Thesis Report

Hz University of Applied Sciences

Made by: Andzhelika Nakova

Student number: 00077625

Organization: Harbich OOD

HZ supervisor: Giuliana Scuderi

Summery

The company, Harbich Ltd., is engaged in the construction of residential buildings. Traditional building materials such as ceramic bricks, concrete and reinforcement are used for construction. Given the fact that the production of these materials requires a huge amount of resources makes them unsustainable and harmful to our environment. With each passing year, the effects of the construction industry on the environment and carbon emissions increase. This leads to the need for a new environmentally friendly solution that reduces or replaces some of the conventional building materials.

The project is for a residential building in Sofia, Bulgaria designed with traditional materials. Harbich Ltd. is interested to start designing their buildings in a more sustainable way. A construction made of sustainable building material would result in great economic efficiency due to the long service life of the structure and low maintenance expenses and it can also provide a potential for increasing the values of the building. However, there is still not lot of data available about the possible applications of natural construction materials in residential buildings. There are several possible options for such materials for which sufficient information regarding their properties has to be gathered and analyzed in order to find the best fit for the project.

The aim of this study is to find a more sustainable solution for construction materials that is in line with the laws and regulations in Bulgaria. The research question, which will be considered as the main-question and will be an object of attention is: “How to improve residential building in more sustainable way with using sustainable construction materials”. A theoretical framework has been developed to provide a foundation of knowledge for the in-depth analysis of the topic in order to answer the question best. The thesis is organized in subsequent research questions in terms of the desired results. Various research tools are used to get the essential information for the specific sub-questions. Furthermore, for the technical requirements it has been essential to study the local conditions and European design standards. These requirements have been used to set up possible variants in terms of different building materials for the sustainable structure. Each variant has been accessed with the Multi Criteria Analysis tool, in terms of Sustainability, Safe and Healthy Environment, Durability, Climate, Availability, Cost. Based on this analysis, it has been concluded that the material that is going to be used for this residential building is Hempcrete, because it is the most suitable and feasible according to the client`s interests and requirements.

This type of material will be used as an alternative to used ceramic bricks. This leads to the conclusion that the structure will not be changed, it will remain reinforcement concrete structure. After the selection of the material, hand calculations were used to calculate the change, which the new material will show. It turns out that the new selected material is many times lighter, which can help to reduce the amount of reinforcement in the floor slabs and lessen the loads of the structure.

Table of Contents

Summery 2

1. Introduction 5

1.1 Background 5

1.2 Harbich Construction Company 5

1.3 Problem statement 6

1.4 Research questions 6

1.5 Goals and objectives 6

2. Theoretical framework 7

2.1 Location and Case study 7

2.2 Current situation 10

2.2.1 Materials 11

2.3 Program of requirements 13

2.3.1 Functional requirements 14

2.3.2 Technical requirements 14

2.4 Solutions 15

2.4.1 EcoCocon straw panels 16

2.4.2 Hempcrete 17

2.4.3 Mycelium 20

3. Methodology 22

3.1 Research tools 22

3.2 Research plan 23

3.3 Multi Criteria Analysis 24

3.3.1 Criteria 24

3.3.2 Weight of criteria 26

4. Results 28

4.1 Variants and scores 28

4.2 Hempcrete detailed characteristics 29

4.3 Application of the material in the case study 31

4.3.1 Construction method 31

4.4 Structural analysis 35
4.4.1 Slab calculations 35
4.4.2 Column calculations 41
4.4.3 Effects of removing the bricks 43
5. Discussion, conclusion and recommendations 44
5.1 Discussion 44
5.2 Conclusion 45
5.3 Recommendation 46
References 47
Appendix 1: Energy efficiency 56
Appendix 2: Structural elements 59
Appendix 3: Tables of construction and installation work 63
Appendix 4: Meetings information with specialists in the field of environmentally friendly materials 64
Appendix 5: Meeting information with specialists in the field of construction engineering 65
Appendix 6: Regulation and standard for construction 66
Appendix 7: Hempcrete construction methods 69
Appendix 8: Slab calculations 71
Appendix 9: Column calculations 76
Appendix 10: GTB tables 82
Appendix 11: Drawings 86

1. Introduction

1.1 Background

Businesses, society, and individuals are all being impacted by climate change. It is becoming increasingly clear that a change to a low-carbon economy is required. This transition is largely driven by the building and construction industry. According to a report published by the Organization for Economic Co-operation and Development (OECD) in 2010, buildings consume more than 40% of all energy produced globally and account for one-third of all greenhouse gas emissions. The materials utilized, as well as the heating, cooling, and lighting of buildings and infrastructure, are key contributors to these emissions. *(Putting the Construction Sector at the Core of the Climate Change Debate | Deloitte Central Europe, 2020)*

The problems of global warming and climate change require actions to make our cities more sustainable and to reduce the carbon emissions. The building sector is the biggest consumer of materials and energy, as well as one of the most significant polluters and emitters of carbon emissions, due to its huge scale, economic strength, and social importance. This is due to the materials used because they are not energy efficient and sustainable and the collection and building processes produce a lot of CO_2 emissions. Concrete production for instance has produced over 2.8 billion tons of CO_2. This quantity will only rise as 4 billion tons of concrete is poured each year. *(Budds, 2019)*. These threatening growth rates of carbon dioxide cause by construction industry imposes the need for abandoning traditional materials and replace them with sustainable ones.

Those environmentally friendly materials have been around for a while, but they have only recently achieved widespread awareness. Green materials are known to optimize resource conservation while minimizing environmental impact. Also, these materials do not compromise the safety, quality, or other fundamental needs of strong buildings. They are the future for the sustainable construction. Construction companies increase their awareness of climate change and that lead to reconsider their strategy for using more environmentally friendly building materials. Due to this data the aim of the research is to find environmental and sustainable building materials that can be used for residential buildings in Bulgaria. *(Author, 2020)*

1.2 Harbich Construction Company

The host organization for which this research is being made is Harbich Ltd. This is a Bulgarian construction firm based in Sofia with founder of the company Eng. Stefan Harbov. Their primary business is the construction of apartment complexes. The company has a long history in the sector and is constantly evolving. It currently provides a wide range of construction services, including design, housing, dry construction, rough construction, plumbing, renovation, insulation, finishing, and roofing, as well as maintenance work.

1.3 Problem statement

Construction materials generate millions of tons of waste each year all over the world. These building materials have a high embodied energy, resulting in significant CO2 emissions. Cement is the most CO2-producing substance, and a significant amount of CO2 is generated in the manufacturing and transportation of construction material. Moreover, if the production and consumption of construction materials are expanding at the same time, cement production could reach over 5 billion metric tons per year, resulting in around 4 billion tons of CO2 emissions. The influence of construction materials is dominated by these materials due to their widespread use, as opposed to the impact of other sources. On the part of the construction of the wall, the brick business has a terrible environmental impact: annually, kilns emit about 1,072 million tons of carbon dioxide, accounting for 2.7 percent of total emissions. Every year, 375,000,000 tons of coal are burned in brick kilns around the world. *("Environmental Impact of Brick Kilns | Habla Zig Zag Kilns," 2021)*

Result of the massive use of construction materials and embodied energy a significant level of resource depletion is occurring all across the world. This tendency of uncontrollable construction material consumption will result in environmental hazards over the world. This is why modifications must be implemented right away. In recent years, there has been increasing talk about "green" construction with natural construction material. By using more natural and sustainable building materials, the consumption of construction materials can be reduced. Natural resources are renewable they can be used, grown and produce on every part of the Earth. In order to avoid catastrophic consequences, the solution to the problem is an alternative sustainable construction. *(Lomite & Kare, 2009)*

1.4 Research questions

The main research question of this research is: How to improve residential building in more sustainable way with using sustainable construction materials?

To help answer this question a set of sub-questions is prepared:

- How green is the current design based on the chosen construction materials?
- What are the negative effects of using traditional building materials?
- Which are the requirements to have green building materials?
- What is the most appropriate and convenient material for the region of Bulgaria?
- How will the selected material effect the structure?
- How can the building be re-designed based on the new construction materials proposed?

1.5 Goals and objectives

This research aims to find the best environmentally friendly and sustainable construction materials for the project. The goal is to find a substitute to the traditional construction materials that is eco-friendlier not only for the planet but for people.

2. Theoretical framework

In order to perform this study, a theoretical framework was created to give a foundation of knowledge for the topic's in-depth analysis. Based on the study sub-questions, this chapter of the thesis provides a summary of the most important sources to be used as background information.

