^3 and its thermal conductivity coefficient is

0,031-0,038 W/(m K), while the density of mineralised wood fibres varies between 320-600 kg/m^3 with a λ of 0,06-0,107 W/(m K).

The properties of different types of concrete vary based on the intended application. Kim et al. (2003) found, that the thermal conductivity of the concrete is highly affected by the volume of aggregates and the moisture content, as results differed in wet and dry conditions. Asadi et al. (2018) presented reviewed information about the thermal conductivity of several types of cement based materials with relatively low densities, including foamed concrete, oil palm shell (non-)foamed geopolymer concrete, polystyrene foamed concrete as well as more conventional concrete. The thermal conductivity of the cementitious materials assessed in the review range from 0,08 W/(m K) with the density of 150-200 kg/m^3 to 3,85 W/(m K) with the density of 2810 kg/m^3. Furthermore, Asadi et al. (2018) revealed the correlation between thermal conductivity and density based on the data retrieved from literature (Figure 5).

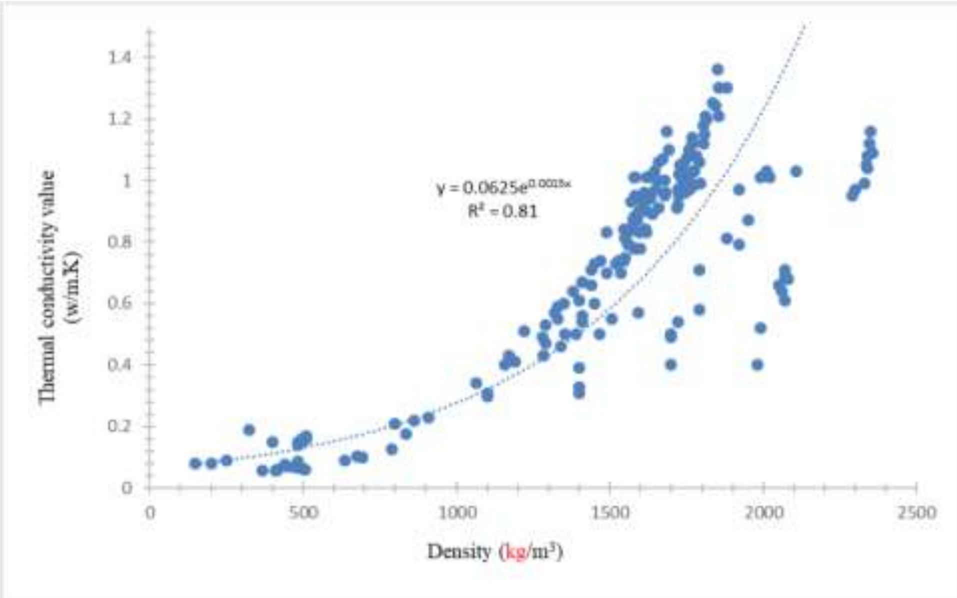

Figure 5. Relation between thermal conductivity and density of materials (Asadi et al., 2018)

Available data about the thermal conductivity of Miscanthus is in research by Schnabel et al. (2019). The experiment described is about the pre-treatment of maize and Miscanthus fibres with the method of steam explosion to achieve sufficient thermal insulation properties. During the treatment, the fibres were exposed to steam of 200°C for 20 minutes after which the fibres were dried and the remaining moisture content was 6-12%. The thermal conductivity of the fibre samples was measured and the average value for Miscanthus fibres was roughly 0,047 W/(m K).

2.3.2.2 Testing

There are several methods to test or measure the thermal conductivity of a material, such as steady state boxes method, steady state hot plate method, transient hot wire method and the transient plane source method.

As illustrated by Asadi et al. (2018), the steady state boxes method includes a hot and a cold chamber and the specimen to be tested is placed in between the two sides. Energy is then transferred from the hot side to the cold side and the thermal conductivity is calculated based on the difference of the temperature of the air in the chambers.

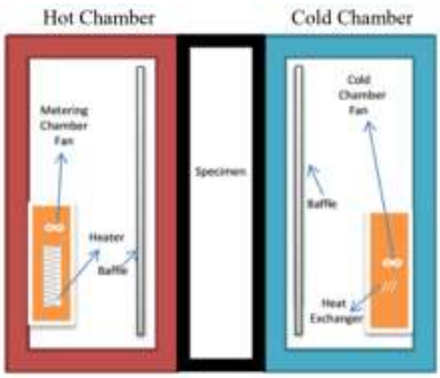

Figure 6. Steady state boxes method (Asadi et al., 2018)

Asadi et al. (2018) explains, that throughout the steady state hot plate method, the sample is placed between hot and cold plates. The thermal conductivity is calculated based on the average temperature difference of the surfaces of the sample and the heat flow during the test.

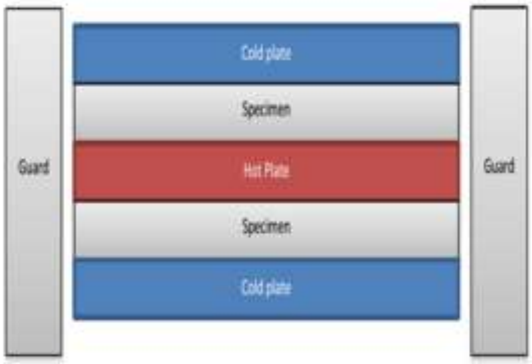

Figure 7. Steady state hot plate method (Asadi et al., 2018)

Lastly, in the same research by Asadi et al. (2018) it is described that during the method of the transient plane source, the used power is measured along with the time/duration of the test. The electric current increases the temperature of a flat sensor. The thermal conductivity is calculated based on the recorded temperature measurements and the power input over time.

Figure 8. Transient plane source method (Asadi et al., 2018)

3. Methodology

3.1 Research method

Two types of research are conducted throughout the duration of the internship to fulfil the objective of the project. First of all, desk research is carried out to review the relating literature to provide detailed information about existing experience with natural fibre enhanced concrete. Afterwards, practical research takes place by performing different types of tests to acquire results. The conclusion is then drawn based on the findings of both the literature review as well as the testing to define the most favourable solution.

3.2 Tests

The materials used for the bio-concrete and therefore the testing are provided by the collaborating companies: cement, aggregates and plasticizer by De Hoop and Miscanthus fibres by Vibers. The mixing as well as most of tests are to be carried out in the concrete laboratory of Scalda in Vlissingen, while the thermal conductivity test is to take place at University Collage Roosevelt (UCR) in Middelburg.

The materials used in this project are as follows:

- cement: CEM I 52.5 R;
- gravel: 4-16 mm;
- sand: 0-4 mm;
- Miscanthus: 0,5-2 mm;
- plasticizer: CUGLA LR-1500 con.20%

3.2.1 Sieve analysis

The purpose of the sieve analysis is to determine the grain size distribution of the aggregates as well as verifying the shipment from the supplier contains the desired or promised material. The test is going to be carried out to check the sand as well as the gravel to be used in the concrete mixture. The grain size distribution of sand is 0-4 mm and it is 4-16 mm for gravel, according to the supplier company, De Hoop.

The sieve analysis requires a sieve machine or sieve column as well as a scale with the accuracy of 0,1 grams. In order to gain the most accurate results, the samples to be sieved must be dried in an oven to minimalize the moisture content. In case of sand, the recommended amount to be sieved for a comparative outcome is at least 200 g. For gravel, a minimum of 10 kg of aggregates should be put through a quarter sieve first, therefore the sample to be sieved shall weigh at least 2,5 kg. After the aggregates have been sieved for 5-7 minutes, each section of the sieve column has to be weighed using the scale.

The data from each weighing is filled in a table corresponding to the type of aggregate. The remaining columns are then calculated: the percentage of materials in each sieve, the cumulative percentage and lastly the cumulative percentages are subtracted, starting from 100%. The results of the last column are compared to the classification tables, based on NEN-EN 933-2 for gravel and NEN-EN 12620 for sand.

Figure 9. Machines used for sieve analysis at Scalda: oven, quarter sieve, fine sieve (for sand) and coarse sieve (for gravel)

3.2.2 Preliminary test of fibre pre-treatment – cement

The method of cement pre-treatment of the Miscanthus fibres was determined to be more effective than the alkali pre-treatment in the research of Adebiyi (2021), therefore it is the chosen technique for continued application. In order to find out more about the amount of cement remaining on the fibres and as an attempt to optimize the method, a preliminary test of the cement treatment was carried out.

For this purpose, 3000 g of CEM I 52.5 R cement was mixed with 3000 g of regular tap water and 500 g of Miscanthus fibres were added into the slurry. All fibres were required to be properly coated with cement after thorough stirring and were planned to be filtered out of the mixture by hand. However due to the density of the slurry, it was poured onto a plastic board and left to air-dry for 7 days, as opposed to the originally intended hand filtering. Three samples were made using this method, all containing the same amount of materials, and were separated for drying.

Figure 10. Fresh samples of pre-treated Miscanthus fibres (preliminary test)

After one week, the three samples were scraped off from the plastic board with a shovel. The chunks of cement and fibres had to be broken in order to create smaller pieces for sieving. The purpose of sieving in this case was to get rid of the excess cement and therefore to reduce the quantity of cement added into the bio-concrete mixture with the fibres. The size of the fibres was previously determined to be between 0,5-2 mm, therefore the weighed sieves were limited to sizes between 0,5-2 mm. The particles caught in sieves larger than 2 mm were collected, crushed and sieved one more time. The particles smaller than 0,5 mm were poured into a separate bucket.

