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Circular Buildings: A Case Study of Sustainable Vacation Homes at Camping de Paardekreek in Kortgene
Research in a Sustainable Delta
Research Paper

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Contents

1 Abstract

The building sector is a large consumer of energy and materials. Most buildings are not sustainable. To mitigate climate change, research into circular buildings is needed. This report includes an analysis of the newly built circular vacation homes in "de Paardekreek"; a camping in the village of Kortgene in The Netherlands. This report aims to answer the research question ’How to improve the sustainability of materials used in vacation homes in Zeeland through analysing the presence of critical raw materials, the produced CO_2 footprint and finding alternative sustainable (bio-based) materials’. The main work of this study including writing a literature review, creating and analysing a material list, defining the critical raw materials (CRMs), conducting a life cycle assessment (LCA) and conducting a practical study to research geopolymer and oyster shell aggregate as an alternative for unsustainable Portland cement concrete. CRMs are materials which have significant economic importance, high-supply risk and lack sufficient substitute. There are only few materials which extract these materials, thus in the future their export may be limited. For those reasons, the European Union has created a list of CRMs. This research investigated CRMs used in the construction industry through analysing the materials used in the construction of the vacation homes. The material analysis concluded that many bio-based materials were used in the circular vacation homes. Therefore, little CRMs were found in the material lists we received from the architects. The CRMs in the products were silicon, magnesium, phosphorous, platinum, rhodium and neodymium. The software "Oneclick LCA" was used to estimate the CO_2 footprint of the vacation homes. LCA is a systematic analysis of potential environmental impacts of products and services during the entire life-time of buildings. Two LCA analysis were done using two different material list. For the first material list, calculations showed that one house emitted 1023 kg CO_2. For the second material list, it was analysed that one house emits 209 kg of CO_2. The material list analysis showed that concrete was the most relevant material for a practical study. The aim of the practical study was to find a sustainable replacement for concrete, with gepolymer concrete and crushed aggregates being the main focus. The strength of the created geopolymer concrete after five days of curing did not achieve the same strength as regular concrete. The compressive strength of geopolymer concrete was between 10 - 13 N/mm^2. A SEM analysis was conducted to research the atomic elements and structure of the crystals and geopolymer concrete. More reserach should be conducted regarding geopolmer and seashell aggregate. In the future, geopolymer concrete has potential to become an alternative concrete replacement.

Keywords: critical raw material, life cycle assessment, geopolymer concrete, oyster shells, aggregates, CO_2 emissions, vacation homes, circular building, bio-based materials

2 Introduction

Sustainable development is a principle with regard to the environment, development and governance which occurred as a response to global challenges. This principle was brought into light in the 1987 Brundtland report, where sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1],[2]. Yet today, the goal of sustainable development is under threat due to the continuous global issues of climate change, resource depletion and ecological degradation. The primary source of these issues are energy and material use, and their increasing consumption urgently needs sustainable solutions [1].

Sustainable, sustainable development and sustainability are often hard to define and some scientists classify these terms as ‘buzzwords’. Buzzwords are popular words without a defined and clear meaning and are often vague. The use of buzzwords can cause wrong assumptions, interpretations, exaggerations, and unsustainable interventions instead of sustainable ones [3]. The definition of sustainable construction is according to Agenda 21 of the Sustainable Construction Industry in Developing Countries is perceived to be an integrative and holistic concept that is striving to restore balance and harmony between the three pillars of sustainability; environment, society, and economy [4],[5].

A large consumer of energy and materials is the building sector, which is of the human activities with the largest environmental impact [6]. According to Memon, the building sector consumes 30 percent of global energy, and produces 1/3 of all greenhouse gases [8]. Furthermore, the building sector has consumed 70 percent of all extracted materials throughout time [9]. More specific consumption numbers are given by Dixit et al, as they state that the building sector “depletes two-fifths of global raw stone, gravel, and sand and one-fourth of virgin wood, and consumes 40 percent of total energy and 16 percent of water annually” [10]. The magnitude of environmental impact due to building and their construction sector stresses the importance for sustainable solutions within this sector.

However, in order to find sustainable solutions within the building sector, it is important to understand the needed standards for sustainable buildings. Berardi points out a definition used in the building sector, where a building is defined as sustainable if it contributes to a healthy environment and is built by ecological principles and is resource efficient [7]. Therefore, a sustainable building needs to be built efficiently in its use of water, materials and energy, and also needs to have little impact on the environment through its life cycle. Parameters to assess the sustainability of buildings are often greenhouse gas emissions and reduced energy consumption [7].

Further clarification on important sustainability criterias is given by the third-party verification program LEED (Leadership in Energy and Environmental Design). Developed by the United States Green Building Council and the World Green Building Council, it was the first official green building certification program which offered clear and specific guidelines for construction of sustainable buildings. Their rating system is primarily focused on resource efficiency, emission reduction, health and sustainable, cost-efficient building life-cycle [11]. Representing the importance of the construction location, building materials and resources, building performance - water and energy efficiency, but also pollution reduction on construction sites. Another aspect LEED takes into account is the project’s innovation with the aim to promote green design and sustainable construction strategies [11].

Within the topic of sustainable buildings, this project will focus on sustainable solutions regarding a vacation home in villapark ‘De Paardekreek’ in Kortgene, Netherlands. The vacation home is designed by the local architecture firm WTS Architecten [12]. The designs from the firm range from residential buildings, vacation homes, and office buildings. Their vision is that a building is a new moment in time to make a difference in sustainability and shapes that are interesting, more beautiful and more exciting [13]. More specifically, the environmental aspect of the vacation home will be focused on the building materials, which will be evaluated by two parameters important for sustainability: critical raw material content and embodied CO_2 emissions. Additionally, a practical case study will be done on a material with a significant environmental impact. A sustainable replacement will be found for this material, followed by testing on its physical properties to verify its suitability as a replacement. Considering the topic of the project, the research question will be the following:

How to improve the sustainability of materials used in vacation homes in Zeeland through analysing the presence of critical raw materials, the produced CO2 footprint and finding alternative sustainable (bio-based) materials.

Throughout the project several sub-questions were in focus. The three sub-questions are:

1. *What critical raw materials are involved in building construction material?*
2. *What is the embodied CO2 emission of building materials in a vacation home?*
3. *Practical study: what material would be a suitable sustainable (bio-based) replacement due to its embodied CO2 emission, critical raw material content and tested physical properties?*

3 Literature Review

3.1 Critical Raw Materials

The development of the modern world and societies well-being is primarily dependent on the secure supply and use of natural resources and raw materials. The continuing population growth and economic growth in recent industrialized countries firmly increases the demand of raw materials. As stated by [14], the consumption of raw materials per capita is considerably higher in the advanced countries than the developing countries. It is evident how pivotal the raw materials are to the global economy, thus it is necessary to provide a secured access to them.

This has been an alarming concern to the European Union. Therefore, the European Commission has created a list of so called "critical raw materials" for Europe [15]. The first list of critical raw materials was published in 2011 which has since been updated 3 times based on renewed methodologies and novel approaches for CRMs selection. The most recent list was created in 2020 and features 30 raw materials.

The materials which are classified as "critical" are not considered scarce, rather they are defined as critical raw materials (CRMs) because of the following:

1. They have a significant economic importance - CRMs are used across all industries and through all supply chains.
2. They have a high-supply risk - CRMs have a high import dependency as many of these materials are only concentrated in certain countries.
3. They lack an adequate substitute - CRMs possess unique and reliable material properties. To give an example, CRMs are irreplaceable in solar panels, wind turbines, electric vehicles, and energy-efficient lighting [15],[16],[17].

The figure 1 below presents the list of critical raw materials assessed in 2020 by the European Union. The European Commission has identified 30 critical raw materials out of 83, from which 66 were considered as candidate materials.

2020 Critical Raw Materials			
Antimony	Fluorspar	Magnesium	Silicon Metal
Baryte	Gallium	Natural Graphite	Tantalum
Bauxite	Germanium	Natural Rubber	Titanium
Beryllium	Hafnium	Niobium	Vanadium
Bismuth	HREEs	PGMs	Tungsten
Borates	Indium	Phosphate rock	Strontium
Cobalt	Lithium	Phosphorus	
Coking Coal	LREEs	Scandium	

Figure 1: List of critical raw material (2020) [16].