2.1 Location and Case study

Harbich currently has several construction projects for residential buildings in Sofia. This research focuses on a building located in Ovcha Kupel, Sofia (Figure 2). The building neighborhood has all of the essentials of daily living including shops, a range of public transportation alternatives, multiple schools and kinder gardens nearby, is close to the city center, and is also close to Vitosha Mountain (Figure 1).

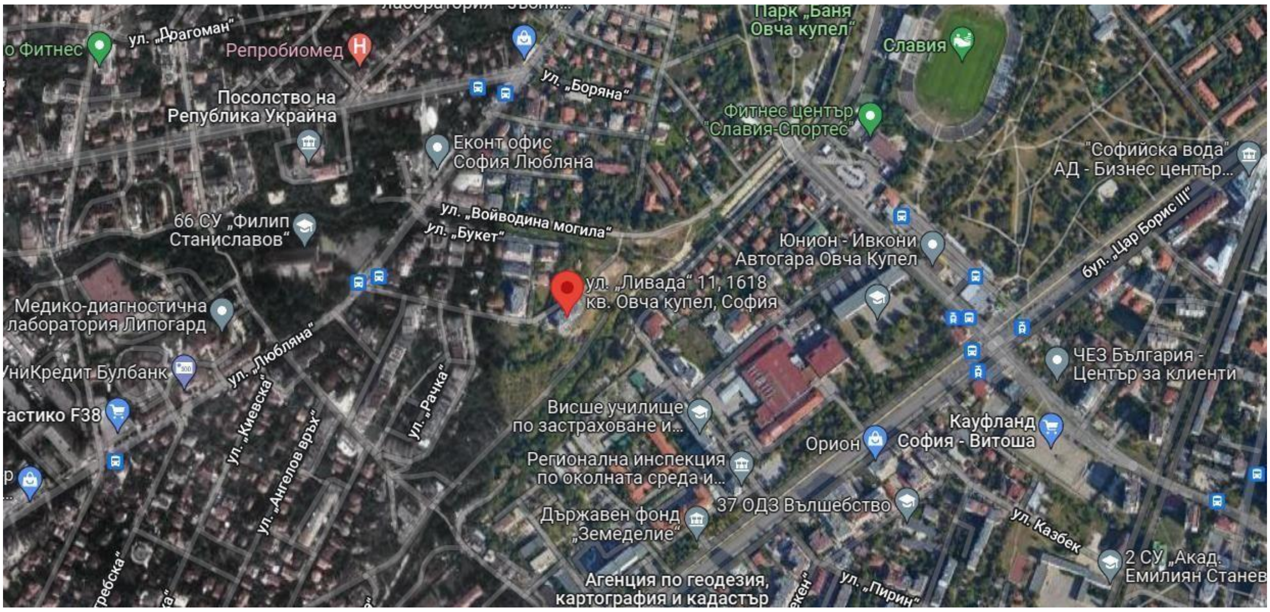


Figure 1: Map with the exact location of the building and with the closest facilities. Photo credit: Google Maps.

The construction began in April 2021 and is now in the early stages of completion. The building comprises of five floors and a one half-floor with two more apartments, for a total of 24 units and 18 underground and above- ground garage spaces. The facades of the building are stylistically designed to blend with the surrounding architecture. Figure 2 provides a colored, three- dimensional visualization of the building.

Figure 2: 3D visualization of the building.

The building has five floors, with a total height of 14.50 m. The area of the floor slab is 430m2 and the total constructed area is 2910 m2 (Figure 5).

It is designed with one entrance on the east side of the building and a second entrance on the west side of the courtyard, with one staircase and has the following layout:

- Basement floor- Underground garage: 5 separate garages for 5 cars and 1 parking space for 1 car, as well as a bicycle parking lot for 7 one-sided bicycle stands. The entrance and exit for the cars will be through the courtyard by a single-lane ramp connecting to Buket Street. The underground garage is separated from the rest of the building by fire walls and a reinforced concrete slab (Figure 3).

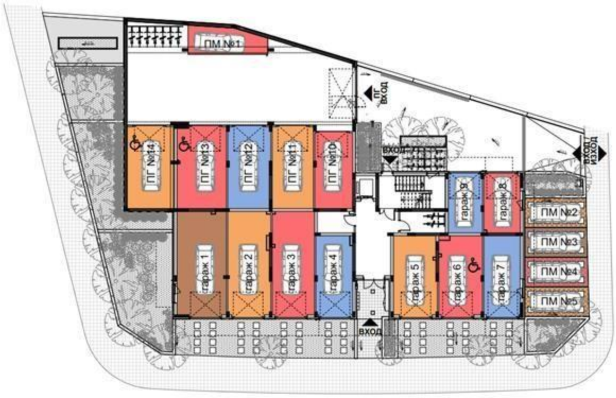


Figure 3: This picture shows the ground floor space with 19 parking spaces. 30% of the area is dedicated for landscape, which is mandatory in the construction of each building.

- Floor 0- Ground floor- with 1 entrance hall, common room, room for hygienist, 9 garages for 9 cars. There is an elevator for 6 people, appropriate for disabled, serving the ground floor and residential floors. There are also 4 above-ground parking spaces for 4 cars accessible from Buket Street.

- 1st floor- ground floor to Livada Street with 4 ground garages for 4 cars and 1 parking space accessible from Livada Street. The garages are separated by fire walls and a reinforced concrete slab from the rest of the building. The residential part of the floor includes respectively 2 one-bedroom, 1 two-bedroom and 1 four- bedroom apartments.
- 2nd, 3rd and 4th floors- residential part with 6 apartments each- 3 one-bedroom, 2 two- bedroom and 1 four-bedroom apartments. (Figure 4)
- Attic floor- with 2 apartments per floor, respectively 1 two-bedroom and 1 four-bedroom apartments.

Floors 2, 3 and 4 are standard floors, which means that there is no difference in their alignment (Figure 4). Drawing of apartments 10, 16 and 22 is shown in Figure 5. The apartment includes 2bedrooms, living room, toilet, bathroom with toilet, hallway and storage room.

Figure 4: Alignment of the apartments on floors 2, 3 and 4

Figure 5: Plan of apartments 10, 16 and 22.

In order to make the building more sustainable, an energy efficiency plan has been made to calculate the energy efficiency. The building is rendered class B in energy efficiency according to the Bulgarian standard - BDS EN 15217.

The external walls are designed from a solid part of 25 cm brick masonry "Porotherm" with 10 cm, thermal insulation EPS "Neopor" from the outside. Thermal insulation is provided as follows:

- Under the floor of residential floors to unheated above-ground garages with thermal insulation of "Multipor" with a thickness of 10 cm.
- Under all bay windows with thermal insulation EPS "Neopor" with a thickness of 12 cm.
- Terraces above residential premises - XPS with 12 cm thick
- On the roofs - thermal insulation with stone wool 12-16 cm thick
- On the walls of the stairwells on the side of the heated rooms, as well as the walls to the unheated garages is provided pre-wall cladding of "Multipor" 7.5 thick cm., which as a system has a total thickness of 9 cm. and is installed glued, doweled and covered with reinforced plaster.

Detailed information of the energy efficiency and thermal conductivity can be found in Appendix 1.

The construction of the building is reinforced concrete with monolithic design. The floor slabs are beamless with a thickness of 20 cm. They are calculated for a load of architectural flooring with a thickness not exceeding d= 5 cm. and partition walls made of a material not heavier than 1350 kg / m3.

A system of mutually perpendicular reinforced concrete washers is provided for absorbing the seismic forces (Appendix 2). From a constructive point of view, the building has six levels. The building is provided for a seismic zone of IX degree with Kc = 0.27.

The foundation of the building is made on a foundation slab with a thickness of 70 cm. To be laid in a solid soil layer according to the geological report: Layer N4 - "Medium gravel with sand aggregate".

The foundation slab is calculated for a conditional calculated soil load Ro = 0.25 MPa.

The construction of the garages is reinforced concrete with a monolithic design. The roof slab has a beam scheme and is 25 cm thick. The slab is stepped through beams of reinforced concrete columns and walls. All vertical elements along the joint with the six-story building step on its foundation slab.

When performing the construction works to observe the requirements of the Regulations on labor safety.