Figure 11. Dried and scraped samples of pre-treated Miscanthus fibres, before crushing (preliminary test)

3.2.3 Slump test

The purpose of the slump test is to determine the consistency and the workability of the wet (bio)-concrete mixture. The required materials are an Abrams cone, a straight rod and a ruler. The surface under the cone must be smooth, horizontal and wet. The cone has to be filled up to 1/3 of its height the first time with (bio)-concrete mortar and the layer has to be compacted using the rod and "poking" the mortar 25 times. The steps are to be repeated until the cone is fully filled and the top is to be evened. The cone is then slowly removed and placed next to the concrete. The deformation of the mortar is measured using the rod placed horizontally on top of the cone and the ruler perpendicular between the rod and the top of the concrete. The shape of the slump may differ based on the consistency of the mixture.

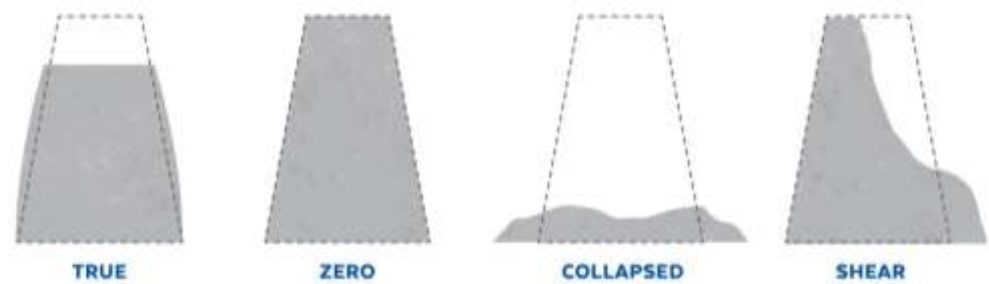

Figure 12. Different types of slump

3.2.4 Fresh density test

The test is carried out using a container of known weight and volume. The properties of the container at the Scalda concrete lab are 7482 g with dimensions of 200 mm x 200 mm x 400 mm. It is filled up with fresh (bio)-concrete mortar and vibrated until no more compaction takes place to make sure the container is completely full. Afterwards, it is weighed on a scale that has a high enough weight limit. The density is calculated based on the results with the following formula:

$$D = \frac{m_{container} - m_{full}}{V_{container}}$$

3.2.5 Compressive strength test

The compressive strength test is carried out using a concrete press or pressure bench that is located at the concrete laboratory of Scalda. Each produced (bio)-concrete cube must be weighed before testing. The press must be started manually, however it will stop automatically when the sample cracks, fails. The information about the applied maximum force and the measured strength of the concrete cube are displayed on the screen of the machine. The data is to be noted for future comparison of the different samples.

3.2.6 Tensile strength test

The tensile strength test is also carried out using the same concrete press at Scalda. However, for this test two pieces of wooden sticks are placed under and on top of the (bio)-concrete cube, one on each side, centred. The machine is manually started and it stops automatically when the concrete fails. The relevant information is displayed on the screen in this case as well.

3.2.7 Thermal conductivity test

The test is to be conducted at the facility of University Collage Roosevelt (UCR) in Middelburg. The sample is required to be a plate of 120 mm x 120 mm with a thickness of maximum 7 cm, however the preferred value by UCR is 10 mm. As the produced bio-concrete cubes are the size of 150 mm x 150 mm x 150 mm, a saw is required to cut the cubes to the desired dimensions. The sawing of the samples is to take place at Scalda.

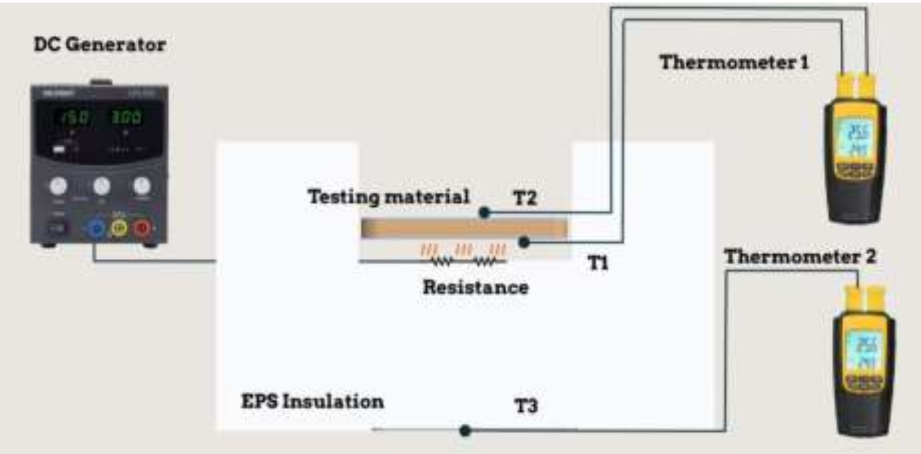

Figure 13. Process Flow Diagram (PFD) of thermal conductivity test at UCR

As described by the technical personnel at UCR, the process of the thermal conductivity test begins with measuring the thickness of the sample to be tested. The sample is then placed into the 120 mm x 120 mm chamber, on top of an aluminium plate and another aluminium plate is placed in top of the sample. There are 2 thermometer devices connected into the system to monitor the temperature during the test. The first device is to measure the temperature of the aluminium plates under (T1) and above the sample (T2). The power unit is set to generate heat at 1,6 W. When first conducting a test with a new material, the temperature values shown on the screen of both thermometers must be recorded every 2-5 minutes throughout the whole duration of the test. When the temperature stops increasing or there is only a slight variation between a lower and a higher value for over 10 minutes, the steady state is considered reached and the generator may be turned off. The duration of the test varies between 30 minutes up to a couple of hours, depending on the material of the sample in question. During the testing of the remaining samples, recording the displayed temperature is required only at the end.

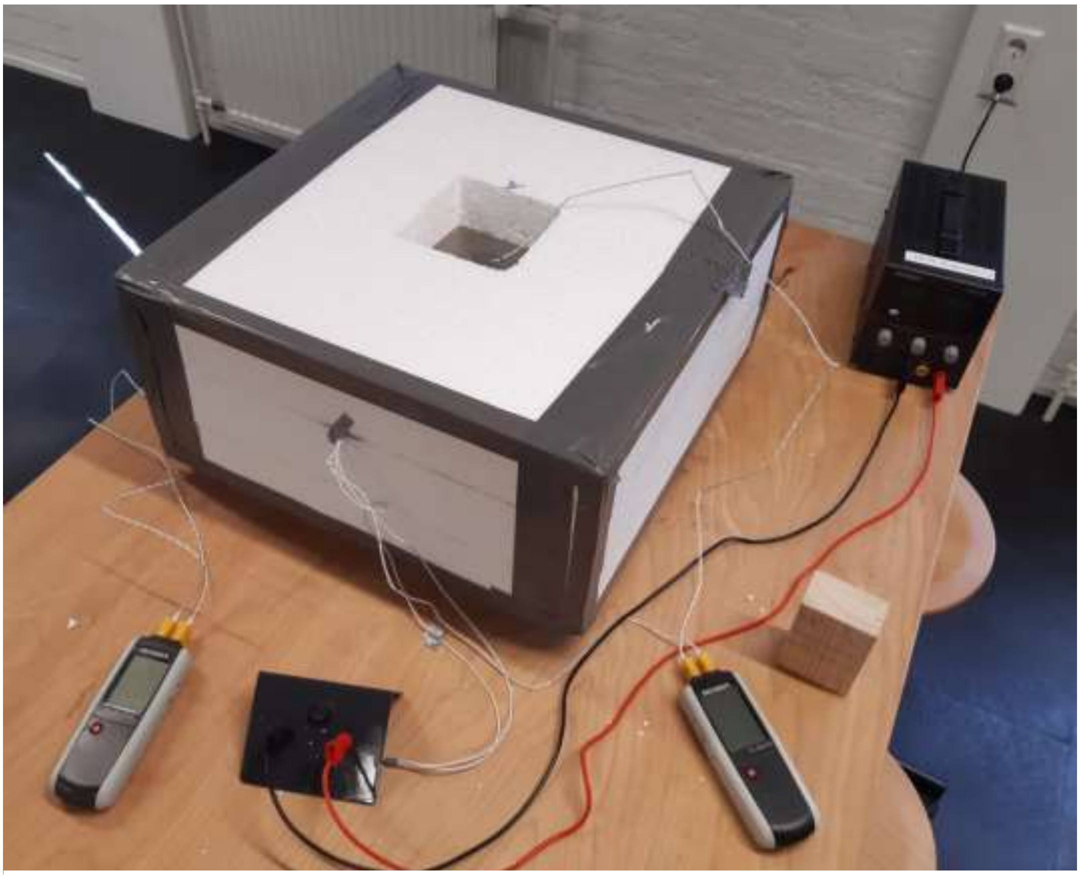

Figure 14. Thermal conductivity testing equipment at UCR laboratory

After the physical process of the test is rounded up, the following formula of the steady state is used to calculate the final results:

$$Q = \lambda \frac{A}{L} DT$$

in which Q is the power at which the heat is generated, λ is the thermal conductivity coefficient, A is the area of the sample, L is the thickness of the sample and DT is the difference between T2 and T1 measured at the end of the test (at steady state). As λ is the unknown value to be determined, the equation is rearranged:

$$\lambda = \frac{QL}{ADT}$$

3.3 Pre-treatment of fibres - cement

Based on the preliminary test of the pre-treatment, different amounts of cement and water were mixed for optimization. The most optimal ratio was found to be using 5000 g of cement, 5000 g of water and 500 g of Miscanthus fibres, because the fibres are more effectively filterable by hand. The filtered fibres are placed on top of a plastic board and are left for air-drying for one week. After the specified time has passed, the fibres are scraped off form the board. The chunks are broken into smaller pieces by hand to eliminate the chance of non-hydrated bits in the wet bio-concrete mortar. Shattering of the chunks is carefully done by hand so the breakage of fibres is limited to the minimum.