The prime concern of CRMs is the aforementioned high-supply risk. A substantial amount of these materials are only extracted in a few countries which raises the risk of supply shortages. In particular, China is the main supplier and consumer of several CRMs e.g antimony, bismuth, magnesium, REEs, etc [16]. Additionally, the processes of smelting, materials processing and refining of metals are only performed in several countries. Some of these countries foist restrictions and limit the export of raw materials hence cause destructive consequences throughout various industries [16], [19].

On that account, today many projects deal with recovery and recycling CRMs from waste electrical and electronic equipment. The study of Løvik et al. [18], highlighted the recent work and improvements of the industries activities and other European research projects on primary production, recycling and substitution of CRMs in order to acquire better supply of raw materials. Their analysis concluded that the recovery of some materials is prioritised without being considered as more "critical". In addition, the research uncovered the existing difficulties in the design for recycling and waste collection, and neglection of recycling other materials such as beryllium and magnesium.

When it comes to materials and design, Hofmann et al [20] and Ferro and Bonollo [15], believe that many material scientists do not take into consideration CRMs when choosing materials for certain applications. Thereby, Ferro and Bonollo [15] proposed a four step method for metallic alloy selection in regards to CRMs. The suggested methodology is not specified only for metallic alloy, but rather it is a strategy that could be implemented for any material selection in order to minimize the use of CRMs. The first step of the methodology demonstrated in [15] is to translate the design requirements into a prescription for a material, identify the constraints that must be met and the objectives that are desired. Second, screen all materials that do not meet the given requirements. The third step is to rank the selected materials in order by their ability to meet the objective. And finally, the last step is to choose the material out of the final material candidates.

Thus far, there has been no research on the activities the construction industry is undertaking with regards to resolving the issue with CRMs. This is a topic which is yet to be explored. The current available information on CRMs and construction building materials, only allows to make a general analysis of what are the most common CRMs used in building construction. Figure 22 in the Appendix presents some CRMs used in the construction sector.

3.2 Life Cycle Assessment

A Life cycle assessment (LCA) is a common tool in order to estimate the CO_2 emissions for the whole life cycle of buildings. LCA is a systematic assessment of the environmental impact of product systems with a "cradle-to-grave" approach [22]. As a part of the assessment, one creates an inventory of inflows and outflows of manufacturing systems, which is related to environmental data [22], [24]. This inventory is called the Life Cycle Inventory (LCI). The life cycle inventory is involved in data collection, validation and calculation procedures, and is therefore at the heart of the process [24]. Data collection for the inventory can be done through a literature review or a simulation process. Also, commercial databases with life cycle inventories exist, which can be used together with software [25]. Generally, there are two types of life cycle inventories: process-based and economic input/output-based [26]. The process-based approach estimates the environmental impact of a good/service through its production process without taking into account the indirect impact in the supply chain. In contrast, an input/output assessment includes indirect impact in the supply chain of the product/service [27]. The picture below comes from a research paper from Beylot et al, where the results from a process-based and input/output-based method were compared.

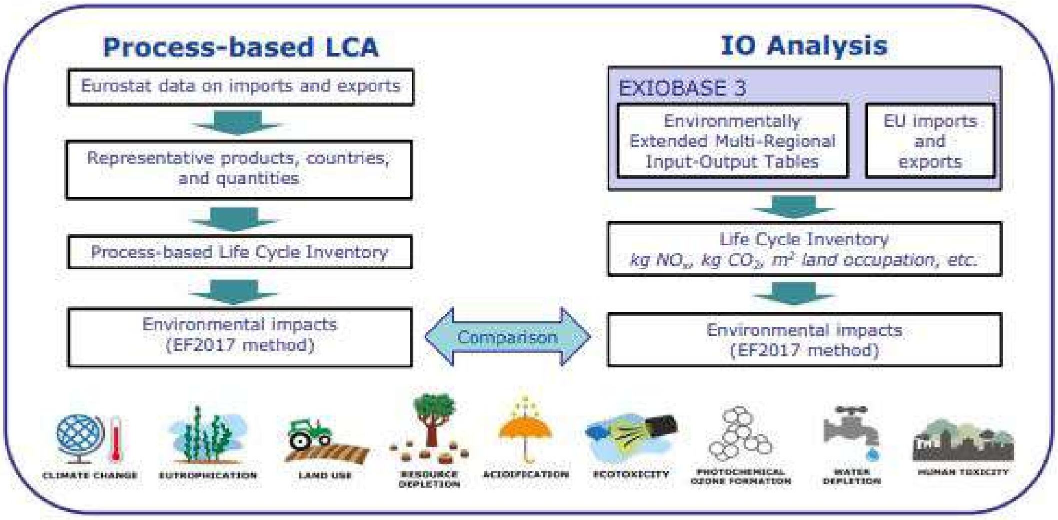

Figure 2: The steps taken to conduct a process-based and input/output-based life cycle assessment from a research paper from Beylot et al [28].

In the existing literature on micro-level research on building emissions, data on building materials are generally found through the existing literature, and used through a process-based analysis to calculate CO_2 emissions . This is the case in a study about the environmental impact of a dwelling home in Scotland carried out by Asif et al. In the study, a life cycle assessment was done on key building materials based on their embodied energy levels given by Berge's The Ecology of Building Materials [29]. The embodied energy levels include the whole life cycle of the materials through production, transportation and disposal/recycling [30]. A similar analysis was done by Yan et al, in a research regarding the CO_2 emissions of a building in Hong Kong. Estimation of the CO_2 emissions in the building materials due to production, transportation and recycling/disposal was included. However, the study also included the energy used in raising the buildings. The emission factors (g CO_2/MJ) used for an estimation of the building materials originate from a research report conducted by Andrew, A. on CO_2 coefficients in building materials. Furthermore, the CO_2 emissions from transporting the materials were estimated by a formula dependent on the mass (in tons), distance (in km) and emission factor of the transportation vessels [31]. The emission factors were based on data from the research conducted by Andrew, and the EEA [32]. Similar process-based life cycle assessments with pre-existing data were conducted by Chen et al, in an analysis of the embodied energy in building materials in Hong Kong [33], and by Dimoudi Tompa, in their investigation of CO_2 emissions due to the construction of two office buildings in Athens, Greece [30].

An input/output analysis is commonly used in macro-level research in existing literature [27], and uses a top down approach to estimate CO_2 levels by sectoral money transactions data [34]. This type of life cycle assessment considers the CO_2 emissions in the whole supply chain of a product/service, which reduces the truncation error occuring in a process-based approach only considering the CO_2 emissions in the product/service [35]. However, input/output data often describes money transactions data on a sectoral scale, which often is not specific enough to use for a life cycle assessment on micro-level. Therefore, the input/output approach is more common in macro level research in the existing literature. For example, Suzuki et al [36] used the input/output approach to estimate the CO_2 emissions due to construction of various Japanese houses. Also, Nässén et al [37] used the input/output approach to estimate CO_2 emissions in the Swedish building sector.

In recent years, there has been improvements in the efficiency of life cycle assessments, due to databases and software. The availability of life cycle inventories has improved through databases, which are linked to and software to carry out life cycle assessments. Most of this development in databases and software has occurred in the United States and Europe, with the development of e.g. the Ecoinvent database, and the Simapro and One Click LCA softwares [22]. This technology has been used in recent research. For example, Petrovich et al used the One Click LCA software for conducting a life cycle assessment on building materials in the construction of a house in Sweden [38].

Despite the technological advancement of the input/output method, there still are pitfalls when using software and databases. First of all, the estimation done by the program often involves assumptions unknown by the user. Secondly, the data used in the software may originate from certain countries, which may not reflect well information about emission levels of similar processes in other countries. Furthermore, the input data used in a software-based input/output method originates from manufacturers, which may have commercial interest and are prone to bias. For example, the manufacturer's may use different standards and justifications when collecting the data. Also, an input/output method is often done in the design stage of a building project, meaning other environmental aspects which unintentionally occur later in the construction will not be included in the life cycle assessment [22].

3.3 Vacation Houses

Before looking at sustainable (bio-based) alternative building materials. It is important to delve into the vacation houses, the area and the environment in which the vacation houses are located.

3.3.1 Location Vacation Houses

The vacation houses are located at the "Camping and Villapark de Paardekreek" located next to the Veerse Meer in Kortgene, a city on the island of Noord-Beveland in Zeeland, The Netherlands (figure 3).