The design complies with all current regulations and regulations:

- "Standards for design of concrete and reinforced concrete structures - 2007."
- "Basic provisions for the design of the structures of the constructions and for the influences on them (ordinance №3 / 21.07.2004)"
- "Ordinance" RD-02-20-2 for the design of buildings and facilities in earthquake areas"
- "Standards for the design of steel structures"

2.2 Current situation

In recent years, the population of smaller towns and villages around Sofia has been forced to move to the capital in search of better jobs and education. This has dramatically increased the need for new residential apartments. For this purpose, residential buildings such as the one in analysis are built. The building process is intended to be complete for a maximum period of 2 and a half years and sustainability and environmental awareness is not a main priority. That is why the materials they use are of high quality, but they cause great damage to the climate and the environment.

The structure of the studied building is monolithic, built with a reinforced concrete structure directly on the construction site in pre-installed formwork. It includes slab beams, columns and rigid vertical washers to secure the building against earthquakes. There are also separate wall washers. The external non-bearing and internal divider walls are designed out of brick masonry. Additional information about the structural elements can be found in Appendix 2 and Appendix 3.

2.2.1 Materials

In the past, much more accessible materials were used, which did not require much processing to be used for construction, respectively did not emit carbon dioxide and did not endanger human life. Nowadays, this has changed a lot, we use a variety of building materials, more and more technological, which require a lot of processing. These threatening growth rates are having a very bad effect on climate and air pollution (Figure 7).

Prior to 4000 BC	**4000 BC–1800 AD**	**1800 AD–to date**
Soil, stones, reeds/thatch, Sun dried bricks/adobe, unprocessed timber Zero-energy materials	Burnt clay bricks, lime, cast iron products, lime-pozzolana cement Medium-energy materials	Aluminium, steel, glass, Portland cement, plastics, other smart materials, nano-materials, etc. High-energy materials

Figure 6. Energy consumption and developments in building materials. (Venkatarama Reddy, 2009)

The materials used to build the building is mainly reinforced concrete. Reinforced concrete is made out of concrete and steel, both of which are commonly causes of CO2 emissions.

In general, reinforced concrete is intimately related with building structures, both low-rise and high-rise. In practice, the use of reinforced concrete as a structural material becomes a strategic issue in the attempt to support green construction, particularly in terms of carbon dioxide emissions, as carbon dioxide emissions are largely attributed to cement and steel production (Figure 7).

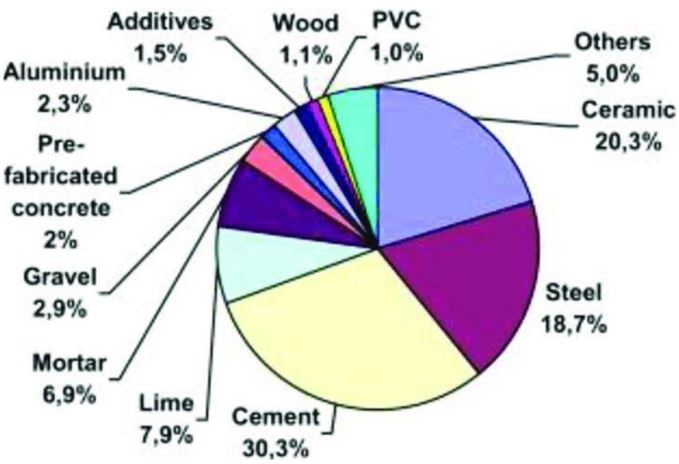


Figure 7. CO2 contribution from various construction materials. (Elsevier, 2015)

- **Concrete and cement**

Concrete is a composite building material obtained as a result of hardening of a mixture of cement, water, sand, coarse aggregate (crushed stone or river gravel) and mineral additives. Among those ingredients, cement is the material that releases more CO_2 as a result of the energy used to burn the material and the chemical reaction that occurs when the combination is heated. *(Wikipedia Contributors, 2022)*

The concrete used is class C30/35. This class is a more durable combination that can withstand climatic change and extreme weathering. Concrete class C25/30 is used for the foundation slab and C10/15 under the foundations.

Generally, cement production and CO_2 emissions is 2800 million tons per 2010 year and CO_2 released are 2070 million tons per 2010. *(Venkatarama Reddy, 2009)*

Each kilogram of concrete emits 0.42 kg of carbon dioxide, according to the National Ready Mixed Concrete Association.

One cubic meter of concrete is equal to about 2 410 kg. The amount of concrete used to construct the Harbich building is around 1 350 m^3 or just under 3 2500 000 kg. When multiplied by the CO_2 that it emits (0.42 kg) the results are that the building produced 1 365 000 kg or 1 365 tons of CO_2 just from the concrete alone.

- **Steel**

After cement, steel is the most commonly utilized material in both infrastructure and non-infrastructure applications. Following the emergence of the global warming crisis, the use of steel in construction has become an alternate option to concrete and is becoming increasingly popular. Carbon dioxide emissions from energy use account for nearly all of the greenhouse gas emissions involved with steel manufacture. To produce steel, we must heat iron ore to over 1,500C by burning fossil fuels. In 2018, every ton of steel produced released an average of 1.85 tons of CO_2, accounting for nearly 8% of world CO_2 emissions. *(Hoffmann et al., 2020); (Steel, Concrete and Climate Change - the Institution of Structural Engineers, 2019)*

According to the plans, the building requires 117 ton of steel class B500 reinforcement. This will result in 216,5 tons of CO_2 emission.

For comparison in order to capture of 1 ton of CO_2 emissions around 60 trees must be grown for one year. This is a rough estimate that varies depending on the region, type of trees, weather conditions, and other factors. Analyses revealed that from seedling to adult tree, 15 to 83 trees are required to trap 1 ton CO_2 on average per year. In northern hemisphere trees requires more time to grown so because Bulgaria is located in northern hemisphere around 60 trees per year are required to capture 1 ton of CO_2. *(What Exactly Is 1 Tone of CO2? We Make It Tangible. - Climate Neutral Group, 2022)*

This means that just between the above-mentioned materials more than 95 000 trees have to be planted to capture the amount of CO_2 that is released.

- **Bricks**

The next such popular material for any traditional building are bricks. Bricks are made from clay in brick kilns. Clay is dried, preheated and fired at 800–1100 ° C for about three hours, which consumes a huge amount of energy and releases extremely hazardous gases that have an impact on human health and the environment. Brick kilns are one of the main stationary producers of black carbon, accounting for 20% of total black carbon emissions together with iron and steel manufacturing. They are substantial contributors to climate change and sources of CO_2, greenhouse gas emissions, and short-lived climate pollutants. Brick kilns degrade air quality and human health, and harmful pollutants have a significant impact on the lives of billions of people. Every year, kilns emit roughly 1,072 million tons of CO_2 into the atmosphere, accounting for 2.7% of the total emissions. Every year, 375,000,000 tons of coal are burned in brick kilns around the world. *(Environmental Impact of Brick Kilns | Habla Zig Zag Kilns, 2019)*

In underdeveloped countries, plumes of hazardous black smoke billowed from brick kilns and are a typical sight. Polluting gases cause:

- Hazardous working conditions.
- High rates of respiratory disease and premature death amongst workers and local communities
- Agricultural impacts – damaging soil, crop production and food security.
- Transboundary black carbon from thousands of kilns directly contributes to glacial melting in the Himalayas and affects monsoonal rainfall patterns.
- Damage to biodiversity

2.3 Program of requirements

The analysis of the construction materials used shows that the current design of the building is very unsustainable and has major consequences not only for the environment but also for human life.

Depending on the type of design, the materials used have an impact on the quality of the elements as well as the quantitative features. The material utilized forms a link between a structure's durability and the technical and structural features of the built environment's design.