3.3.1 Testing the importance of pre-treatment

The intention of the test is to determine whether it is necessary to apply the described pre-treatment method for the fibres. Two different mixtures are created for the purpose of the investigation, one with untreated Miscanthus fibres of 0,5-2 mm size (Mixture A) and another with likewise untreated fibres of 2-10 mm size (Mixture B). The amount of Miscanthus fibres to be added into the matrix is determined by an approximation: it is assumed that 80% of the total mass of the pre-treated fibres is cement, while the remaining 20% is Miscanthus fibres. For the sake of comparison, 5,6 kg of pre-treated fibres are added to Mixture 4, therefore 1,1 kg of untreated fibres are to be blended into both “test mixtures”. The cement content is raised based on the same scheme, 13,3 kg of cement is to be added instead of the original 8,8 kg. All other materials remain the same amount as the original mixtures.

Table 1. Bio-concrete mixture design of test mixtures A and B

Mix A & B		
Materials	Density (kg/m3)	Amount (kg)
CEM I 52.5 R	3100	13,3
Sand 0 - 4 mm	2640	13,6
Gravel 4 - 20 mm	2640	19,5
Miscanthus	160	1,1
Water	1000	5,8
Plasticizer		1,25

The first step after measuring the quantities of components is to pour and stir the cement, the fibres and the water in the concrete mixer for roughly 5 minutes. When the slurry is homogenised, the rest of the aggregates and the plasticizer may be added as well. The same previously described steps apply for the slump test, the fresh density test and the compression strength test as for the original 5 mixtures.

3.4 Concrete mixture

One of the aspects of bio-concrete with Miscanthus fibres to explore is the strength and durability of the material as a structural element, for which the minimal compressive strength is 25 MPa. The results of mentioned investigation are out of the scope of this report, however it is a crucial element of the project. Therefore the control mixture was determined to be similar to Mixture 3 of research and testing carried out by Adebiyi (2021), as Mixture 3 has the highest pre-treated Miscanthus fibre content (in volume) with 50,5% and an average compressive strength of 35,13 MPa. Adjustments are required to take place with the intention of improving the workability of the mixture. Table 2 below represents the amount of components added into the bio-concrete matrix to create the different designs for this project.

Table 2. Bio-concrete mixture designs 1 to 5

Materials	Density (kg/m3)	Mix 1 (Control)	Mix 2	Mix 3	Mix 4	Mix 5
Cement: CEM I 52.5 R	3100	8,8 kg	8,8 kg	8,8 kg	8,8 kg	8,8 kg
Sand: 0 - 4 mm	2640	13,6 kg	13,6 kg	13,6 kg	13,6 kg	13,6 kg
Gravel: 4 - 16 mm	2640	19,05 kg	19,5 kg	19,5 kg	19,5 kg	19,5 kg
Miscanthus	160	3,2 kg	4 kg	4,8 kg	5,6 kg	6,4 kg
Water	1000	5,4 kg	5,8 kg	5,8 kg	5,8 kg	5,8 kg
Plasticizer	-	0,11	0,11	0,11	0,11	0,11
Water / cement ratio	-	0,61	0,66	0,66	0,66	0,66
Fibres in volume	-	49,25%	54,14%	58,62%	62,30%	65,38%

The adjustments of the control mixture compared to Mixture 3 of Adebiyi (2021) are:

- the water content is increased from 4,4 kg to 5,4 kg and therefore the water/cement ratio is changed from 0,50 to 0,61;
- the amount of plasticizer added is increased from 0,088 kg (1% of cement content) to 0,11 kg (1,25% of cement content).

3.4.1 Increase of Miscanthus fibres

As mentioned earlier, the most preferred mixture from the previous research is to be used as control for the current project, therefore 3,2 kg of pre-treated fibres are to be added into the first mixture. Each following concrete mixture design contains an increased amount of Miscanthus fibres compared to the one before it. The increase is set to be 0,8 kg. Mixture 5 is to contain 6,4 kg of pre-treated fibres, which is double the amount in mass than in the in the control mixture and approximately 16% more in volume (Table 2).

The purpose of increasing the Miscanthus fibre content of the concrete matrix, while not changing the amount of the other ingredients, is to compare the properties (fibre content, cement content, thermal conductivity, strength, weight, workability) of the different mixtures and determine which design is the most optimal composition in terms of application and sustainability.

The pre-treated fibres added into the bio-concrete matrix are a composition of Miscanthus fibres and cement. It means that one part of the pre-treated fibres is Miscanthus and the remaining part is cement. The ratio is calculated based on the amount of fibres and the amount of cement used for the pre-treatment as well as the weighing measurements of each treated, dried batch before usage. In percentage, it is expected that approximately 20% of the pre-treated fibres is Miscanthus, while the remaining 80% is cement. The percentages are then applied to the total amount added into the concrete to determine a more accurate value of fibre content.

3.5 Multi-Criteria Analysis (MCA)

The Multi-Criteria Analysis is a form of assessment, where the different solutions or designs are compared based on chosen criterion. The variants are assigned scores for each criterion and the scores are multiplied by the weight factor of the criteria. The final points of a design option are calculated by summing its scores for all considered aspects. Depending on the definition of the scoring system, the alternative with either the highest or lowest overall points is the most preferred option or the winning variant.

3.5.1 The criteria

In order to be able to carry out a Multi-Criteria Analysis, the criteria based on which the alternatives are going to be evaluated must be defined. The criteria are the different aspects that are considered most important regarding the requirements of the final product set by the client.

3.5.1.1 Fibre content

One of the main goals of the project is to maximise the content of Miscanthus fibres in the concrete as possible partial replacement of aggregates. The amount of fibres and cement after pre-treatment is to be calculated and the value considered for this criterion is the percentage of the actual fibre content, without additional cement. Consequently, it has a greater influence and the mixtures with higher fibre content are more favourable.

3.5.1.2 Thermal conductivity

The other main focus of this research is to determine based on test results, if the created bio-concrete with Miscanthus fibres is suitable for production of thermal insulation bricks. Considering the requirements of the client, the importance of the thermal conductivity of the concrete is equal to the fibre content. A lower thermal conductivity coefficient is evidently more suitable for the purpose of the application.

3.5.1.3 Cement content

Taking into account the environmental impact of cement production, it is urgent to attempt to reduce the cement content in concrete. However, the Miscanthus fibres used in the different mixtures are pre-treated with cement, therefore the usage of cement beyond a component of the concrete matrix is necessary in this project. The values considered for this aspect are the quantities of cement in the total volume of the mixture, expressed in percentage. As the pre-treatment is an essential part of the process and the method is preferred over other options, the cement content is of slightly lesser importance.

Nevertheless, the lowest cement content is the most preferable. It should be noted however, that increasing the amount of Miscanthus in the concrete will potentially result in an increase of additional cement due to the pre-treatment.

3.5.1.4 Self-weight/density

One of the disadvantages of concrete is its high self-weight. When selecting bio-concrete with Miscanthus fibres as insulation material, the weight of the bricks is going to be taken into consideration. However, for determining the most optimal variant, the self-weight is of lower significance.

3.5.1.5 Compressive strength

According to the requirements by the client, the final product as an insulation brick should have the compressive strength of a minimum of 2,5 MPa. From this point of view, a higher strength has the potential to be unexploited and result in wasting material and resources, hence the low influence. However, the higher values are more favourable for the overall performance of the bio-concrete.

3.5.1.6 Workability

The workability of the different mixtures is determined with the slump test. A set range of values of deformation (corresponding to consistency class S3) are a result of a more optimal ratio of components in the mixture and therefore are more favourable. However, a greater deformation is the result of a high water content, which may cause the heavier aggregates to settle, resulting in segregation and spoiling the homogeneity of the concrete. The separation of components within an overly moist mixture reduces the strength and reliability of the final product, which is less advantageous. Moreover, in case a fresh bio-concrete mixture is hardly workable due to a low moisture content and/or high water absorbance, it is also awarded less scores. However, the workability is of low importance based on discussions with the client.

3.5.2 Weight factors and score system

The weight factors are used for the calculation of the overall scores of each alternative. The weight factors are decided based on the goals set by the client and the importance of the criteria described above. Points of 1 to 3 are assigned to each of the five different bio-concrete mixtures with Miscanthus fibres for every criterion. There is a range defined for the scores of the different aspects based on calculations and test results. Table 3 below contains the relevant information about the weight factors and the score ranges of the criterion applied for the MCA of the various concrete designs.

Table 3. Weight factors and score ranges considered in the MCA

Criteria	Weight factor	Scores		
		1	2	3
Fibre content	30%	x < 19%	19% < x < 20%	x > 20%
Thermal conductivity	30%	x > 0,5 W/(m K)	0,5 W/(m K) > x > 0,3 W/(m K)	x < 0,3 W/(m K)
Cement content	20%	x > 15%	15% > x > 14%	x < 14%
Self-weight/density	10%	x > 2100 kg/m^3	2100 kg/m3 > x > 2000 kg/m^3	x < 2000 kg/m^3
Compressive strength	5%	x < 20 MPa	20 MPa < x < 25 MPa	x > 25 MPa
Workability	5%	x < 5 cm	x > 15 cm	5 cm < x < 15 cm

4. Results

4.1 Sieve analysis

The outcome of the sieve analysis confirms that the coarse and fine aggregates supplied by De Hoop are indeed the correct sizes: 4-16 mm for gravel and 0-4 mm for sand. The results of the weighing of the sieve sizes as well as the tables used for verification are in Appendix I.

The design area I. of the grain group 0/16 form NEN 8005 is used to determine the grain size distribution. The upper and lower boundaries are set values from the Eurocode. The distribution of the combination of sand and gravel are compared to the boundaries in the graph of Figure 15 below.