Figure 3: Aerial view of De Paardekreek sight [23].

The Veerse meer is a lake and is not connected to the sea due to two deltaworks the Veerse Gatdam on the West and the Zandkreekdam on the East [39]. The vacation houses will be built on top of an artificial dike. In figure 4, you can see the vacation homes, the dike is actually higher and not located next to the water. This artificial dike is not intended to serve as coastal protection.

Figure 4: Design, cross section and dimentions vacation homes (WTS Architecten).

The lake has salinity levels fluctuating between brackish water and salt water due to a lock that can be opened to improve water quality and water levels [40]. It is important to select materials that can stand the salinity levels of the Veerse Meer. Temperate weather conditions in the Netherlands are quite unpredictable [41]. According to the data there is an on average of 7 percentage precipitation in The Netherlands per year [41]. On average there falls about 800 to 900 millimeters of precipitation a year [41], [42]. The effect of the location, climate, weather conditions, and salinity levels should be considered when the building materials and possible alternative (bio-based) materials are selected.

Figure 5 shows the building site of the vacation homes. Komo concrete plates were placed on top of the dike to create the foundation. Recycled concrete 'lego' blocks were stacked and place on the sides of the building. The vacation houses are prefab wooden boxes. These wooden boxes are placed between the concrete blocks and on top of the concrete foundation. The wooden houses are not fixed and can be relocated if needed, making the houses reusable and circular.

Figure 5: Construction site vacation homes.

3.3.2 Isolation

Energy efficiency and the use of low-emitting products are other important parts of the LEED label [43]. Isolation can be done on various parts of the vacation house, such as, the windows, roof, walls, and flooring.

Regarding the isolation of the windows the most energy efficient is the high efficiency glass HR+++. This glass is also known as Triple-pane High Efficiency glass. There were no mentions of this glass nor any window isolation on google scholar, information could be found on websites found on a google search. These websites were from companies that create or are selling this glass. This information can be biased because these companies want to sell the product. The benefits of HR+++ glass are the high energy and heat efficiency, high isolation and high comfort [44]. Less energy gets wasted, this results in lower energy bills and relatively low extra costs [44]. The cons can sometimes be a color difference of the glass (blue/ bronze) and some light will be blocked by the HR+++ glass [44]. According to Isolationvalue.eu the different U-values, the amount of heat that is lost in the glass, are explained. With these U-values it is important to note that a smaller value means less warmth is lost. A higher value means more energy and warmth are lost [44]. All the windows in the vacation house will be equipped with HR++ glass.

- Standard double glass: U-Value 2,8 – 2,9 W/m^{2}K [44]
- HR+: U-Value: 1,2 – 1,6 W/m^{2}K [44]
- HR++: U-Value: 1,1 W/m^{2}K [44]
- HR+++ (triple glas): U-Value: 0,5 W/m^{2}K [44]

The roofs will not be completely covered with soil. According to the WTS architect the soil used on the roof will not be thick enough to count towards roof isolation. Instead Rockwool isolation is used for the roof and Steico Flex, a bio-based wood fibre isolation, is used for the walls (section 4)

3.4 Bio-based Materials

According to the European Committee of Standardisation (CEN) bio-based can be defined as a material derived from biomass, which can have undergone chemical, physical or biological treatment(s) [45]. A bio-based product is partly or wholly derived from biomass [45]. Biomass is a material with a biological origin but excludes fossilized or geologically formed materials [45]. Examples of bio-based materials include whole or parts of plants, animals, marine organisms, algae, mycelium, plants, trees, etc. Bio-based materials are materials that are derived from a renewable resource, a resource that recovers faster than it gets depleted, and are biodegradable [46]. Furthermore, bio-based materials are often made with a considerably lower energy consumption compared to non-bio-based materials such as aluminium, steel and concrete [46]. Forest biomass can act as a carbon sink and lower energy consumption and reduces CO_2 emissions [46]. Furthermore, to increase sustainability the replacement of nonrenewable to renewable resources are advised [46].

3.5 Geopolymer Concrete

Concrete is the most commonly used material in the building sector, due to its low price, durability, availability of constituent materials and its possibility to be shaped. The most extensively used binding material in concrete is cement, which is a powder that creates hydration products when in contact with water [48]. This hydration product "glues" rock fragments together, creating traditional concrete. Portland cement, which is the most common type of cement, consist of limestone and clay as basic raw materials. These raw materials are heated to 1450 degrees during the production process, which emits one ton CO_2 for every ton of cement [52]. In total, the production of Portland cement is responsible for 6% of global CO_2 emissions, with its production expected to increase by 9 percent annually [48]. In order to reduce greenhouse gas emissions, it is important to find sustainable solutions regarding the production of cement.

A suitable replacement for Portland cement is geopolymer cement. This cementing material has a patchy silicate-alumino polymer structure, which is created in the geoplymerization process between a alumino-silicate source and an alkali activating solution [48]. The reaction between the alumino silicate solids and the activating solution creates a binder paste that begins to solidify. The alumino silicates are often acquired by burning and recycling watershed materials, and often occur as industrial byproduct materials. Examples of alumino silicates are red mud, fly ash, blast furnace slag and metakaolin. The alkali activating solution is made by mixing sodium silicate and sodium hydroxide or potassium silicate and potassium hydroxide . Also, an alkali activator solution can be made by mixing sodium hydroxide, silica fume and water [53] [48].

3.6 Oyster Seashells as an Aggregate

The high use of concrete around the world results in the high demand of concrete's ingredients like crushed aggregate, coarse aggregate and cement [49]. The extraction of the aggregates and manufacturing of cement creates huge worldwide ecological dis balance. According to Mohanalakshmi et al., almost all construction industries use river sand for the making of concrete. Thus, its large extraction may lead to depletion of river sand. To prevent this from happening, recently many researchers have investigated and tested the properties of concrete with seashell waste as an aggregate alternative. Oyster seashells are especially preferred option. Through the work of Mohammad et al., it has been proven that oyster seashells develop better and stronger concrete.

For instance, one study created concrete while using oyster seashells are crushed aggregate. The oysters were collected from the bank of Okwagwe river in Nigeria, and since they are used as crushed aggregate, the particle size was less than 4.75 mm [51]. Six specimen with different crushed aggregate percentages were created, varying from 0% to 25%. The compressive strength test was performed after 3, 7, 14 and 28 days of curing. The study concluded the increase of the concentration of crushed aggregate decreases the strength of concrete and instead creates more workable concrete. Furthermore, the concrete achieved the best strength after 28 days of curing which is the same case as regular concrete.

4 Material list

Throughout the project, the researchers have received two different material lists from WTS architects. Based on these lists, three excel material lists were created. Each material was included in the list in dutch and was translated into English. The dimensions, volumes, weight, density, origins, the sources of this information and additional notes were included in the excel file and web links were added. For several materials, the dimensions, measurements, weight for one and all eight houses, density and origin were not specified. Due to this lack of information several estimations were made. The original material lists, excel files and estimation methods can be found in subsection 10.2.1.

The previously mentioned materials in the excel files were color-coded. Using green, red, yellow and transparent (no color).

1. Green: was used for bio-based materials.
2. Red: was used for Critical Raw Materials (CRM) and/ or non-bio-based materials.
3. Yellow: was used for materials that were unclear.
4. Transparent: was used for non-material items in the list.

Most materials in the material list were bio-based. In total 51 bio-based materials were found. Examples of these bio-based materials were Spruce, Birch and Picea Abies wood for window frames, walls and flooring. Furthermore, a wood fibre insulation was used called Steico flex. Only 11 materials were non-bio-based, such as Rockwool, vapor foil and concrete.

In the original material list, 20.426 kg galvanized steel was used to fortify the roof to hold the soil and plant layer. Buying this amount of recycled galvanized steel is hard. Due to a lack of available galvanized steel, the architects updated the design. In which soil was only used in two small plant boxes on top of the roof. With this change, steel was not needed anymore.

The materials, in the excel lists, were used to create the LCA. The materials included in the LCA were noted down in a separate column the excel sheets.

5 Methods

5.1 Critical Raw Materials

The first step when identifying CRMs was to check the chemical composition of all materials used in the construction of the vacation houses. Then, select those which consist of CRMs. To clarify, only the CRMs of 2020 were considered when selecting the building materials.