2.3.1 Functional requirements

The materials that are going to be researched and assessed should meet the following functional requirements:

- Use of products with recycled content and renewable materials.
- Products and systems that reduce water consumption in buildings, as well as water conservation in green areas.
- Products and systems that prevent the formation of moisture and the growth of biological contaminants in buildings.
- Materials and components that help reduce energy consumption in buildings.
- Materials and components that provide negligible or even zero environmental impact.
- Materials and components that provide great mechanical resistance, strength, durability and stability.
- Materials and components that are safe and non-toxic/radioactive.
- Materials and components that can be produced in large quantities.
- Materials and components that are safety in case of fire
- Materials and components that have noise protection

2.3.2 Technical requirements

When dealing with the issue of material selection, a preliminary consideration is required. Construction materials and structure must meet a wide range of requirements established by national laws, national/international standards, codes of practice, and local building habits, at least in terms of:

- Mechanical properties (for structural materials), such as strength, stiffness, seismic behavior.
- Thermal performance, in order to achieve a satisfactory energetic behavior during the operating phase.
- Acoustic performance, in order to produce a comfortable indoor environment
- Weight and dimension constraints, in accordance with the building's special features.
- Durability in the specific environmental context where the structure will be located (the durability issue has important significance in sustainability, as it effects the materials' life cycle).
- Safety during the handling and placement of materials, as well as in the event of afire.
- Special performances related to the usage of structures.
- Aesthetic result, in keeping with local construction traditions.
- Cost, which is determined by the available budget, making material selection multi-criteria and difficult.
- Must comply with Bulgarian State Standard for energy efficiency BDS EN 15217 (Appendix 1)

- The standard BDS EN 1990 shall be applied together with the respective parts of Eurocodes 1 to 9. for the design of structures and the determination of the impacts on them. (Appendix 6)
- The production, transportation and laying of concrete mixtures must meet the requirements of BDS 4718.
- BDS EN 1990 / A1: 2005 / NA Eurocode: Basic principles for the design of building structures
- BDS EN 1992-1-1: 2004 / NA Eurocode 2: Design of concrete and reinforced concrete structures. Part 1-1: General rules and rules for buildings
- BDS EN 1998-1: 2004 / NA Eurocode 8: Design of structures for seismic impacts. Part 1: Basic rules, seismic effects and building rules
- BDS EN 1996-2: 2006 / NA Eurocode 6: Design of masonry structures. Part 2: Considerations in design, choice of materials and execution of masonry

2.4 Solutions

Natural resources such as soil, stones, and timber/biomass are ideal building materials in terms of low carbon emissions, carbon footprint, and recycling and reuse potential. Natural materials that are unprocessed or minimally processed have limitations, notably in terms of strength and durability. Energy is expended in the processing and transportation of natural materials, resulting in carbon emissions. To reduce carbon emissions, it will be necessary to develop technologies that allow building materials and products to be made with the least amount of energy.

After a deeper investigation on possible solution for greener construction materials and interview with a specialist in this field, there are 3 different alternatives that are going to be presented in the following chapter. To make a sufficient comparison to the current situation on the building, the current design will be put into a Multi-Criteria Analysis and compared to the other 3 alternatives. This way it will be seen how well the current design is performing within the set criteria. The 3 alternatives that are going to be compared are:

- EcoCocon straw panels
- Hempcrete
- Mycelium

An important aspect to be paid attention to in the alternative designs is to see if the proposed alternative designs can in fact be used for construction of residential building in the center of Sofia. This aspect is especially important due to the fact that in Bulgaria the availably for sustainable construction materials is limited.

The focus of this research is to find the best “green” and sustainable substitutes for traditional materials. The primary purpose of using sustainable building materials is to produce a home that will last a long time and will require less maintenance.

2.4.1 EcoCocon straw panels

EcoCocon Straw Panels are made of 98% natural renewable materials. Making them as natural as possible leads in excellent indoor air quality and no toxic compounds being released. The entire system is permeable, allowing excess humidity to escape. (Figure 9) Cold bridges and airtight gaps are removed, resulting in a mold- and draught-free atmosphere. Natural materials help to produce a healthy interior microclimate with consistent temperatures throughout the year - warm in the winter and cool in the summer.

EcoCocon Panels have a double wooden frame and are entirely structural. The external surface is covered with wood fiber boards. The plywood strips level the surface by compensating for straw protruding from the wooden frame (Figure 10).

They can sustain floors and roofs without the use of any additional materials. Straw density of more than 100 kg per m3 ensures energy efficiency as well as robustness. EcoCocon panels are certified to withstand 120 minutes of fire. Even for a self- builder without a crane on site, the assembly of panes is extremely quick. It is possible to create the home shell and seal it off in a matter of days, making the rest of the structure weather-proof.

The system accomplishes the airtightness required by the passive house standard while maintaining total vapor permeability of the walls.

Condensation in the walls is efficiently prevented, which is a major problem in modern, sealed structures. A draught-free and healthful indoor atmosphere is also created by the airtight, vapor- permeable system. Clay plaster, because of its ability to regulate humidity, can be put directly to the surface of the straw panel. The system obtains a U- value of 0.119 W/m2K when panels are paired with internal clay plaster and an outer layer of 100 mm wood fiber board.

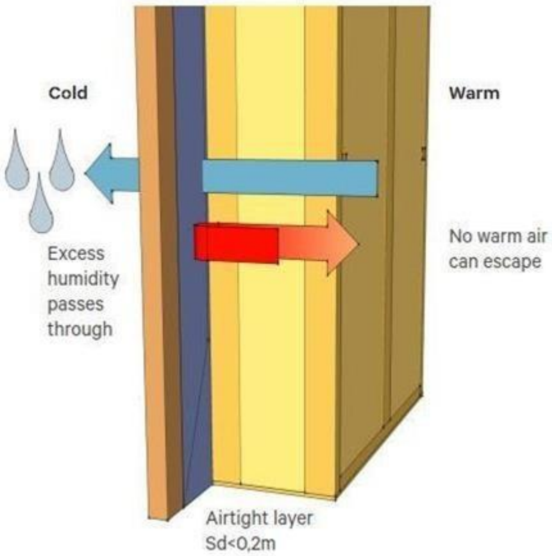


Figure 8. Cross-section of EcoCocon panel.

Figure 9. EcoCocon Straw Panels.

The panels are prefabricated at a factory under strict quality control, allowing for a high level of precision. As a result, the panels all fit perfectly into position, and because there are no wet processes involved, the entire structure can be put together in a fraction of the time it would take in traditional construction. Panels may be customized to fit any building design and provide architects more creative freedom. *(The Panel, 2019)*

EcoCocon panels are delivered once the foundations are complete. Panels are delivered by lorry and can be unloaded by hand or with the use of a forklift or crane. If necessary, panel scan be stored on-site, but they must be carefully covered to avoid contact with water.

After that, a base plate is created. Its aim is to provide insulation from the concrete beneath it. The panels are screwed into position on the base plate. The assembly is done in accordance with the panel project. Each panel is identified by a number as well as a color code. An impact screwdriver, a hammer, a saw, and a few other carpentry tools are all that is required. The panels come with all of the essential hardware, such as screws. *(Building with EcoCocon, 2020)*

Pros	Cons
• 98% NATURAL RENEWABLE MATERIALS • EXCELLENT THERMAL PERFORMANCE • CARBON-STORING CONSTRUCTION • EXCEPTIONAL INDOOR AIR QUALITY • CUSTOM-MADE TO FIT ANY DESIGN • CONSISTENT AND CERTIFIED QUALITY • INSULATION COEFFICIENT U = 0.12 W/m^2K • AIRBORNE SOUND INSULATION 54 dB • FIRE RESISTANCE 120 min • DENSITY OF PRESSED STRAW 110 kg/m^3	• Moisture and mound are significant risks. • As it is not a conventional building material, familiarity among builders, and building regulations approval can present obstacles to use. • Care must be taken to keep rodents and other small animals from infiltrating straw bales during construction.

Figure 10. Pros and cons of EcoCocon panels.

2.4.2 Hempcrete

Hempcrete (Figure 12) is a bio-composite that is made from the inner wood core of the hemp plant and mixed with the lime and other natural materials. It was originally utilized in construction in the early 1990s in France to create non- weight bearing infill walls. Hempcrete's modest weight can help reduce a building's embodied energy by minimizing emissions associated with hauling heavy materials.

Hempcrete, unlike normal concrete, does not have a negative carbon imprint due to the utilization of hemp and the properties it possesses. Hemp plants store carbon while releasing pure oxygen as they grow. As a result, the captured levels of carbon dioxide are kept in the structure of the building rather than being released into the atmosphere during the development of Hempcrete and its use in construction

One of the best prices for natural and sustainable materials is that they can either be reused or, if their life cycle ends, they do not pollute nature when disposed of.

Hemp concrete is also not inferior in this respect. What did not enter the formwork during construction can be added to the next mixer. If you need to demolish the built wall of hemp concrete, it can be added to the new mixture (up to 10% of the mixture). But even if it is not used again, it can be composted in nature without polluting it, and would even improve it in determining the conditions. (Figure 13)

Figure 11. Hempcrete blocks.

Figure 12. The mixture that is not used in construction.