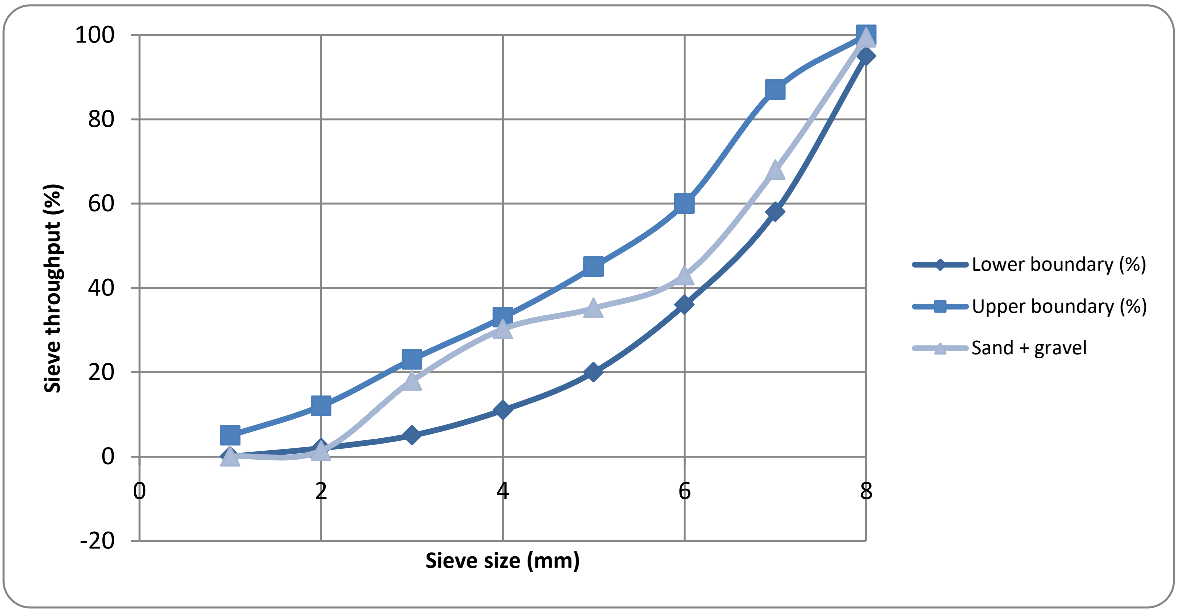

Figure 15. Grain size distribution of sand and gravel delivered by De Hoop

4.2 Slump test

Apart from the control mix, which is Mixture 1, the slump and consequently the workability of the concrete mixes are decreasing. The reduction is the consequence of the increasing amount of pre-treated fibres in the matrix, which results in additional cement content in the mix, therefore the water/cement ratio is decreasing. Hence, the mixtures with a higher quantity of pre-treated fibres are drier. In addition, the cement creates a protective layer around the individual Miscanthus fibres due to the pre-treatment, which hinders the water absorbing capacity of the fibres. Therefore, it is assumed that the Miscanthus takes up less water than the extra added cement itself. Furthermore, the water/cement ratio is influenced by the additional cement. The water content remains the same for all mixtures, with the exception of Mixture 1, therefore the water/cement ratio decreases.

The consistency class is determined based on the measured magnitude of deformation of the concrete, using the Eurocode chart of consistency classes NEN 8005. Table 4 below exhibits the results of the slump test, the classification and the water/cement ratio.

Table 4. Slump, consistency and W/C ratio of mixtures 1 to 5

	Slump (cm)	Class	W/C ratio
Mix 1	0,5	-[1]	0,49
Mix 2	14,5	S3	0,48
Mix 3	10,0	S3	0,46
Mix 4	4,5	S2	0,43
Mix 5	1,0	S1	0,41

As Mixture 1 appeared to have a minimal slump and a low workability, the amount of water added into the concrete mortar was increased from 5,4 kg to 5,8 kg with the ambition of improving the workability. Hence the significant difference between the first two slump tests. Afterwards, the same quantity of water was used continuously for the remaining mixtures. Illustration of the slumps on Figure 16.

Figure 16. Slump tests (left to right): mix 1, mix 2, mix 3, mix 4 and mix 5

4.3 Density

The density of each mixture is calculated twice, first when determining the fresh density and later when measuring the weight of the cubes before the strength tests. In the second scenario, the density of each cube is computed and an average value is drawn. It is observed that there is a slight difference between the fresh density and the average density of the cubes, the latter is lower in case of all mixtures with the exception of Mixture 5. The deviation is likely to be the result of the evaporation of moisture during the hardening phase.

Table 5. Fresh and dry densities of the bio-concrete designs 1 to 5

	Fresh density of mix (kg/m^3)	Average density of cubes (kg/m^3)
Mix 1	2148,75	2129,76
Mix 2	2150,13	2089,37
Mix 3	2083,19	2052,95
Mix 4	2146,38	2117,85
Mix 5	1922,38	1978,48

[1]: Classification of consistency based on the slump test starts from 10 mm in NEN 8005

4.4 Cement pre-treatment

The pre-treatment method was carried out four times in total. The first time 3 kg cement and 3 kg water was used for the slurry, the second time 6 kg of cement and 6 kg of water was mixed, and 5 kg cement with 5 kg water for the last two occasions as those appeared to be the most optimal amounts. In each case, the amount of Miscanthus fibres was 0,5 kg. Each sample was weighed after 7 days to determine the ratio of cement and fibres following the treatment. The first batch of pre-treated fibres differs from the rest, as the dry samples were sieved before measuring and adding into the concrete mixture. As a consequence, a greater quantity of excess cement is excluded from the bio-concrete mixture containing the first pre-treated fibres. Table 6 below presents the calculated percentages of fibres and cement for each pre-treatment and the average percentages regarding the treatments where no sieving took place.

Table 6. Ratio of cement and Miscanthus after pre-treatment

	Total (g)	Cement %	Fibre %
Pre-treatment 1	5166	71,0%	29,0%
Pre-treatment 2	7621	80,3%	19,7%
Pre-treatment 3	9626	84,4%	15,6%
Pre-treatment 4	28951,3	81,9%	18,1%
Average %		82,2%	17,8%

Each concrete mixture originally contains 8,8 kg cement, however due to the addition of pre-treated fibres, the cement content is increased. By raising the amount of materials in the bio-concrete matrix, the overall volume of the mixture is increased as well. Therefore, when evaluating the cement content, the percentage of cement with respect to the total volume of the mixture is considered.

Figure 17 below presents the initial expectation of the Miscanthus fibre content in each variant, the more accurate Miscanthus fibre content after the pre-treatment and the overall cement content of the mixtures. The first values were calculated using the density of Miscanthus and the quantity of fibres to be added over the total volume of the mixture. However, the impact of the pre-treatment is not considered for the initial expectation. The percentages of fibres in the bio-concrete are calculated using the values of Table 6 above and the overall volume of the mixtures. Similarly, the percentages of cement in the concrete are calculated based on Table 6 and the total volume of the mixture. The reason behind Mixture 1 containing almost as much Miscanthus fibres in volume as Mixture 5 is the sieving of pre-treated fibres before mixing the concrete. Note however, that Mixture 5 was made without measuring the samples of the pre-treatment before preparing the right quantity for the concrete matrix. Therefore an average of previous data of fibres without sieving is used to estimate the fibre content as well as the cement content.

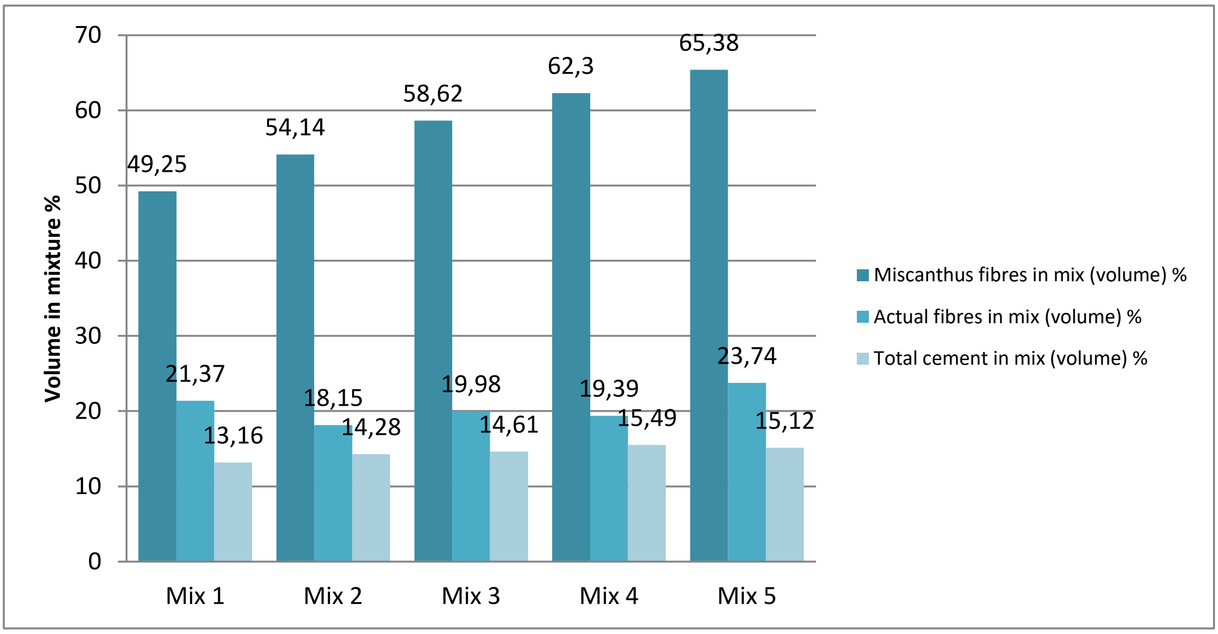

Figure 17. Miscanthus fibre and cement content in bio-concrete mixtures 1 to 5

4.4.3 Testing the importance of pre-treatment

The one main difference in Mixture A and Mixture B is the size of the untreated Miscanthus fibres in the matrix. However, it appears to have a significant influence on the characteristics of the concrete. With the same water/cement ratio, the slump of Mixture A is remarkably lower than of Mixture B. It is assumed, that the smaller fibres absorbed more water from the matrix due to the higher surface area compared to the lager fibres in Mixture B. Table 7 and Figure 18 display the difference of the slumps tests carried out for the two mixtures.