The final step was to calculate the percentage of CRMs in the previously marked materials. The following formula was implemented for calculating the presence of CRMs percentage in the building materials:

$$\frac{Mass\ (of\ CRM)}{Mass\ (of\ total\ compound)} \times CRM\ \%\ in\ building\ material \tag{1}$$

Please refer to subsection 10.2.1 in the Appendix to find the sources used for doing this analysis.

5.2 Life Cycle Assessment

The method used to perform LCA was fairly simple. Since there was restricted choice of materials available in the LCA software, the materials chosen must have had similar material properties to those in the material list.

Furthermore, the materials should originate from Europe because the materials used for constructing the vacation houses almost all come from the Netherlands. Transportation carbon emissions are also included in the analysis done by the LCA software.

The LCA analysis was performed for only one of the vacation homes. So all input data relates to the amount of materials needed for the construction of one house. The units used for the quantity of the materials were tons.

For more information how each material was selected from the LCA data please refer to subsection 10.2.2 in the Appendix.

5.3 Practical Study

The aim of the practical study was to create a sustainable material, which would act as a suitable replacement for a material in the vacation homes with environmental impact. Furthermore, the suitability of the created material would be verified by testing its physical properties. In the vacation homes, concrete appeared to be the construction material of significance with the largest environmental impact, while the other materials of significance were bio-based. Hence, the focus of the practical study was to identify a sustainable replacement for concrete, create this material and conduct relevant testing of its physical properties.

Geopolymer concrete was chosen as the material to make and test in this practical study. This material is a sustainable replacement for concrete, due to the lower CO_2 emissions in its production process [53]. More information concerning geopolymer concrete can be found in the literature review, in subsection 3.5. Furthermore, oyster shells were used as an alternative fine aggregate for sand. More information concerning oyster shells as an aggregate can be found in subsection 3.6. As concrete is mostly used to withstand compressive forces, compressive strength is the most important characteristic for quality control of concrete and its usage in structural design [55], [56]. For this reason, compressive strength testing is the most common test carried out on concrete, and is the test which was conducted in this practical study on geopolymer concrete [57].

The making of the geopolymer was based on a recipe included in a paper from Albidah et al, where metakaolin was used as an alumino-silicate source, and a combination of sodium hydroxide, sodium silicate and water was used as an alkaline activating solution [58]. The comprihensiveness of this recipe, and the accessibility of the ingredients, where the main reasons why metakaolin-based geopolymer concrete was chosen for the practical study.

5.3.1 Ingredient List

In the paper from Albidah et al, seventeen mixes were made with different amounts of metakaolin, sodium hydroxide, sodium silicate, water and aggregates. The purpose of this research was to obtain an understanding of mix design impact on the properties of metakaolin-based geopolymer concrete. The result from the research can be seen in Figure 6, which displays the compressive strength of seventeen mix designs (from M1 to M17) over a curing time from 7 to 28 days. Mix design M3 is the reference mix [58].

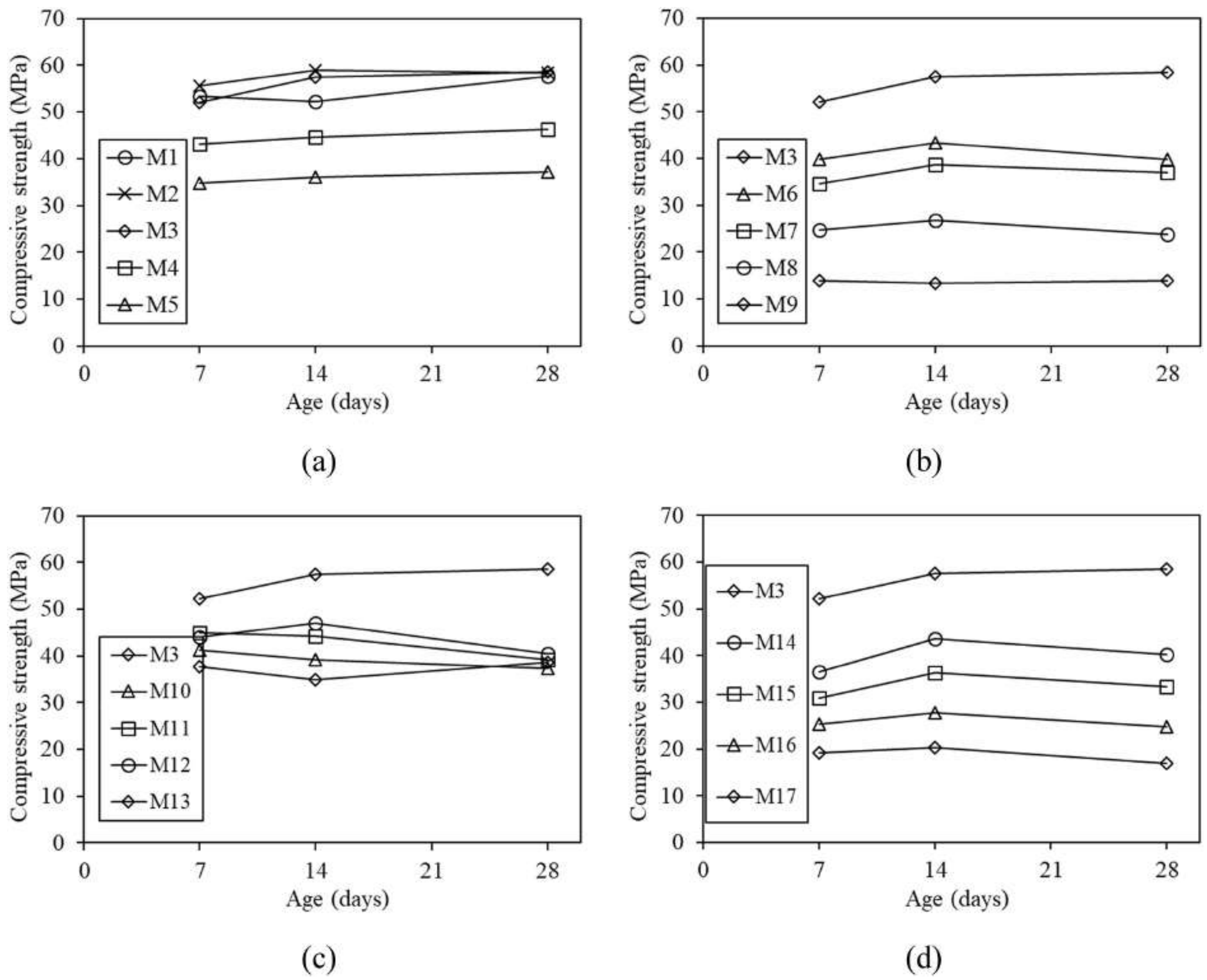

Figure 6: Compressive strength of the seventeen mix designs over a curing time from 7 to 28 days [58].

Because of the limited time to complete the practical study, the curing time of the geopolymer concrete could maximum last for five days. Therefore, in the research conducted by Albidah et al, the mix design with the highest compressive strength after 7 days (shortest curing time in the research), named M2, was chosen as an ingredient list for the practical study. The relative amounts of each ingredient (in kg/m^3) in M2 are given in Table 1 [58].

Ingredient	Amount (in kg/m3)
Metakaolin	350
NaOH solution	126
Sodium silicate solution	181
Water	4.7
White sand	419
Crushed aggregate (max size: 4.75 mm)	180
Coarse aggregate (max size: 10 mm)	1272

Table 1: Relative amounts of the ingredients in the M2 mixture in the research by Albidah et al [58].

For the practical study, some adjustments were made to the M2 ingredient list from Albidah et al (Table 1). The crushed aggregate was replaced by the same weight of sand. Then, 17% of the total amount of sand was replaced by finely crushed seashells. The relative ingredient list used in the practical study is shown in Table 2.

Ingredient	Amount (in kg/m3)
Metakaolin	350
NaOH solution	126
Sodium silicate solution	181
Water	4.7
White sand	497
Crushed seashells	102
Coarse aggregate (max size: 10 mm)	1272

Table 2: Relative amounts of the ingredients in the practical study

5.3.2 Preparation Oyster Shells

Oyster shells were collected on a small rocky beach next to the Westerschelde near the village Griete in Zeeuws-Vlaanderen (figure 7).