Furthermore, hemp is the fastest-growing annual crop that grows in just 14 weeks. It has high tensile strength. During cultivation fewer pesticides and herbicides are used, which makes hempcrete a non-toxic building material and cause less environmental damage from the use of chemicals on the fields. *(Hempcrete Buildings - Thermal Performance and Costs - UK Hempcrete, 2014)*

Hempcrete is versatile and may be used for a variety of purposes, including insulation, floors, walls, and roofs. It has numerous advantages over other commonly used standard and environmentally friendly materials. Hempcrete is just as easy to use as concrete, but it's far more durable, flexible, waterproof, and fireproof. Furthermore, its structure is up to three times stronger than normal concrete in terms of earthquake resistance. All of these advantages are attributable to the material's strength while remaining light and breathable. When used in building, it can last more than 100 years, compared to 40 to 100years for other materials now in use. Hempcrete is a powerful, versatile and long-lasting material.

Hempcrete compositions have strong vapor permeability and may quickly absorb or release water vapor from the air when employed in structures. These qualities enable for better control of the indoor environment's thermo-hygrometric conditions, lowering the risk of vapor condensation and increasing thermal comfort. Hemp shives slowly mineralize as a result of lime action, becoming inert and minimizing the risk of rot and mold growth. It's mold-resistant because it absorbs moisture. Hemp walls can collect up to 14 liters of water per square meter, which can then be recycled or released into the earth. Moreover, heat is stored in the thermal mass of hempcrete walls, which is slowly released when the building cools. This implies that when you open a window, all of your heat will not escape. *(Arrigoni et al., 2017)*

The compressive strength of hempcrete is 1/20 that of concrete, coming in at 1 MPa, meaning it can't be used as a foundation material or in situations where it may be load-bearing. It's resistant to cracking due to its low density making it an attractive alternative to areas prone to earthquakes.

Hempcrete also provides thermal mass, as well as insulation, due to density of the lime binder once it has set. Hempcrete has the ability to store heat inside the fabric of the material itself. It differs from lightweight insulations in this regard, which merely store heat inside the air trapped within the material. Hempcrete's capacity to store heat while also insulating offers two significant advantages. The typical u-value for a 350mm thick hempcrete wall is 0.17 W/m2K. compered to u-value of 100 mm of concrete blocks is 1.13 W/m2K.

Hempcrete can be cast or sprayed around a hardwood or steel frame and is not load-bearing on its own. There is no need for additional insulating layers, such as a cavity wall, when utilizing lime hemp. The requirement for heating or air conditioning systems becomes even smaller as a result of its permeability and heat-storing capacity.

Hempcrete consists of high silica content which helps to give high strength. The main function of the silica is to bind other natural materials with each other.

Another variant to use hempcrete for construction is to use Hempcrete Blocks. The blocks use the same formula as hempcrete, but in ready-to-use, lightweight blocks with the amazing heating qualities of hemp fiber. This material is highly sturdy, breathable, and long-lasting. Ideal for creating a healthy and enjoyable living environment.

Hemp blocks can be used to rapidly and simply construct walls. Because the blocks are not load- bearing on their own, a supporting structure is required. Because of the light blocks, the frame can also be light. *(Building with Hempcrete, 2020)*

Pros	Cons
• Hempcrete is a non-toxic building material • Heat is stored in the thermal mass of hempcrete walls • Hemp is the only building material capable of removing carbon dioxide from the atmosphere. • It's mold-resistant because it absorbs moisture. • Hemp is the fastest-growing annual crop that grows in just 14 weeks. • Three times stronger than normal concrete in terms of earthquake resistance • Light and breathable material • Hempcrete is a long-lasting building material. • The use of Hempcrete bricks makes construction simple and quick. • Provide excellent sound and heat insulation • Resistant to fire and insects	• There is a lack of builders who are knowledgeable about the product. • Hempcrete can add 8%-12% to the overall price of a home. • Not always as easily available as typicalbuilding materials like concrete. • The crop requires use of fertilizer, which can have a negative impact on our ecosystem. • Hempcrete has low compressive strength. • It cannot be used for heavy loads; it requires frames to carry loads. • Hempcrete is not suitable for use as a building foundation. • It also has low elastic modulus which makes it unsuitable for direct loads

Figure 13. Pros and cons of Hempcrete.

2.4.3 Mycelium

Mycelium is a completely natural building material. The root structure of fungus and mushrooms is made up of mycelium, a natural unicellular creature. In moulds or forms, it might be coaxed to grow around a composite of other natural materials, such as ground-up straw. The lightweight and sturdy bricks or other shapes are then air-dried (Figure 15).

Figure 14. Mycelium-based composite materials.

Mycelium could be molded into practically any shape and utilized as a remarkably strong building material when combined with pasteurized sawdust. There is the ability to create robust and lightweight bricks and construction parts with unusual shapes. Because the mushroom-based building material can resist severe temperatures, it's a natural and compostable alternative to home insulation, Styrofoam, and even concrete.

The mycelium brick has taken a long time to develop and is made as farmers add mycelium to crop waste, which is then put into molds and grown and dried into a durable material. This is known as "biocycling," and it involves breaking down demolition trash and combining it with mycelium to offer industrial-level strength that bonds the material as it grows. The combined elements are then crushed to form new construction materials.

These materials can then be utilized as insulation or carved into bricks. It takes about five days for the brick to grow and become functional.

Although the mycelium brick is progressing, it is still a long way from becoming a practical and widely used building material because its compressive strength is around 200 kN/m^2, which is significantly less than concrete's 27 000 kN/m^2 compressive strength. However, a mycelium brick is stronger than concrete in terms of weight, with a cubic meter of mycelium brick weighing 43 kg versus 2400 kg for concrete.

There are numerous advantages to using this method of production. Because mycelium is 100 percent biodegradable and may be used as soil, there is a large reduction in the dependency on fossil fuels, the embodied energy necessary for fabrication, and the amount of building waste that is left at the end of the product's life. A carbon-neutral building process can be achieved via bio fabrication, which eliminates the usage of artificial insulation in walls, MDF, and other non-load bearing structures. Additional benefits of mycelium products include termite proofing, which involves making products that attract termites but when eaten activate a fungus spore within the insect, killing it and forming a fungus whose spores repel other termites. *(Ilvy Bonnefin, 2017)*

Mushroom materials are durable and naturally fire resistant, and they can be easily molded to any shape. Moreover, they are environmentally friendly. They are carbon neutral and if exposed to living organisms, they can be decomposed. Mycelium as a construction material offers excellent opportunities for upcycling agricultural waste into allow-cost, sustainable and biodegradable material alternative.

Although the use of mycelium in the construction industry is still experimental, its growth reflects a desire within the industry to create and foster a more "cradle to cradle" approach to building, with people aiming to reduce the embodied energy of their products while also aiming for as little net waste as possible at the end of their life. This product has the potential to become a fundamental part of the building construction process in the future, being utilized for things like insulation and in place of traditional brickwork. *(15 Sustainable and Green Building Construction Materials - Conserve Energy Future, 2020)*

Pros	Cons
• 100percent biodegradable • Termite proofing • Durable and naturally fire resistant • Can be easily molded to any shape. • environmentally friendly and carbon neutral material	• Compressive strength is around 200 kN/m^2 • There are not many buildings buildout of this material • It still under development

Figure 15. Pros and cons of Mycelium.

3. Methodology

Optimizing the conventional residential building in Bulgaria in a more sustainable way by using sustainable construction materials requires consideration of mutually solutions in order to select the optimal materials among the alternative. Most importantly, the decision maker needs to consider: smarter production technologies, recyclability, material longevity, biodegradability, lower CO2 emissions, a well-established circular economy and social acceptance. The methodology tools such as literature surveys, communication with professionals and multi criteria analysis were used for the decision making process.

This chapter will outline the research methodology as well as the research tools that will be used during the investigation. It is vital to identify the correct and structured research technique in order to acquire the most relevant material for answering each question. The exact research tools that will be used to get the required information are discussed. Each subsequent question is studied to acquire the best possible overview of the approach, and thus the specific study strategy for each of the related sub-questions is established.

3.1 Research tools

Literature survey:

- Google Scholar
- Research Gate
- Search databases: Science Direct
- Harbich Ltd. database
- Sofia Library

Face-to-face interviews with design experts:

- Interview with specialists in the field of environmentally friendly materials.
- Interview with specialists in the field of construction engineering.

Multiple criteria analysis:

- Identifying alternatives and compiling tables of comparisons.
- Definition of weighting factors for each selected criterion.
- Choosing a grading system.
- Combining the weights and grades for each variant to derive an overall score value.
- Conducting a multi criteria analysis (MCA) and selecting the winning variation.