Table 7. Slump, consistency and W/C ratio of Mix A&B

	Slump (cm)	Class	W/C ratio
Mix A	0,5	- [2]	0,44
Mix B	11,5	S3	0,44

Figure 18. Slump tests of Mix A and Mix B

[2] : Classification of consistency based on the slump test starts from 10 mm in NEN 8005

Similarly to the original mixtures, the density is calculated twice, using the same formulas. According to the results, the density of both variants is lower after the 28-day hardening process (Table 8). Furthermore, the density of Mixture A is less in both cases, in fact, it is lower than the lowest of the original mixtures. The Miscanthus content of Mixture 5 is 23,74%, while it is calculated to be 23,30% in both Mixture A and B. However, the cement content of Mixture 5 is assumed to be above 15%, which is higher than the 14,54% cement content of Mixtures A and B. Therefore, comparing the mixtures with the same size of Miscanthus fibres, the difference in density is likely to be the result of the lower amount of cement in the bio-concrete.

Table 8. Fresh and dry densities of mixtures A and B

	Fresh density of mix (kg/m^3)	Average density of cubes (kg/m^3)
Mix A	1902,4	1834,7
Mix B	2074,9	2019,2

Another critical aspect of determining the importance of the pre-treatment is to assess the strength of the two testing mixtures. Both Mixture A and Mixture B were made on the same day and were tested for compression after 28 days of hardening. All five of the prepared cubes of Mixture A deteriorated and failed under the pressure in a way that no assessable results were obtained. The concrete press is automated, it releases when cracking occurs in the testing subject, however it was necessary to stop the machine manually. The observation of the tested cubes revealed that the concrete was dry on the inside, while it was wet on the outside.

Figure 19. Failed cube Mixture A

On the other hand, no complications of any nature occurred during the testing of Mixture B. Overall, the acquired results of the compressive strength of the bio-concrete with the larger untreated Miscanthus fibres appear to be lower than almost all of the original mixtures with the smaller pre-treated fibres. Table 9 below presents the compressive strength of the individual cubes and the average compressive strength, regarding Mixture B.

Table 9. Compressive strength of Mix B

	Compressive strength (MPa)	Average compressive strength (MPa)
Cube 1	15,01	15,522
Cube 2	16,28	
Cube 3	15,15	
Cube 4	13,39	
Cube 5	17,78	

4.5 Compressive and tensile strength test

Five cubes per each bio-concrete mixture were prepared to conduct tests on the hardened products. Three cubes were tested for compression and one cube was tested for tension. The last specimen was put aside for an accelerated aging/weathering test to evaluate the durability of the produced bio-concrete. As it is outside the main scope of this paper, the test is elaborated in Appendix II.

Throughout the research of Adebiyi (2021) it was revealed, that the compressive strength of bio-concrete decreases with the increase of cement pre-treated Miscanthus fibres in the matrix. The results of current project support mentioned finding, as the same tendency is observed. However, there is not a clear pattern regarding the influence of the natural fibre content on the tensile resistance. There is a slight difference between the first 2 results, with Mixture 2 performing better than Mixture 1, while the tensile strength of Mixture 3 is lower than both (Figure 20).

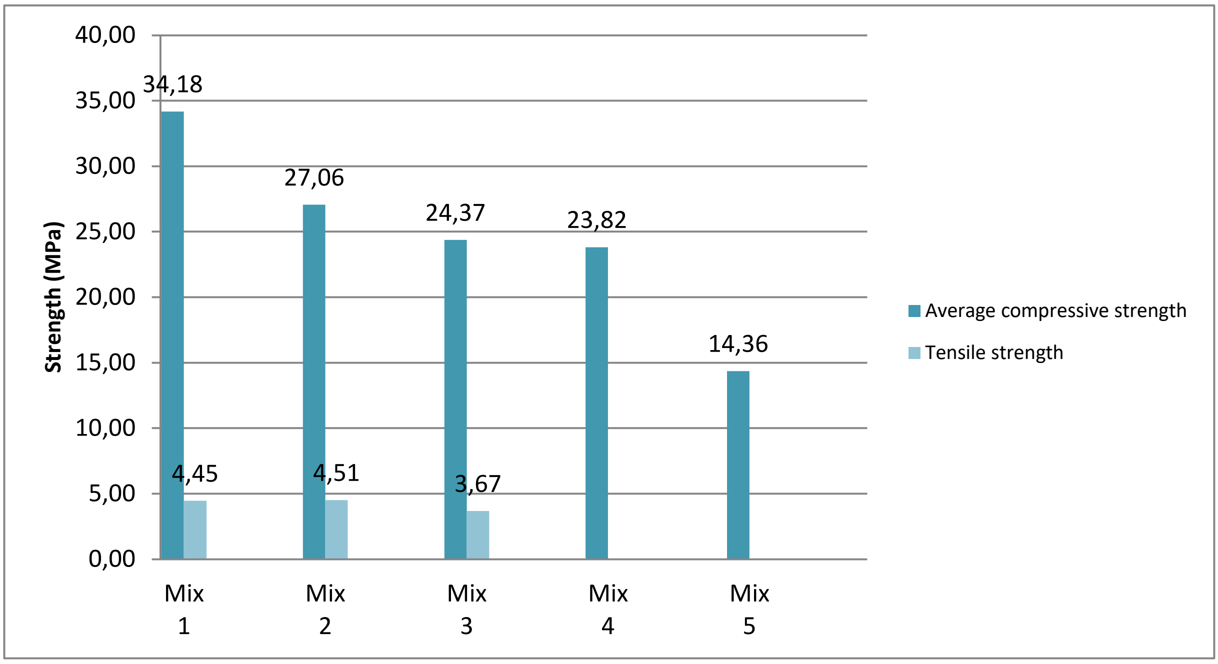

Figure 20. Compressive and tensile strength of bio-concrete mixtures

While conducting compressive tests for the samples of Mixture 2, an unusual result was obtained which is noted as a failure, therefore it does not contribute to the calculation of the average compressive strength of said mixture. After the inspection of the specimen, it was found that a thin piece of the surface snapped off, however no other damage was visible. Another two issues were encountered during the split tensile tests of both Mixtures 4 and 5, where the sticks placed on top of the cubes were pushed into the concrete, resulting in an inaccurate outcome. The values of the failed tests are highlighted in light blue in Table 10 below.

Table 10. Summary of testing - strength of individual cubes, average compressive strength, tensile strength, measured failures in light blue

	Compressive strength (MPa)	Average compressive strength (MPa)	Tensile strength (MPa)
Mix 1	37,09	34,18	4,45
	34,88		
	30,56		
Mix 2	27,38	27,06	4,51
	9,42		
	26,73		
Mix 3	23,6	24,37	3,67
	24,14		
	25,36		
Mix 4	23,41	23,82	17,49
	24,1		
	23,95		
Mix 5	12,33	14,36	8,63
	15,91		
	14,83		

A possible reason of the error for Mixture 2 could be segregation, however no problems were encountered with the remaining cubes, therefore it is unlikely to be the explanation. Another, more probable possibility is that the specific cube was vibrated for a longer duration when filling the form with fresh concrete, causing separation. In case of the specimens of the tensile test, it is suspected, that the combined influence of the wooden sticks being too narrow or too thin and the resistance of the concrete being too low resulted in the failure.

Figure 21. Close-up damage Mix 2 and split tensile tested cube Mix 5

4.6 Thermal conductivity

The diagram on Figure 22 below reveals the results of the thermal conductivity tests of the different mixtures of bio-concrete with Miscanthus fibres. Due to the duration of the test and the limited amount of available time, 2 samples of each mixture went under testing. The values displayed and considered as results are the calculated average values of λ.