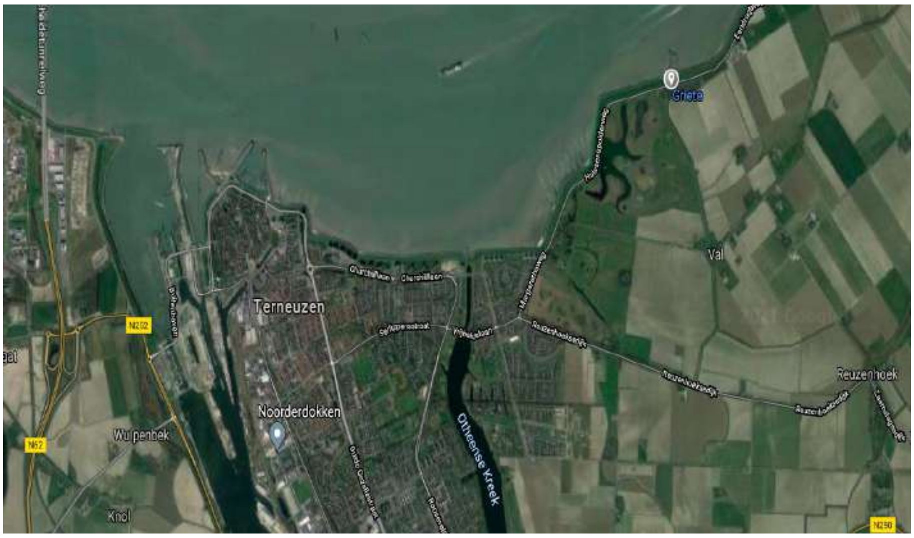

Figure 7: Collecting oyster shells in Griete location indicated with a grey arrow.

To prevent contamination of the specimen with salt, sand and organic remains the oyster shells were cleaned, brushed and rinsed with water. Thereafter, the shells were spaced out and dried in the sun (figure 8).

Figure 8: Drying oyster shells.

The seashells were crushed into fine grains to make them suitable as a crushed aggregate. A plastic bag was cut open to make a plastic sheet. Then, the sheet and a rug was used to surround the shells. The surrounded shells were smashed with a hammer. A picture of the process can be seen in Figure 9.

Figure 9: Smashing the seashells.

Ideally a mill is used to make the oyster shell aggregate fine. The lab the researchers used had no mill. Alternatively, a coffee grinder was used to make the oyster shells smaller. Using this coffee grinder made the creation of crushed aggregate easy. Eventually the coffee grinder broke and a mortar and pestle was used instead. This process took a lot of time and only a small amount of crushed oyster shells was created. After crushing the oyster aggregate was sieved (figure 10).

Figure 10: Sifting crushed oyster aggregate.

5.3.3 Preparations, Casting and Curing

The procedure of initally preparing ingredients and casting and curing the geopolymer specimen was based on Albidah et al, with minor configurations in the usage of equipment. The result was the following procedure list for the practical study:

1. The total volume of geopolymer concrete was calculated by summing the volume each mold. Then, the mass of each ingredient can be calculated from the amounts (the mass relative to the total volume) given in Table 2.
2. A sodium hydroxide solution with a concentration of 14 molar was made by dissolving 97% pure sodium hydroxide pellets into tap water. The pellets were slowly added to the water while stirred. The method of slowly increasing the concentration by adding sodium hydroxide into water is important for safe handling of the corrosive substance. A hazardous situation would occur if one changed the order of mixing the ingredients. If water was added into a given volume of sodium hydroxide, a highly concentrated reaction would occur initially in the mixing. The heat released from the highly concentrated reaction could boil the water, causing violent splashing of the corrosive sodium hydroxide solution. Such a situation would be hazardous.

3. All liquids (water, sodium hydroxide solution and sodium silicate) were mixed.
4. All dry components including coarse aggregate, crushed aggregate and metakaolin were mixed with an electric mixer.
5. The liquid was added to the dry component mixture, and stirred with the electric mixer until a homogeneous mixture was achieved.
6. The geopolymer concrete paste was then added into molds, and vibrated using a vibrator table.
7. The filled molds were cured in room temperature. The top surface of the molds were exposed to air.
8. After 3 days, the specimen were demolded, and cured in room temperature to the testing day (5 days).

5.3.4 First Attempt

In the first attempt to make the geopolymer concrete, 9 cylindrical molds with a diameter of 4cm and a height of 15cm were planned to be used. For the estimation of ingredient amounts, the volume of an additional mold ($0.000\,188\,4\,\mathrm{m}^3$) was accounted for as a buffer in case of spillage during the mixing and molding process. Therefore, the plan was to make a geopolymer concrete mixture with a total volume of 10 molds, giving a total volume of $10 * 0.0001884 = 0.001\,884\,\mathrm{m}^3$. The mass of each ingredient (in kg) was calculated by multiplying the total volume with the relative amounts (in $\mathrm{kg/m^3}$) of each ingredient given in Table 2.

The first attempt to make the geopolymer concrete differed somewhat from the procedure list given in subsection 5.3.3, due to the lack of an electric mixer and vibration table. The ingredients were rather stirred by hand, and the step of vibrating the molds was skipped.

During the mixing of dry and liquid components, additional water was added as the mixture appeared too dry. An excessive amount of water was added, as the mixture turned into liquid with the exception of the coarse aggregates. Due to the mistake of adding an excessive amount of water in the geopolymer concrete mixture, the first attempt was considered a test-run. Still, the mixture was added into three molds, to investigate if the mixture would harden. More attempts were needed to create a thicker geopolymer paste.

5.3.5 Second Attempt

In the second attempt to make the geopolymer concrete, six cube-shaped molds were planned to be used with side lengths of 15cm. When estimating the total volume of geopolymer concrete mixture needed, the volume of one additional mold was included as a buffer that accounts for spillage in the mixing and molding process. As the volume of a single mold was $0.003\,375\,\mathrm{m}^3$, the total volume of the geopolymer mixture was $0.033\,75\,\mathrm{m}^3$. The mass of each ingredient was then calculated by multiplying the total volume of the mixture with the relative amounts given in Table 2.

The second attempt to make a geopolymer concrete also differed from the procedure list subsection 5.3.3, as the mixtures were stirred by hand, due to the lack of an electric mixer. However, an electric concrete vibrator was acquired for vibrating the molded geopolymer concrete specimen.

The total volume of the geopolymer mixture was larger than in the first attempt (5.3.4), causing the stirring of ingredients to be a cumbersome process. The stirring of ingredients was slowed down to the weight of the mixture, causing the geopolymer binder (mixture of the metakaolin and water components) to harden before a homogeneous mixture was acheived. Small lumps occured in the mixture, as can be seen in Figure 11. The mixture was not workable, so the remaining process to make the geopolymer concrete was stopped at this point. A third attempt was needed with improved mixing equipment.

Figure 11: Lumps of aggregates and hardened binder occured, as the binder started to harden before a homogeneous mixture was achieved.

5.3.6 Third Attempt

The third attempt to make the geopolymer concrete was carried out in the concrete lab at the Scalda facilities in Vlissingen, Netherlands. Four cube-shaped molds with side lengths of 15cm were used, giving a total volume of $0.0135\,\mathrm{m}^3$. The total mass of each ingredient was calculated by multiplying the total volume of the mixture ($0.0135\,\mathrm{m}^3$) with the relative amounts (given by $\mathrm{kg/m}^3$) in the ingredient list shown in Figure 2.

The procedure list in subsection 5.3.3 was closely followed, as an electric mixer was used for the stirring process, and a vibration table was used to release air bubbles from the molded geopolymer concrete specimen. Figure 12 shows the electric mixer prior to mixing the dry components (step 4 in the procedure list in subsection 5.3.3). After mixing the wet and dry components, the mixture seemed too dry for a good workability. Therefore, 800 ml of water was added. More water could have been added for even better workability. The mixture was added into the four molds, and left for 3 days to cure. The molded specimen can be seen in Figure 13.

The demolded specimen before curing can be seen in Figure 14. Each specimen was weighed after being demolded, and their densities were calculated. After curing for 5 days, the specimen were again weighed, and their densities were calculated.

Figure 12: Electric mixer used for the stirring processes.

Figure 13: The four molded specimen.