Hand calculations:

- Calculating structural elements.
- Comparing results for the new material to the current one.
- Checking whether any changes could benefit the structure.
- Designing the structural elements to accommodate the changes.

3.2 Research plan

How green is the current design based on the chosen construction materials?

The question at hand requires a breakdown of the main materials used for the construction of the building. The materials are then analyzed for their environmental impacts using literature from scholar sources. Furthermore, information of the energy efficiency and thermal conductivity is provided based on country standards.

Product in chapter: 1.3 Project, 2.2 Materials and Appendix 1.

What are the negative effects of using traditional building materials?

Similar to the previous question, the approach here is to analyses and assess the materials and their impact on the environment and how much CO_2 and pollution they cause.

Product in chapter: 2.2 Materials.

Which are the requirements to have green building materials?

There is a wide range of construction materials available. A number of criteria are considered in order to choose the best one. The criteria are established after conducting research on the client's requirements. The requirements are chosen through a combination of book study on construction standards and collaborative brainstorming with structural engineers.

The meeting notes can be found in Appendix 4 and the requirements can be found in chapter: 2.3 Program of requirements.

What is the most appropriate and convenient material for the region of Bulgaria?

In order to select the material that is best fit for the project a multi criteria analysis is performed comparing and weighing the three proposed variants. The material is then analyzed further to see if it can be used with the client's preferences.

Product in chapter: 3.3. Multi-criteria Analysis.

How will the selected material effect the structure?

The answer to this question requires research and knowledge about structural integrity of a residential building. The approach is literature research on the mechanical characteristics of the selected material as well as consultations with professional constructors that work with this material. Furthermore, calculations for substituting the current structure with the new one must be made.

Product in chapter 4. Results.

How can the building be re-designed based on the new construction materials proposed?

The approach for this question is to create an outline based on the literature used to answer the previous questions. The new designed has to be consulted and approved by professional engineers and architects.

Product in chapter 4. Results.

3.3 Multi Criteria Analysis

Multi-criteria analysis compares various designs or solutions for a specific problem, usually in projects, based on a set of criteria. This method is based on a weighted average evaluation of solutions or actions.

For each criterion, the versions to be compared receive an estimated score, and more details on how these estimations were made and what drove the scores will be provided.

3.3.1 Criteria

For this MCA, six criteria have been formulated to compare all of the variants. These criteria best reflect the important aspects set by client which were required to achieve the goal and objectives of this research report. Each of the chosen criteria is connected to a certain demand from of the client. In order to select the right one a number of criteria have to be considered:

- **Sustainability**

The need for building materials is increasing as the construction industry evolves, which is also responsible for an increase in carbon footprint, as the usage of cement increases carbon emissions. As a result, rather than using cement or concrete, eco-friendly and sustainable construction materials like as earth, bamboo, metakaolin, silica fume, rice huskash, and so on are preferable. Reusable materials are the greatest since they lessen the need for new materials to be produced in the future. The way these materials are put and fixed can have an impact on their ability to be reused. Locally sourced materials also save time and money in terms of transportation, lowering emissions.

- **Safe and Healthy environment**

An important requirement for green building materials is to ensure a safe and healthy environment on the one hand, and on the other - to have a minimum of harmful impact on the environment, in the period from construction to operation. Materials for the construction of green buildings create a healthier and safer workplace. These are materials that do not contain or are reduced in content toxic ingredients. These are usually substances released during the production of certain materials such as insulation that deplete the ozone layer, as well as those that can cause health problems.

Healthy materials are those that result from minimal processing and are made from natural products. They are defined as green once because of the low energy consumption in production and the second time because of the reduced risk of emitting harmful emissions during their production. This category includes materials from wood, agricultural and other plants, as well as products from natural stone, clay and others.

- **Durability**

The materials should be able to last as long as traditional materials or preferably longer (100+ years) and should be more resistant to corrosion and moisture. Also, they should be able to adapt to changes in weather and climate. Some materials degrade quickly, especially when exposed to moisture. The materials chosen must be durable and strong enough for the location and conditions in which they will be used. As a result, it's preferable to choose materials that require as little care and replacement as possible, so they can last the entire life of the building and provide a profit to the user.

- **Climate**

The environment is another important consideration when choosing materials. Consider factors such as the typical degree of heat or cold throughout the year, the amount of rain or snowfall, the amount of daylight, and the amount of ventilation required. The building material should adapt to the temperature and surroundings. When climate enters the scene, material properties change and assist in responding to the climate.

The project is located in Sofia, Bulgaria so the climate there is considered. Climate in Sofia is humid continental with an average annual temperature of 10.9 °C. Winters are relatively cold and snowy, however the summer is warm and sunny. Weather can be very unstable and dynamic with sudden significant temperature amplitudes.

Precipitation is scarce, with just 640 millimeters falling per year, however it is evenly distributed throughout the year, with a relative maximum in May and June due to afternoon thunderstorms and a relative minimum in winter.

From May to September, when the sun shines frequently, the amount of sunshine in Sofia is good, but from November to February, when the weather is typically dreary and foggy, it is relatively low. There are around 2,250 hours of sunshine every year.

- **Availability**

Certain materials are only available locally and are difficult to transfer. Not only does shipping become more expensive, but it also causes the work to be delayed. On the other and, if the material is readily available locally, shipping costs are reduced. It also saves time and allows work to be finished efficiently.

- **Cost**

The cost of materials is an important consideration when selecting building materials because it will ultimately protect your structure. It is necessary to consider the product's lifespan or utility. When you buy low-quality materials, you may find yourself having to fix them frequently, which may be pricey. It will be cost-effective to choose building materials that will last a long time.

3.3.2 Weight of criteria

The main goal of giving weight to each criterion is to show and understand which one(s) is(are)more valuable for the final outcome of the project and the involved stakeholders. This means that some criteria will be more ‘significant’ than others.

For this current MCA, the weight of each criterion will be entirely based on the demands of the clients. The following table will show the weight of the chosen criteria in % with a cumulative value of 100%.

Criteria	Weight
Sustainability	30%
Safe and Healthy Environment	20%
Durability	15%
Climate	10%
Availability	5%

Figure 16. Weight of each criterion.

Sustainability covers the largest share with 30% because the aim of this research is to find sustainable construction materials. This factor is most important in this situation because it will save energy, improve the life-cycle of the building and reduce huge amount of CO2 emissions. The sustainability and the potential re-use of the construction material is its strongest selling point. Firstly, this provides an opportunity for greener and ecological construction. Secondly, provides an opportunity for selling the building with higher price, because the sustainability benefits increase the value of the property.

Safe and Healthy Environment takes 20% from the total score. Aside from importance of the material to be sustainable, it must not contain harmful substances which can cause health problems during manufacturing, construction work and living after completion of construction. Furthermore, all of detrimental agent can harm the soil, water and air. The above reasons rank this category as one of the most important

The reason that durability is 15% is that the materials should last the entire life of the building and to require as little care and replacement as possible. This is important for the aim of the research, because if the material needs frequent repairs this will make it not sustainable construction material, because of the additionally work and improvements.

Climate is another important factor, valued with 10%, because it is of great importance for natural building materials, such as humidity, ventilation, temperature and daylight. This factor, if not considered, could negatively affect the building material and make it lose its mechanical functions.

Availability is only 5% and has the lowest percentages. It is huge advantages to have the material locally but it is not so important. Nowadays the transportation from one country to another is easy so this will not make difficulty so this is not a concern.

Cost has a big percentage- 20%. This is because of the investor doesn't want to spend additional money to what they already spend make and also if the price of a material is lower, respectively, the home will be at a more attractive price and will be sold quicker. On the other hand, if the product is cheap, it might be of poor quality, which will lead to a shorter life of the building. Therefore, the cost is an important part of choosing a construction material.

4. Results

4.1 Variants and scores

The Multi Criteria analysis allows to find out what is the most suitable variant. The scale that is used to evaluate each criterion goes from -2 to +2, with -2 being the most unwanted result and +2 being the most desired result for each of the criteria. The score of 0 is regarded neutral, meaning that the outcome of the project will have no effect on the criteria with that value.

The variants are evaluated based on criteria for Sustainability, Safe and Healthy Environment, Durability, Climate, Availability, Cost. For every solution and each criterion, a score is estimated and the information about the estimation is given. Table 18 the complete MCA assessment.