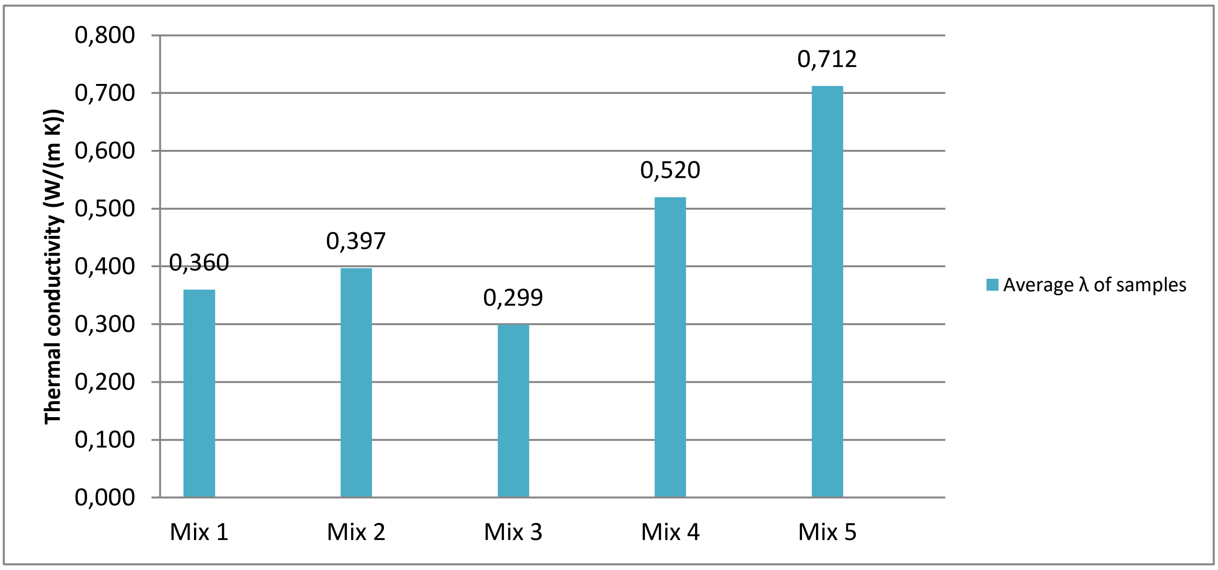

Figure 22. Thermal conductivity test results mix 1 to 5

With Miscanthus having a relatively low thermal conductivity compared to concrete, it was expected to achieve a decreased value for λ with the increase of Miscanthus fibres. While the achieved thermal conductivity is generally lower than of conventional concrete, which varies between 1,7-3,3 W/(m K) according to Kim et al. (2003) and Kodur and Khaliq (2011), the expected scheme is not fulfilled. For instance, although Mixture 5 has the highest fibre content, all of the other mixtures have a lower λ value. Furthermore, as it was summarised by Asadi et al. (2018), materials with a higher density usually have higher thermal conductivity. In case of the results of this project, said correlation cannot be observed, as the mixture with the lowest density has the poorest performance.

Table 11. Comparison of λ, density, fibre content and sample thickness of mix 1 to 5

	Average λ (W/(m K))	Average density (kg/m^3)	Fibre content (%)	Thickness of samples (mm)	
Mix 1	0,360	2129,76	21,37	20	20
Mix 2	0,397	2089,37	18,15	20	20
Mix 3	0,299	2052,95	19,98	18	18
Mix 4	0,520	2117,85	19,39	20	23
Mix 5	0,712	1978,48	23,74	23	25

The comparison of the outcome however is complicated due to the unevenness of the tested samples. All specimens were prepared at Scalda, from cubes that were previously crushed to determine the strength. According to the information received from UCR, the test results of thinner samples are usually more accurate, therefore a thickness of 1 cm is preferred for testing. Concrete is generally a stiff material, therefore sawing the samples to the required size and thickness with the available equipment without causing breakage appeared to be a challenge. The surface of each of the samples is uneven and the thickness of some individual pieces differs from the rest. The lack of surface smoothness created gaps between the specimen and the aluminium plate during the test, which could have resulted in a less accurate result. Furthermore, the varying thickness appears to have a significant influence on the value acquired for λ, as the mixture with the thinnest samples achieved the lowest thermal conductivity, while the mixture with the overall thickest samples has the highest results. All differences considered, the results are slightly questionable and it is presumable that the outcome would change or be more accurate if the samples were uniform.

Figure 23. Samples intended for thermal conductivity test

4.7 Multi-Criteria Analysis

All mixtures are evaluated based on the ranges of the different criteria. After calculating the overall scores, Mixture 1 appears to have achieved the highest amount of points with 2,4 closely followed by Mixture 3 with 2,35.

Table 12. Outcome of the MCA

	Weight factors	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Fibres content	30%	3	1	2	2	3
Thermal conductivity	30%	2	2	3	1	1
Cement content	20%	3	2	2	1	1
Self-weight	10%	1	1	2	1	3
Strength	5%	3	3	2	2	1
Workability	5%	1	3	3	1	1
Total score		2,4	1,7	2,35	1,35	1,8

The main advantages of the top 2 mixtures originate from the criteria with the most influence. The Miscanthus fibre content of Mixture 1 is almost as high as in Mixture 5, even though the amount of pre-treated fibres added into Mixture 5 (6,4 kg) is the double of what is added into Mixture 1 (3,2 kg). It is the result of the sieving of fibres after the pre-treatment, which eliminated a considerable amount of cement in case of Mixture 1. Moreover, the sieving positively affected the cement content of Mixture 1, as it is decreased and it is the overall lowest in percentage, for which Mixture 1 is awarded the highest point. The outcome of the thermal conductivity test is vastly influenced by the thickness of the examined specimens, therefore the mixture with the thinnest samples achieved the highest score.

Observing the scores regarding the criterion with lesser importance, Mixture 3 performed mostly well for each of the evaluated aspects. Mixture 1 received the lowest scores for its self-weight, as it was the heaviest of all concrete mixtures. Moreover, Mixture 1 was given a low score for workability as well, due to the fact that the result of the slump test was nearly 0 cm. However, it obtained the most points for its compressive strength, resulting in the highest overall score.

4.7.1 Possible alterations

The approach of evaluating the compressive strength applied originally is that higher strength is awarded with higher scores, because the aim in most instances is for the concrete to have the best possible resistance. The weight factor of this criteria, on the other hand, is 5%, due to the fact that the lower limitation of compressive strength for the final product is 2,5 MPa in this project.

After further analysis, it was revealed that changing the approach of evaluation by turning the scoring criteria around, meaning that the lowest strength receives the highest points, alters the final outcome of the MCA. The reason behind the modification is also the required minimum compressive strength of 2,5 MPa for the end product as an insulation brick. In this case, Mixture 1, having the highest average resistance, is given the least amount of points, while Mixture 3 is awarded the same score as before, as it is still in the middle range of the criteria. Keeping the weight factor of 5%, the total score of Mixture 1 is reduced to 2,3 and the total score of Mixture 3 remains 2,35, resulting in the latter as the most preferred bio-concrete design.

The decision about which outcome to consider as a final result is dependent on the application of the product. In case a higher strength is preferred, as the product will be utilized as a structural element, the first result is more advantageous. However, when the strength of the concrete is of lesser importance for the application, the second option may be more favourable. Mixture 1 remains the most optimal concrete design in this project, as the relevance of the compressive strength is originally already reduced by assigning 5% as the weight factor to the criteria.

With thermal conductivity having a significant influence on the outcome on the MCA, it must be noted that conducting the test with more appropriately shaped samples could have changed the scores and potentially the final result as well.

5. Conclusion

5.1 Multi-Criteria Analysis – the most preferred variant

According to the results of the MCA, Mixture 1 has the highest overall score, which concludes that it is the option that fulfils the requirements of the project the most. The final bio-concrete mixture design containing Miscanthus fibres is displayed in Table 13 below.

Table 13. Concrete mixture design of Mixture 1

Materials	Amount (kg)
CEM I 52.5 R	8,8
Sand 0 - 4 mm	13,6
Gravel 4 - 16 mm	19,05
Miscanthus (pre-treated)	3,2
Water	5,4
Plasticizer	0,11
Actual W/C ratio	0,49

To summarise the main characteristics of Mixture 1, the results of the conducted tests as well as supporting calculations are collected. The consistency class is not determined, as the result of the slump test was 0,5 cm, while the classification of consistency based on the slump starts from 1 cm in NEN 8005. The fresh density of the concrete matrix is approximately 2149 kg/m^3 and the average density of the produced cubes for the tests is rounded to 2130 kg/m^3. The pre-treated Miscanthus fibre content of the bio-concrete is over 21% and the overall cement content, including the amount form the pre-treatment, is slightly more than 13%. Both percentages are with respect to the total volume of the mixture. The average compressive strength is slightly over 34 MPa, corresponding to concrete strength class C20/25 according to NEN 6720 and CUR-97 recommendations. The result of the tensile resistance test is 4,45 MPa, which corresponds to class C53/65. However, it is the strength of only one tested cube, therefore it cannot be considered as the average tensile strength of Mixture 1. The average thermal conductivity coefficient of samples with the thickness of 2 cm is 0,360 W/(m K).

5.2 Importance of pre-treatment

The main takeaway of the tests carried out to determine the importance of pre-treatment, is that the application of cement pre-treatment does indeed have a beneficial effect on the bio-concrete. It enhances the bonding of the Miscanthus fibres with the concrete matrix as well as it positively influences the hydrophobic property of the natural fibres, which improves the workability. Furthermore, the increase of adhesion between the fibres and the concrete mortar enhances the strength as well. The lack of pre-treatment resulted in concrete cubes severely deteriorating under compressive forces, as it was experienced with Mixture A.

Due to the larger size of Miscanthus fibres in Mixture B and therefore the less surface area, less water was absorbed from the matrix, which resulted in an overall better consistency and performance compared to Mixture A. However, it is possible that a higher strength could be achieved if the fibres were pre-treated. To be able to determine if the assumption is correct and to draw a final conclusion, further testing is required to be carried out.

5.3 General conclusion

The results obtained and presented in this research continue to prove the potential of using pre-treated Miscanthus fibres to produce bio-concrete. The goal of decreasing the coarse and fine aggregates in concrete is possible to achieve by adding natural fibres into the mixture, as the volume is increased. Although the strength of bio-concrete is reduced with the higher quantities of natural fibres, it is still feasible to reach high enough strength for structural applications. Considering the outcome of the compressive strength test and the thermal conductivity test, the final bio-concrete mixture design cannot be implemented as an insulation material, however it may be feasible to be applied for the production of space divider internal walls.

An even higher Miscanthus fibre content in bio-concrete has the potential to fulfil all the goals the project set by the client. The lowest compressive strength of the produced mixtures is approximately 14 MPa, which is higher than the required minimum of 2,5 MPa. Even though the final product of bio-concrete with Miscanthus fibres as thermal insulation material is currently less favourable over conventional insulators, the results obtained throughout the testing period are encouraging and provide basis for further research. According to literature review, decreasing the density could result in better performance as thermal insulation. Therefore the intention of maximizing the ratio of natural fibres in the concrete is suitable for optimization in the future.