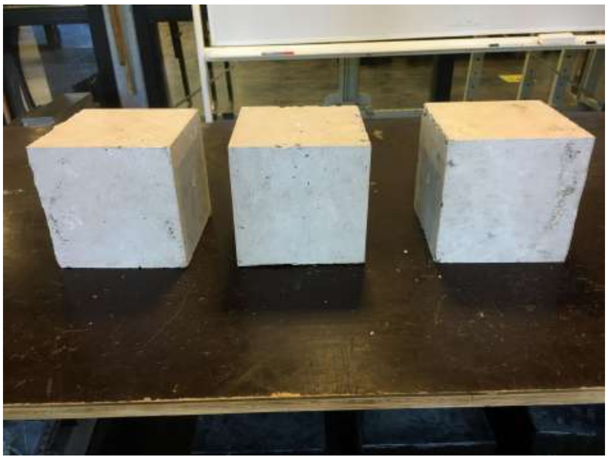

Figure 14: specimen after being demolded and before curing.

Compressive Strength Testing

The compressive strength test was conducted on one of the four specimen before curing. The other three specimen were tested after curing. Then, the compressive strength of the specimen before and after curing was compared.

6 Results and Discussion

6.1 Critical Raw Materials

The CRM analysis concluded that there are four building materials which consist of CRM. Those materials are: concrete, cement, hard steel and glass (see Figure 15). Concrete and Cement consists of: silicon and magnesium. The difference is the quantity of silicon in the composition of concrete. Hard steel has silicon and phosphorus in its constitution. Lastly, there is glass. Glass has the most critical raw materials in its composition. Glass contains silicon, magnesium, platinum, rhodium and neodymium.

The last adjustments made in the material list resulted in removing almost most of the steel used for constructing the vacation houses. Thus, the final CRM analysis concluded the list of construction materials consisting of CRMs contains only three materials: concrete, cement and glass.

Construction Materials	CRMs in construction materials
Concrete	Silicon (47.06%), Magnesium (0.6-1.8%)
Cement	Silicon (9.34-11.68%), Magnesium (0.6-1.8%)
Hard Steel	Silicon (0.5%), Phosphorous (0.03%)
HR++ Glass	Silicon (32.21-34.55%), Magnesium (0-9.64%), Platinum (10%), Rhodium (1%), Neodymium (4.28-12.86%)

Figure 15: Presenting CRMs in construction of vacation homes in Zeeland.

6.2 Life Cycle Assessment

The first LCA analysis suggested that one vacation house produces 1023 kg carbon emission and thus was graded with the worst grade - G. These were surprising results since most of the building material used is wood. It was hypothesised this result might be due transportation. When working on the LCA, if some materials couldn't have been found in Europe, their alternative was selected from somewhere else. However, when the LCA was reexamined only one material was identified to be outside of Europe, indicating transportation was not the problem. This is also confirmed by the figure below (see Figure 16).

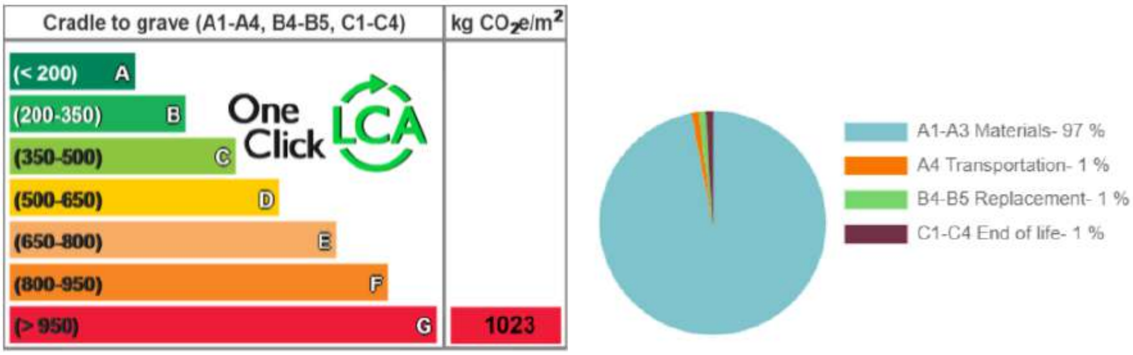

Figure 16: Results from the first LCA analysis.

As discussed above, the material list has experienced a few changes during the duration of the research project. The latest changes included replacing the "regular" concrete with a recycled concrete, and removing almost most of steel in the building construction. When the LCA was upgraded with this information, the following results were achieved (see Figure 17). The LCA graded one vacation house with B. In fact, when steel was removed, the emissions were decreased for 77%. Therefore, the end result is that one house produces 209 kg of carbon emission.

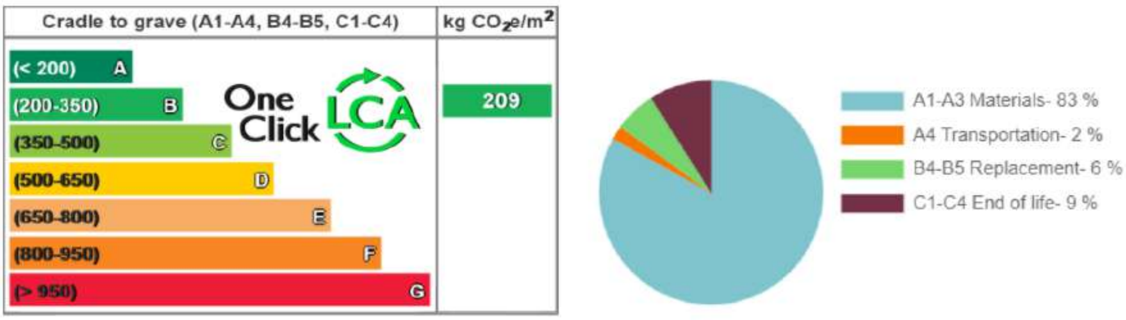

Figure 17: Results from the second LCA analysis.

A third LCA analysis has been performed for the very first material list provided by the WTS architects. To see the results from that LCA please refer to subsection 10.3.1 in the Appendix.

6.3 Practical Study

6.3.1 First Attempt

The first attempt was considered a test-run to make the geopolymer, due to the mistake of adding excess water to the mixture, causing the mixture to be in liquid form with low viscosity. The result was three porous geopolymer specimen that were easily breakable and unsuitable as a concrete replacement. The resulting properties of the specimen are supported by conclusions found by Albidah et al **??**. According to their research, compressive strength of metakaolin-based geopolymer concrete decreases with increased water to solids ratio. Furthermore, increased water to solids ratio increases water absorption properties (related to porosity) of the material [58]. In Figure 18, one can see a specimen that broke during the demolding process due to its fragility.

Figure 18: Fragile specimen due to excess water usage in the mixing process.

6.3.2 Second Attempt

The second attempt was stopped when the mixing of dry and wet components failed to give a homogeneous mixture. The result was a mixture with lumps. After a couple days of curing, the mixture had solidified in the bucket.

6.3.3 Third Attempt

The third attempt was considered successful, as the procedure list (in subsection 5.3.3) was closely followed, and the demolded specimen before and after curing had properties seemingly similar to concrete. The weight, density and weight difference (given numerically and in percentage) of each specimen before and after curing is showed in Table 3.

Specimen	Weight before curing (kg)	Density before curing (kg/m3)	Weight after curing (kg)	Density after curing (kg/m3)	Weight & density change (in %)
1	7.506	2223.941	7.285	2158.607	2.938
2	7.416	2197.452	7.2022	2133.985	2.888
3	7.7851	2306.696	7.548	2236.444	3.046

Table 3: Weight, density and percentage change of the concrete specimen before and after curing.

The fresh geopolymer specimen (before curing) are less dense than fresh specimen in the research from Albidah et al [58]. In the research conducted by Albidah et al, the densities of the fresh specimen range from 2376 to 2411 kg/m^3, while in this practical study, the densities of the fresh specimen range from 2225 to 2307 kg/m^3 [58]. The most reasonable explanation for less dense specimen in this practical study compared to Albidah et al, is the usage of less dense aggregates. The ingredient list was obtained from Albidah et al (original ingredient list from Albidah et al is shown in Table 1). However, the crushed aggregates (gravel with max length of 4.75mm) were replaced with sand. Furthermore, 17% of all sand aggregate was replaced with fine grained oyster shells (practical study ingredient list can be seen in Table 2).

The percentage change of weight and density before and after curing were similar for this practical study and Albidah et al. The percentage change in this practical study ranged from 2.9% to 3%. In the study conducted by Albidah et al, the percentage change ranged from 2.8% to 4.35% for a curing time of 7 days [58]. The similar percentage change in density/weight for this study and Albidah et al indicate a similar percentage of excess water evaporated in comparison to the original water content.