CRITERIUM	Weight	SOLUTIONS		
		EcoCocon Straw Panels	*Hempcrete*	*Mycelium*
	[%]	*Score:*	*Score:*	*Score:*
Sustainability	30%	2	2	2
Safe and Healthy Environment	20%	1	2	2
Durability	15%	2	2	-1
Climate	10%	2	2	2
Availability	5%	2	1	-1
Cost	20%	1	2	0
TOTAL	100%	**1.6**	**1.95**	**1**

Table 17. Multi Criteria Analysis.

According to the criteria for Sustainability all of the materials are classified with sustainability factors. Therefore, all are rated with the highest rating. In this report, the most important goal is to find natural construction material, so all the proposed materials are highly appreciated with this degree *(Building with Hempcrete, 2020); (Buildingwith EcoCocon, 2020).*

Safe and Healthy Environment is the next evaluation condition. Here, Hempcrete and Mycelium are evaluated with a higher degree because they do not hold any harmful impact, while Straw Panels has a minimum of harmful impact because they include glue.

The next criterion is Durability, this is an important part because it allows for a longer use of a product without being repaired or replaced, which increases the quality of the building material. In this section hempcrete and Eco Cocon Straw Panel have highest points compared to the Mycelium bricks. Hempcrete has excellent durability because of articles that show that it is more durable than traditional materials and has been proven that after each passing year the material becomes stronger. According to Eco Cocon company Straw Panel have life expectancy that can be measured in centuries. While Mycelium bricks can have a lifespan of approximately 20 years which put them in the lowest position. *("FAQ," 2014); (Building with Hempcrete, 2020)*

Climate is also an important part, as it could infuse the quality of the product, such as the humidity or the degree of cold and freezing in the area where the construction will be located. In this category, all three materials are evaluated with the highest point because they are produced and sourced in Europe. In addition, the climate in Bulgaria is very favourable for them. *("Hemp," 2022); ("The Panel," 2019); ("MME | Home Page," 2018)*

Availability is the category that shows which product can most easily be used. The panels here are at the highest point because there is a factory in Bulgaria that produces this type of material. Hempcrete is with one point lower because the nearest factory for this material is in Rumania, but it is only 500km from Sofia. The distribution and manufacturing of Hempcrete in Bulgaria is expected in the coming years, so the accessible will be greater. From the point of view of Mycelium, it is evaluated with a low degree, because in Bulgaria and the surrounding countries there is no project with such material and no one has tried to build or create this material. However, the Mycelium like resource can grow on the territory of Europe and Bulgaria. *("The Panel," 2019); ("Hemp in Romania | Cavvas," 2022); ("MME | Home Page," 2018)*

For the construction of a perfect home, the pricing is important for both the investor and the buyer. That's why Cost is the next evaluation criterion. Here, hempcrete is the most expensive because it is not located in Bulgaria and there are a few projects made with this material. After it are the other two materials. The straw panels for now are cheaper than the hempcrete because there is not transportation cost and also there are precast which decrease the price. On the part of Mycelium bricks, there is no data on buildings in which it is used as a brick and therefore the price is difficult to determine so it is rated with 0 as a neutral indicator. *(Price, 2014); (Technical Information for HCB Hempcrete Blocks, n.d.)*

According to the analysis made above, hempcrete comes out with the highest rating after assessing the scores and multiplying them by the weight of the criteria. The following chapters will explain in more detail the positive aspects of hempcrete and how it will affect the structure of the building.

4.2 Hempcrete detailed characteristics

Hempcrete is versatile and may be used for a variety of purposes, including insulation, floors, walls, and roofs. It has numerous advantages over other commonly used standard and environmentally friendly materials. Hempcrete is just as easy to use as concrete, but it's far more flexible, waterproof, and fireproof. Furthermore, its structure is up to three times stronger than normal concrete in terms of earthquake resistance. All of these advantages are attributable to the material's strength while remaining light and breathable. When used in building, it is designed to last significantly longer compared to 40 to 100 years for other materials in use. *("Hemp Building: Using Hemp for Construction Materials - Cleveland School of Cannabis," 2020)*

The compressive strength of hempcrete is 1/20 that of concrete, coming in at 1 MPa, meaning it can't be used as a foundation material or in situations where it may be load-bearing. It's resistant to cracking due to its low density making it an attractive alternative to areas prone to earthquakes. The density of hempcrete ranges from 300 to 900 kg/m3.

It aids in the natural regulation of humidity and temperature in the structure, allowing moisture to evaporate, reducing condensation and creating natural insulation leading to over 70% energy savings. *(“Physical and Mechanical Properties of Hempcrete,” 2020)*

Hemp stores carbon in every plant while emitting pure oxygen as it grows. The total CO2 balance for traditional hempcrete is such that the carbon dioxide captured is maintained inside the building structure.

Hempcrete is fully recycled material which can be reused for making fertilizers. When demolishing buildings, there is usually a lot of hazardous waste. Because hempcrete is a natural material, its waste can be easily treated and recycled. In this way, the costs of special waste are eliminated for construction companies. *(Hempitecture, 2021)*

- **Ingredients properties:**

The soft, woody, highly absorbent core of a hemp stalk is known as the hemp sawdust. They come in a variety of grades and are a natural by-product of the hemp stalk's removal. Hemp hurt is also known as hemp wood or shives, and it's similar to flax shives.

A lime binder is a bonding substance that is derived from limestone. For thousands of years, it has been employed in the construction of mortar and plaster. It comes in a variety of grades, kinds, and mixing ratios, all of which affect its durability, strength, and setting time.

Tradical binder is a binder that has been pre-formulated using a high purity air lime that has been prepared in compliance with BS EN 459. It's made up of Tradical12 lime from the United Kingdom, cement, and various pozzolanic and mineral additives. It has been designed and tested over a long period of time to provide consistent, high-quality outcomes when used with hemp. *(“Building with Hempcrete,” 2020)*

In conclusion, the following advantages and disadvantages can be observed:

Advantages:

- Hempcrete is environmentally friendly and energy-efficient building material.
- Hempcrete aids in thermal control, which keeps the building at a comfortable temperature.
- Hempcrete is light in weight and easy to carry from one location to another.
- Hempcrete aids in the creation of permeable walls.
- It is a disaster-resistant material that contributes to building safety.
- It is a sturdy and long-lasting environmentally beneficial building material.
- Hempcrete provides excellent sound and heat insulation.
- Hempcrete is resistant to fire.
- The use of hempcrete makes construction simple and quick.

- Hempcrete is a long-lasting building material.
- It offers residents with a healthy indoor environment.
- Hempcrete may be the most suitable material for use in building renovations.
- It has high moisture handling capacity.

Disadvantages:

- Hempcrete has low compressive strength.
- It also has low elastic modulus which makes it unsuitable for direct loads.
- It cannot be used for heavy loads; it requires frames to carry loads.
- Hempcrete is not suitable for use as a building foundation.
- Hempcrete is more difficult to come by than regular concrete since hemp is tough to come by.
- Builders are unaware of the benefits of hempcrete construction.

4.3 Application of the material in the case study

4.3.1 Construction method

Hempcrete is made by a mixtures of raw materials like hemp shives, tradical binder + lime and water are mixed properly in the right proportion. 1 time hemp shives to 1.5 tradical binder + lime to 2 times water. It can be installed in three ways, similar to normal concrete: prefabricated blocks, moulded in place, and spraying.

Due to the lack of a factory in Bulgaria hempcrete blocks method is unsuitable, as it will require very high transport costs. The method with spraying is expensive to acquire, store, transport, clean and maintain. Also, there are some material loses during applying, which increases the cost of the material. Another negative feature is the need for another machine, which further complicates the work and increases the final cost. Due to the listed shortcomings, these options are rejected.

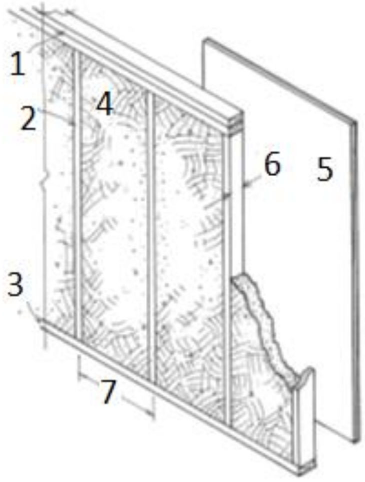
The best option is by moulding in place. Hempcrete will be casted on site in formwork over a structural timber frame. In this variant the material is mechanically mixed before being delivered to the shuttering in big tubs, where it is manually put. However, this variant can cause delays, because of drying. However, with good management on site using the right materials, mixing and placing them correctly the drying time can be drastically reduced. So in this variant the project manager has to ensure proper work. A full description of the three construction methods is reported in appendix 7.