As it is the most environmentally harmful material in concrete, the overall reduction of cement consumption is an urgent matter. However, using cement for the pre-treatment of Miscanthus fibres increases the cement content of the concrete matrix when more fibres are added. On the other hand, as described by Adebiyi (2021), the method of cement pre-treatment was found to be more feasible and more effective than using alkali. Consequently, the increased usage of cement was unavoidable throughout the project.

Overall, the main research question of the project ("What is the most optimal ratio of components in concrete mixture with natural Miscanthus fibres to achieve sufficient thermal insulation properties?") remains unanswered due to the outcome of the testing. However, constructive revelations have been achieved regarding the pre-treatment as well as the testing methods over the course of the research period.

5.4 Reflecting on the process

The duration of the internship/research period was set to start on 7th February 2022 and end on 8th July 2022. According to the initial plan, the natural fibre mixed into the concrete matrix to test the behaviour and properties of bio-concrete was bamboo. BambooLogic, the company interested in collaboration for research, agreed to look for an opportunity to provide bamboo fibres for bio-concrete.

During the first two months of the process, desk research was being conducted in order to build up the structure of a project proposal around bio-concrete and bamboo in general. The literature review provided basis to understanding what to be aware of during testing, such as previous experiments, the processes and results, already known material behaviour and patterns of influence, etc. Alongside the desk research, preparations for mixing bio-concrete at the concrete laboratory of Scalda took place, starting with the sieve analysis. The next step was to test the cement pre-treatment method, which was done using Miscanthus fibres, for a possible future comparison with bamboo fibres. However, the company BambooLogic was unable to deliver the desired bamboo fibres, which resulted in the decision of changing the topic of the research along with the used material to avoid further delay.

While adjusting the written work to the slightly new aspects of the project, the physical processes continued with the application of Miscanthus fibres. The company Vibers, that provided Miscanthus fibres to support the research of Adebiyi (2021), was able to deliver the required amount of material in the desired size for this project as well. As a consequence, the remaining actions (mixing and testing) were carried out at Scalda without further disturbance. In addition, executing the thermal conductivity tests of the bio-concrete samples at UCR in Middelburg generated a valuable connection between the two universities, UCR and the HZ.

The physical testing appears to be an effective way of research. Being able to conduct the pre-treatment of the natural fibres, the mixing of bio-concrete as well as the testing within the scope of the internship had its advantages. For instance, it was possible not only to be in control of the processes, but also to gain experience about them. First-hand information and data was collected, analysed, interpreted and explained. The results reflect the success of the research: previous findings of the Vibrescrete project about the correlation between the increasing Misacnthus fibre content in the bio-concrete and the decreasing compressive strength were proven and supported. On the other hand, the relationship revealed by review of Asadi et al. (2018) regarding the lower thermal conductivity of materials with lower density (Figure 5) cannot be observed in this project (Table 11).

6. Recommendations

Based on the experience gained, practical recommendations are provided with the intention of improving the process, methods and results of future research and testing.

- The Miscanthus fibre content of the concrete is still possible to be increased and it is advised to do so in small portions as was done for this project. More precisely, add 0,8 kg more pre-treated Miscanthus fibres into the new mixture, compared to the previous one. The gradual increase provides a better overview and understanding of the behaviour of the materials. Keep in mind that the water/cement ratio is required to be adjusted to improve workability in case the result of the slump test is below 1 cm. Moreover, the effect of a higher Miscanthus content on the thermal insulation performance of the bio-concrete is recommended to be investigated further.

- The size of Miscanthus fibres used in this project is 0,5-2 mm. However, tests of the bio-concrete with larger, untreated Miscanthus fibres (2-10 mm) were conducted as well. It is recommended to take a deeper look into the possibilities of using the larger fibres. Furthermore, investigating the effect of cement pre-treatment on the 2-10 mm fibres is advised.

- The method of cement pre-treatment may be improved by using an old sieve to "fish" out the fibres from the wet cement mixture. It will limit the loss of fibres during the treatment process as well as potentially lower the amount of excess cement before hardening. Sieving after hardening is also effective, however it is extremely time consuming. Furthermore, cement has a drying effect on the skin, therefore it is advised to wear gloves or use a stick or a tool for mixing the cement with water and Miscanthus fibres. Take notes about how much Miscanthus fibres, cement and water is mixed together to conduct the pre-treatment method. When the hardening is completed (after 7 days), always weigh the total amount of pre-treated fibres before starting to prepare the required quantity for mixing the bio-concrete, so that the fibre content is calculated more accurately.

- When filling the forms with fresh bio-concrete to produce cubes for testing, it is recommended to vibrate them for only one (maximum two, in case of less moist fresh bio-concrete) cycle on the vibrating table. The vibration is used to eliminate as much air from the concrete as possible, however over vibrating may cause segregation. Therefore, the purpose of limiting the usage of the vibrating table is to avoid similar errors occurring as experienced with Mixture 2.

- Develop a formwork to produce uniform samples of the required size with smooth surface to obtain a more accurate result for the thermal conductivity test. The reliability of the outcome of the test is significantly influenced by the specimen itself, comparing samples that have different sizes may be misleading, therefore evenness is crucial.

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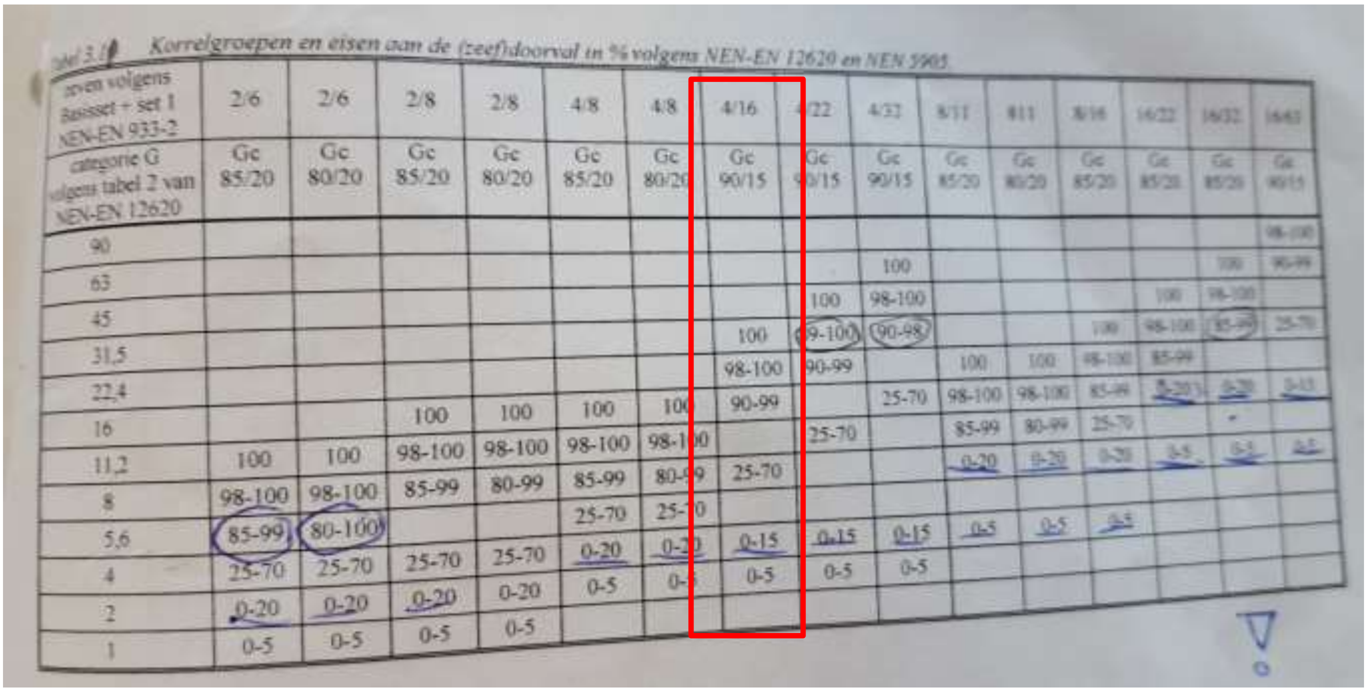
Appendix I. – Sieve analysis

The result of the sieve analysis of gravel is in Table 14 below. Mass residue R is the weight of the stones remaining in each sieve. The verification of the sizing was done based on the values in the last column of Table 14 and Figure 24.