During the curing process, a thick dark layer was formed on the top side of the concrete. This side was continuously in contact with air. Furthermore, crystals occurred during the curing process on the sides of the specimen that were in contact with the mold (every side of except for the top and bottom of the cube). The crystals on the specimen can be seen in Figure 19. The crystals were analyzed with a SEM microscope, with the results being documented in subsection 6.3.5.

Figure 19: Crystals occurred on the sides of the cube that were in contact with the mold.

6.3.4 Compressive Strength Testing

The compressive strength of each specimen is shown in Table 4.

Specimen	N/mm^2
1	13,22
2	12,25
3	12,71
4 (tested before curing)	10,53

Table 4: Compressive strength of each specimen.

As one can see in Table 4, the compressive strength (in N/mm^2) of the specimen increased after curing for five days. The increase in compressive strength after curing correspond to descriptions in the existing literature [59]. Furthermore, the compressive strengths of this practical study (10.53 N/mm^2 - 13.22 N/mm^2) falls within the range of compressive strengths found for metakaolin-based geopolymer concrete by Kalaiyarrasi et al. In their research, the specimen had the same shape and dimensions (cube shaped with side lengths of 15cm) as in this practical study, and the range of compressive strengths were from 8.4 N/mm^2 to 21.5 N/mm^2 [60]. The impact of ingredient composition on the compressive strength of metakaolin-based geopolymer concrete is beyond the scope of this practical study.

The compressive strength of the geopolymer concrete in this practical study is only a suitable replacement for Portland cement-based concrete with a low compressive strength. The compressive strength for standard concrete specimen with a cube shape and side lengths of 15cm, ranges approximately from 10 N/mm^2 to 30 N/mm^2 when cured for seven days [61]. Therefore, the compressive strength range of the geopolymer specimen in this practical study (10.53 N/mm^2 - 13.22 N/mm^2) overlaps only with the lower part of the compressive strength range for standard concrete.

The curing time (five days) of the geopolymer specimen in this practical study was shorter than curing times used for geopolymer concrete in the existing literature. Usually, curing times last from 7 to 24 days [58] [60]. The compressive strength of the geopolymer specimen may have been negatively affected by the relatively short curing time.

6.3.5 Scanning Electron Microscopy

After the compressive strength testing small pieces of the collected formed crystals and geopolymer concrete specimen were analyzed with Scanning Electron Microscopy (SEM).

Geopolymer Concrete specimen

Figure 20 shows a the structure of the geopolymer breaking fracture. Clear breaking lines are visible. The blue square indicates area of the atomic element analysis. Table 5 includes the atomic element concentrations in the geopolymer concrete. The highest atomic element concentration is oxygen, followed by silicon, carbon, aluminium, sodium and iodine. The highest weight atomic concentration is oxygen followed by silicon, aluminium, sodium, carbon and iodine.

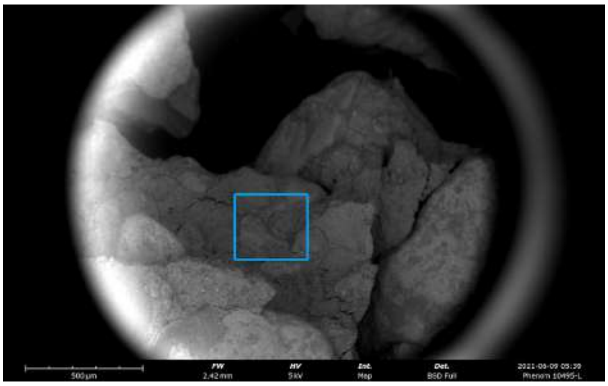

Figure 20: SEM Map concrete specimen.

Element name	Atomic concentration %	Weight concentration %
Carbon	12,6923	8
Oxygen	54,1855	45,5
Sodium	7,45601	9
Aluminium	12,3637	17,5
Silicon	13,2274	19,5
Iodine	0,0750699	0,5

Table 5: SEM concentrations elements in 'crystals'.

'Crystal' specimen

Table 6 shows the concentrations of elements in the crystals that formed on the geopolymer concrete. Figure 21 is showing the structure of the crystals, the blue square indicates area of element analysis. The structure of the crystals were not formed as expected. The structure was rough and completely covered with 'canyons' and holes. The crystals seemed very brittle.

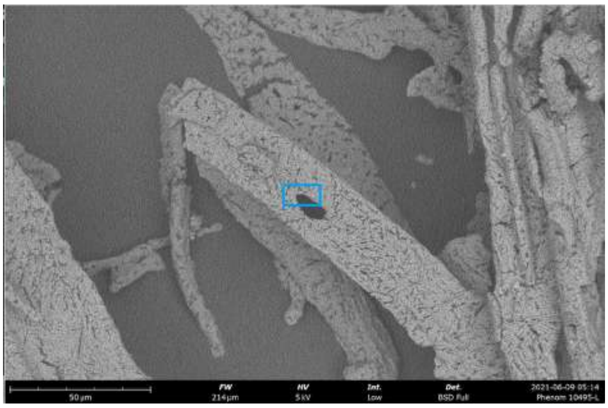

Figure 21: SEM analysis crystal formed on geopolymer concrete.

The highest concentration of atomic elements is oxygen followed by sodium and carbon (table 6). The highest weight concentration of the elements are sodium followed by oxygen and carbon. Zink is likely to be an anomaly and a mistake of the SEM equipment. Another possibility is that Zink contamination occurred during the preparation of the geopolymer concrete.

Element name	Atomic concentration %	Weight concentration %
Carbon	13,7462	8,95522
Oxygen	48,725	42,2886
Sodium	36,6871	45,7711
Zink	0,841704	2,98507

Table 6: SEM concentrations elements in 'crystals'.

The SEM analysis of the article written by Alidah can be found in subsection 10.3.2 [58]. In the article's SEM analyses, the elements are similar to the ones were found in the practical study. The weight concentration percentages were quite similar to our concentrations. The highest atomic element concentration is oxygen, followed by silicon, carbon, aluminium, sodium and iodine. The highest weight atomic concentration is oxygen followed by silicon, aluminium, sodium, carbon, calcium and iron. In the practical study Iodine was found which was not found in the article. In the article in rccipes M1, M6 and M15 Calcium was found. Furthermore, in M6 and M15 iron was found. Even though seashells were used consisting mostly cf calcium carbonate no Calcium was found in the SEM of the practical study. Furthermore, iron was not found in the practical study.

7 Further Research

Since the CRM list is updated every 3 years, we encourage architects and others from the construction industry to regularly review it and be mindful of it when choosing materials for future construction projects.

Regarding the LCA, further analysis on the vacation houses may be done by calculating the annual water and energy consumption. Moreover, the LCA could be also used to analyse the energy use, water use and waste generated on the construction site.

During our literature research we found that limited research was done to compare compare the strength and other measurements of different recipes of geopolymer concrete and Portland concrete. Furthermore, seashell aggregate alternatives were researched for Portland concrete but no studies were found using seashells and geopolymer concrete. The possibility of using shells as an aggregate to replace part of the coarse and crushed aggregates should be researched further.

When more water is added to Portland cement concrete the strength decreases. During the creation of the geopolymer the mixture that was created by following the recipe was very dry. Due to this dryness the mixture was impossible to work with. More water was added to made the mixture easier to work with. This might have resulted in a lower strength of the geopolymer concrete. More research should be conducted on the impact of adding more water to geopolymer concrete and the strength of the end product.

More research should be conducted to find the optimum recipe for geopolymer concrete. Furthermore, it would be beneficial to look into the costs of geopolymer concrete more closely. A comparison should be made between Portland concrete and geopolymer concrete to understand the viability to use geopolymer in the building sector.

Geopolymer concrete has a lower CO_2 footprint and is in this way more sustainable compared to Portland concrete. The chemicals used in geopolymer concrete might have an impact on the environment and on the health of construction workers. More research should be conducted to understand the impacts of the chemicals used in geopolymer concrete.