Table 14. Sieve analysis - gravel

Used method: dry sieving				
Mass dry total (M1):			**2063** gram	
Sieve (mm)	Mass residue R (g)	Percentage material rest R/M1*100%	Cumulative percentages sieve residue	Cumulative percentages fall 100%-sieve residue%
32	0	0	0	100
22,4	0	0	0	100
16	22,6	1,10	1,10	98,90
11,2	527,8	25,58	26,68	73,32
8	639,5	31,00	57,68	42,32
5,6	446,4	21,64	79,32	20,68
4	281,9	13,66	92,98	7,02
2	126,8	6,15	99,13	0,87
1	7,2	0,35	99,48	0,52
Pan	9,3	0,45	99,93	0,07



Tabel 3.1 Korrelgroepen en eisen aan de (zeef)doorval in % volgens NEN-EN 12620 en NEN 5905

Zeven volgens Basisset + set 1 NEN-EN 933-2	2/6	2/6	2/8	2/8	4/8	4/8	4/16	4/22	4/32	8/11	8/11	8/16	16/22	16/32	16/63
categorie G volgens tabel 2 van NEN-EN 12620	Gc 85/20	Gc 80/20	Gc 85/20	Gc 80/20	Gc 85/20	Gc 80/20	Gc 90/15	Gc 90/15	Gc 90/15	Gc 85/20	Gc 80/20	Gc 85/20	Gc 85/20	Gc 85/20	Gc 90/15
90															98-100
63									100					100	90-99
45								100	98-100				100	98-100	
31,5							100	9-100	90-98			100	98-100	85-99	25-70
22,4							98-100	90-99		100	100	98-100	85-99		
16			100	100	100	100	90-99		25-70	98-100	98-100	85-99	0-20	0-20	0-15
11,2	100	100	98-100	98-100	98-100	98-100		25-70		85-99	80-99	25-70			
8	98-100	98-100	85-99	80-99	85-99	80-99	25-70			0-20	0-20	0-20	0-5	0-5	0-5
5,6	85-99	80-100			25-70	25-70									
4	25-70	25-70	25-70	25-70	0-20	0-20	0-15	0-15	0-15	0-5	0-5	0-5			
2	0-20	0-20	0-20	0-20	0-5	0-5	0-5	0-5	0-5						
1	0-5	0-5	0-5	0-5											

Figure 24. Table used for verification of gravel – NEN-EN 12620 and NEN 5905; the relevant column is highlighted in red

The result of the sieve analysis of sand is in Table 15 below. Mass residue R is the weight of the sand remaining in each sieve. The verification of the sizing was done based on the values in the last column of Table 15 and Figure 25.

Table 15. Sieve analysis - sand

Used method: dry sieving				
Mass dry total (M1):		**546** gram		
Sieve (mm)	Mass residue R (g)	Percentage material rest R/M1*100%	Cumulative percentages sieve residue	Cumulative percentages fall 100%-sieve residue%
8	3,2	0,59	0,59	99,41
5,6	31,5	5,77	6,36	93,64
4	36,8	6,74	13,10	86,90
2	53,2	9,74	22,84	77,16
1	58,0	10,62	33,46	66,54
0,5	145,2	26,59	60,05	39,95
0,25	201,0	36,81	96,87	3,13
0,125	16,8	3,08	99,95	0,05
0,063	0,1	0,02	99,96	0,04
Pan	0,0	0,00	99,96	0,04

Tabel 3.10 Algemene Graderingseisen NEN-EN 12620 voor toeslagmaterialen $D \leq 4$ mm.

zand 0/4	zeef [mm]	eis in doorval [%(*m/m*)]
2*D*	8	100
1,4*D*	5,6	95-100
D	4	85-99*

zand 0/2	zeef [mm]	eis in doorval [%(*m/m*)]
2*D*	4	100
1,4*D*	2,8	95-100
D	2	85-99*

zand 0/1	zeef [mm]	eis in doorval [%(*m/m*)]
2*D*	2	100
1,4*D*	1,4	95-100
D	1	85-99*

* Het % mag 100 zijn, indien onderliggende zeven gedefinieerd worden.

Figure 25. Table used for verification of sand – NEN-EN 12620; the relevant rows are highlighted in red

Appendix II. – Accelerated aging, durability

The chosen method to explore the durability of the bio-concrete with Misacanthus fibres is to conduct an accelerated weathering/aging process, which takes place at the concrete laboratory of Scalda. For the test, the spare cubes of each mixture are subjected to the imitation of extreme weather. During the 30 cycles of alternating conditions the cubes are submerged in water at room temperature for 6 hours, after which the cubes are put into the oven at 70°C for 18 hours. After the completion of the 30 cycles, the compressive strength of each sample is evaluated.

Figure 26. Bio-concrete cubes after accelerated weathering/aging process

The weight of the cubes was measured before as well as after the aging process. Observing the acquired data, it appears that the mass of the cubes decreased, except for the sample of Mixture 5, where the weight increased slightly. It is an odd phenomenon, as occasional loss of materials (small stones near the edges) occurred on the fifth cube during the test, while the other cubes remained intact.

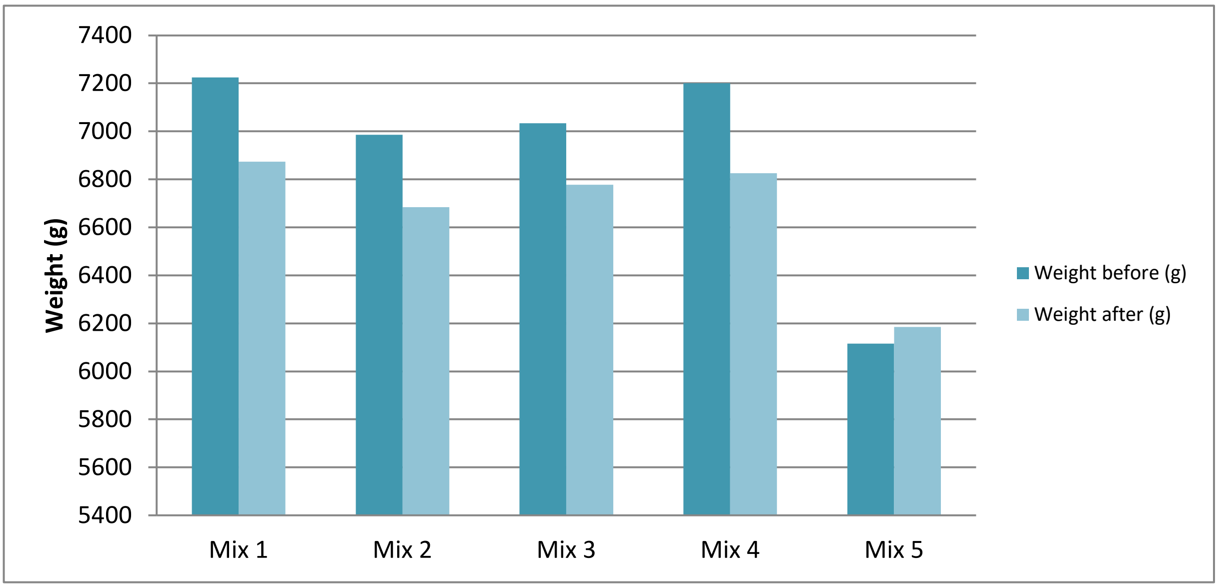


Figure 27. Weight of cubes before and after accelerated weathering/aging process

The results of the compressive strength test after the aging do not reveal a straightforward trend. Compared to the average values measured after 28 days of hardening, loss of strength is observed in case of Mixture 1 and Mixture 5, while the resistance of Mixture 3 and Mixture 4 is increased. The compressive strength of Mixture 2 measured after the 30 cycles is slightly lower, but nearly the same as the average of the original test after 28 days of hardening.

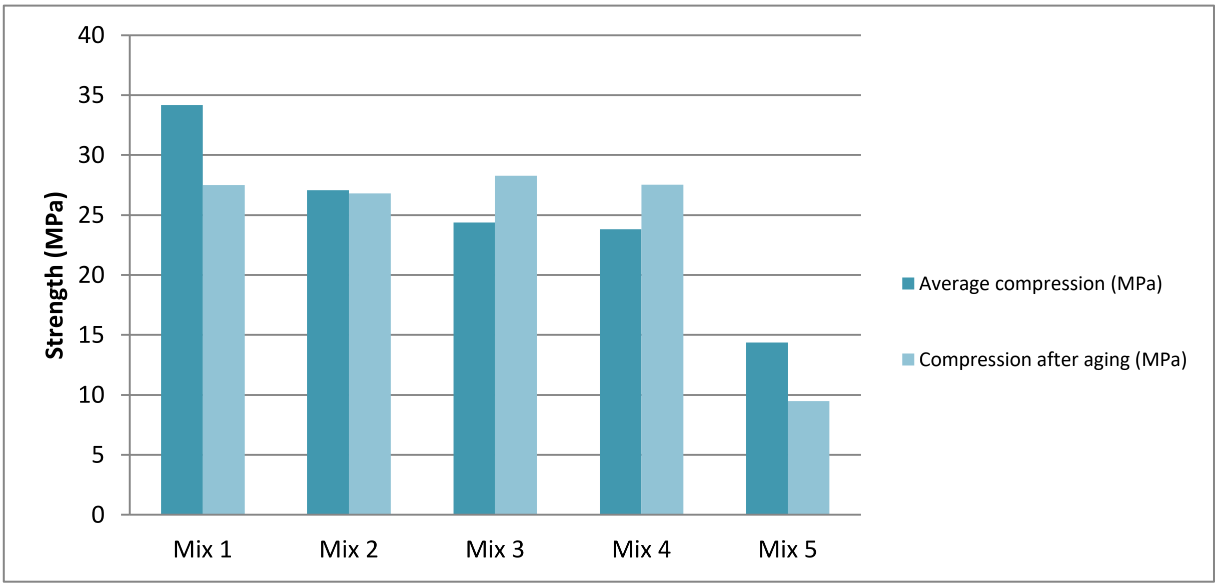


Figure 28. Comparison of compressive strength

Presumably, the results of the compressive strength test after the aging are influenced by the Miscanthus fibre content of the bio-concrete mixtures. The mixtures that experienced a loss in resistance contain the most amount of fibres, above 21% and 23%. The Miscanthus content of Mixture 3 is approximately 20%, while it is 19,4% of Mixture 4 and according to the comparison, these two mixtures gained strength. Mixture 2, achieving roughly identical results before and after the aging process, contains the least amount of Miscanthus fibres, slightly over 18%. The revelation suggests that the higher Miscanthus fibre content decreases the durability of the concrete. However, one specimen of each mixture was subjected to and was tested after the aging process, therefore further research and testing with more samples is required to be able to draw a more reliable conclusion.

Figure 29. Example of cracks on three different aged cubes after the compressive strength test