8 Conclusion(s)

The building sector is a large consumer of energy and materials. Most buildings are not sustainable. To fight climate change it is important to change. After researching the material list we could conclude that many bio-based materials were used in circular vacation homes designed by WTS architects. Little CRMs were found in the material lists. The CRMs in the products were silicon, magnesium, phosphorous, platinum, rhodium and neodymium. After conducting the LCA for the old material list with the software Oneclick LCA a G label and 1023 kg carbon emissions were found. After steel was taken out of the LCA and concrete was replaced by recycled concrete in the updated list the label improved to a B with 209 kg carbon emissions.

In regards to the practical study, the recipe used resulted in a dry and unworkable mixture. Therefore, additional water was added in the mixing process. After five days of curing, the geopolymer concrete only achieved similar strength as the lower part of the strength range for standard concrete.The compressive strength of geopolymer concrete was between 10 - 13 N/mm^2. After curing a dark top layer and crystals were formed on the specimen. A SEM analysis was conducted to research the atomic elements and structure of the crystals and geopolymer.

More research should be conducted as mentioned in subsection 7. The created geopolymer concrete in the practical study was not ideal. In the future, geopolymer concrete is likely an alternative concrete replacement.

9 Acknowledgement

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10 Appendix

10.1 Literature Review

10.1.1 Critical Raw Materials

CRMs	CRMs characteristics
Cobalt	→ In the context of construction it is used in ceramics and pigments such as paint → other uses: hard metals, superalloys, magnetic alloys, catalyst, electrodes LIB → typically mined as a by-product of copper, nickel and iron → widely distributed in different mineral deposits like sulphides, sulphosalts, arsenides, oxides and carbonates → there is a rapid increase of world cobalt mining production → has recovery efficiencies of 60-80% from secondary resources
Indium	→ In the context of construction it is used in architectural glass → other uses: photovoltaic modules, automotive glass, lead-acid batteries, monitors, television, computers → high indium concentrations have been reported around the Mount Pleasant → recovered as a by-product of zinc production, indium resources → more than half of the global refined indium is produced in China → only 1% of indium is recycled worldwide
Magnesium	→ used in construction (not specified) → other uses: transport, pressurised containers (e.g beverage cans), aerospace → widely used as an alloy to produce steering wheels, steering column, support brackets, etc. → 2.1% concentration in the Earth' crust → typically mined → can be produced through electrolytic methods or thermal-reduction methods (e.g Pidgeon process)
Niobium	→ used in building construction (not specified) → other uses: superconductors, vehicles, aircraft, ships and trains, gas turbines, pipelines → mined as a primary product → niobium extraction currently takes place in 9 countries; 95% of world production is done is Brazil → has 50% recoverable efficiency as a constituent of ferrous scrap → has only very little percent of physical recovery
-PGMs (Rhodium)	→ In the context of construction it is used in glass → other uses: electricals, chemicals, autocatalysts → majority of rhodium is derived from mafic-ultramafic igneous complexes → minor production is from nickel sulfide deposits → worldwide mining production has decreased → the life recycling rate is considered to be 24% by EU
Tungsten	→ In the context of construction it is used in construction tools (cemented carbide) → other uses: steel and super alloys, lighting, electronics, catalysts and pigments → typically mined → 85% of world's tungsten production was from China during the period of 2010 to 2014 → 67% of tungsten consumed in EU is used for manufacturing tungsten carbides

Figure 22: General overview of CRMs used in building construction materials [17], [21].

10.2 Methods

10.2.1 Critical Raw Materials

The following links leads to two different material lists we received, the original list and the circular versus traditional list.

Three excel files were created the old list, the new list with values per house and the updated material list.

The material excel lists consists of all building materials used for the construction of the vacation houses, the material quantity, material properties (dimensions, density), CRMs they are composed of, origin of the material, general notes and the source of the information. Furthermore, the materials are color-coded as mentioned in subsection 4.

The following document explains the method of estimating the volume, density and mass of the materials from the material lists.

10.2.2 Life Cycle Assessment

This link leads to the Methods document for LCA. This document provides an explanation on how and why each material was chosen from the LCA data.

10.3 Results

10.3.1 Critical Raw Materials

The last LCA analysis was done for the very first material list. This list consisted of normal concrete, hard steel and glass wool insulation which is later replaced with rock wool insulation. If this list was implemented, one housed would have produces 1043 kg carbon emission as indicated by the figure below (see Figure 23).

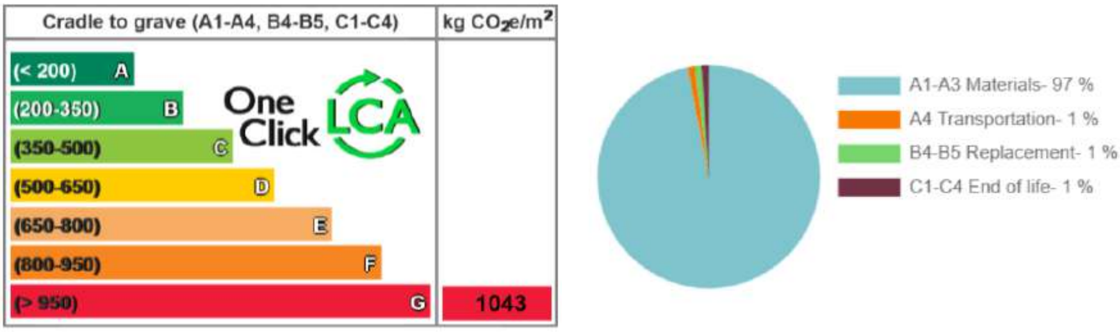

Figure 23: LCA analysis for the first material list.

10.3.2 Scanning Electron Microscopy

In the practical study we used the M2 geopolymer recipy from Albidah [58]. The SEM results for recipe M1, M6, and M15 can be found in figure 24.

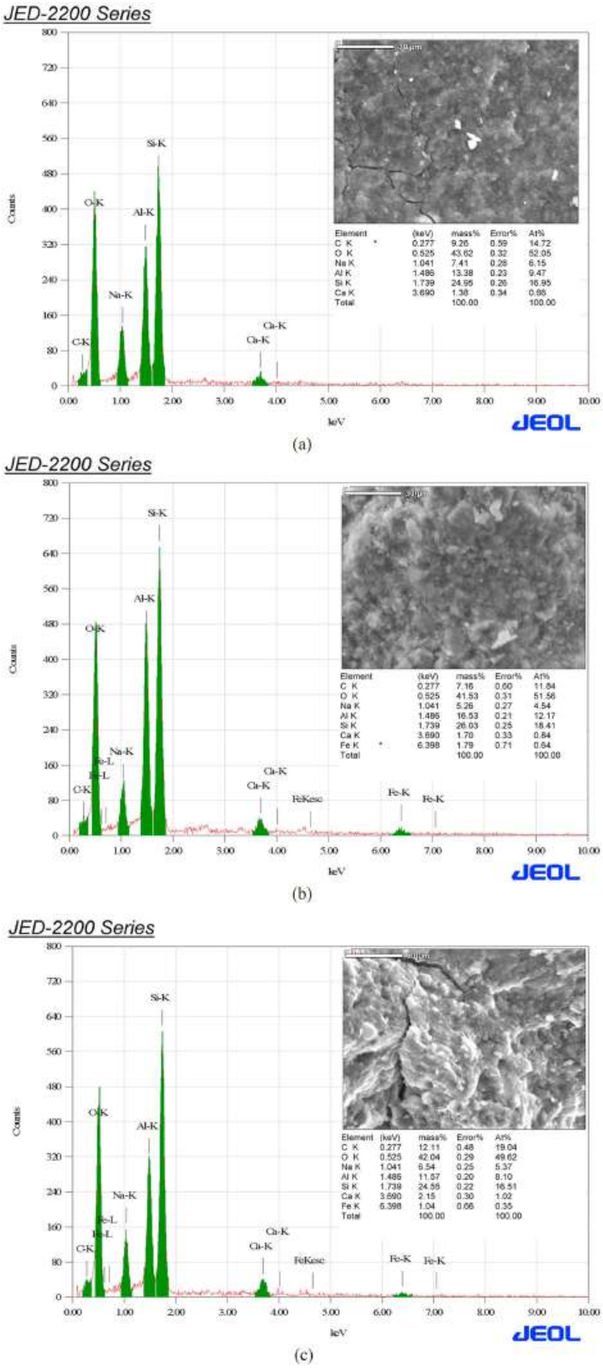

Figure 24: SEM different geopolymer recipies (a) M1, (b) M6, and (c) M15 [58].