- **Wooden frame**

The structure of the building will be reinforced concrete, as per the project. The chosen method for installing the hempcrete is by pouring the mixture between wooden frame and formwork. The wooden frame will be Single Stud Framing. This type of framing has a simple structure. The frame is built out of 5x25 cm lumber and the stud cavities are filled with hempcrete insulation. The simplicity of frame construction matches code and trades expectations. The simplicity of attaching formwork; wood framing is exposed on both sides of the insulation. The narrow wall profile matches conventional expectations. In the picture below is shown a drawing of Single Stud Framing. *("New Society Publishers," 2022)*

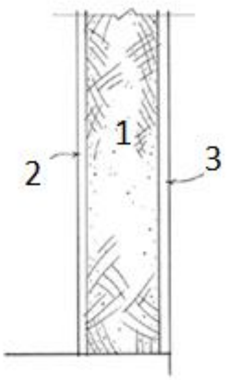
General provisions Eurocode 5 is used for the sizing of wooden frame according to European standards, which consists of the following parts:

- BDS EN 1995-1-1 Eurocode 5: Design of wooden structures. Part 1-1: Basics. Basic rules and rules for buildings;
- BDS EN 1995-1-2 Eurocode 5: Design of wooden structures Part 1-2: General rules. Design of structures against the impact of fire



1. Top plate 5 cm width (length depends on the length of the wall)
2. Stud 5 cm x 25 cm
3. Sill plate 5cm width (length depends on the length of the wall)
4. Hempcrete 340 kg/m3
5. Plaster adhered to hempcrete
   - Clay plaster for the interior side
   - Lime-hemp plasters for the outside walls.
6. Wall framing width 25 cm
7. Stud spacing in 60 cm

Figure 18. Single stud framing.



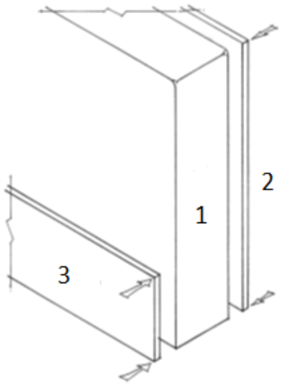
1. Hempcrete with density of 340 kg/m3, tamped moderately
2. Plaster finish applied directly to hempcrete
3. Plaster finish applied directly to hempcrete

- Width of the wall- 25 cm, height- 265 cm

Figure 19. Cross section of hempcrete wall

- **Formwork**

Before doing the pouring activities, temporary formwork must be installed. Because the installation and removal of the forms increase the construction time and add labour and cost to the workload a streamlined formwork system can be created. This project will use one side fully shuttered, and one side with slip form wooden formwork. This type of formwork is a temporary sheeting on one side of the wall which eliminates the added time and cost of putting and then removing formwork on the said side. Slip forms on the other side are required so that the hempcrete can be placed and tamped by the installers. Also, this method allows flexibility to the installation because the formwork can be lying flat and the mixture can be added to the wall, saving time and effort. The materials which will be used for the formwork are plywood or oriented strand board (OSB). *("New Society Publishers," 2022)*



1. Hempcrete wall - 25 cm width
2. One side of wall fully shuttered (temporary)
3. Slip form 60 cm high, will be moved up the wall as hempcrete is added

Figure 20. Formwork plan.

The following figure explains in detail how the wooden frame and hempcrete will be installed.

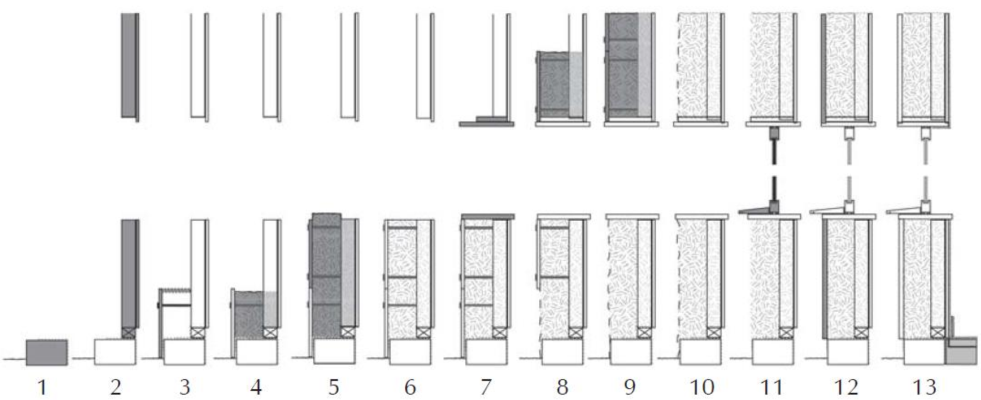


Figure 21: Construction sequence with hempcrete timber-frame wall (with hempcrete cast on site inside formwork)

1. The damp-proof membrane was lapped over the loadbearing wall footing after the groundwork was finished.
2. Timber was installed according to the structural engineer's plans.
3. A damp-proof course has been installed and the frame has been lapped up. First, the shuttering was installed and secured to the frame. Temporary timbers reinforced the shuttering.
4. Fill the shuttering with hempcrete mix and lightly tamp it down, tamping harder in the corners and edges.
5. Installed second level of shuttering and overfilled with hempcrete to the top of the sill line.
6. Hempcrete cut to create level finish to underside of sill.
7. The shuttering for the opening has been installed. Shuttering and filling with hempcrete continues. Shutteringlower down removed and re-used after 24 h drying time.
8. Shuttering and filling with hempcrete continues. Where shuttering is removed, screw holes are filled with hemp limemix and wall is protected for rain/water as it dries.
9. Once wall complete and shuttering removed, hempcrete mix left to dry for 4–8 weeks depending on weather and temperature.
10. Once largely dry, windows can be installed. These can fixto dry hemp lime or, if fitted sooner, back to timber-frameelements.
11. Lime plaster added to protect hempcrete external face.
12. Internal finishes applied.

("Hemp Lime: An Introduction to Low-Impact Building Materials Downloadable Version: BREbookshop.com," 2021)

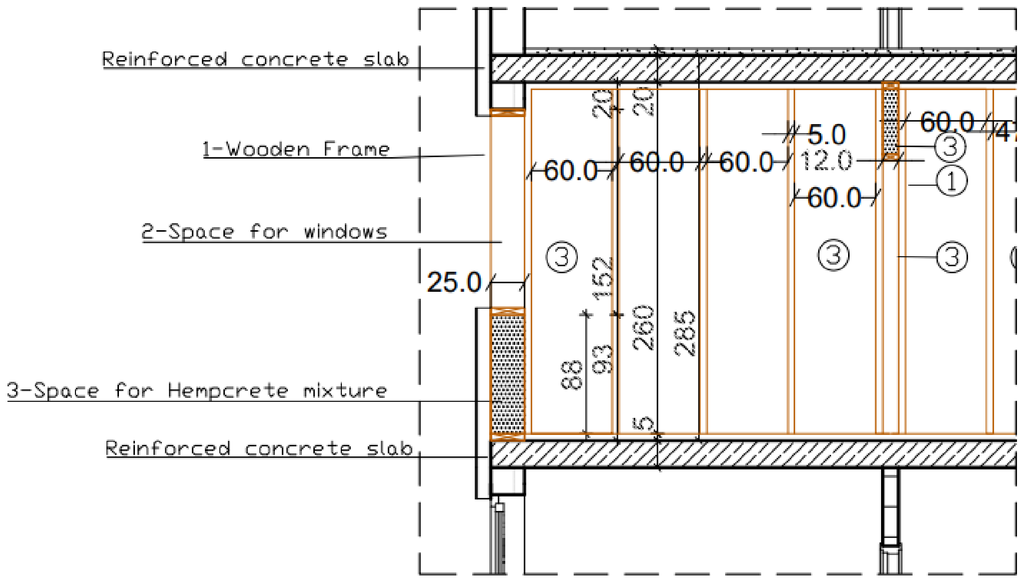


Figure 22. Sample of the drawing for the wooden frame.

4.4 Structural analysis

In this section of the report, a comparison between the new material- hempcrete, and the previously utilized ceramic bricks will be made. This comparison aims to highlight the effects that both materials have on the structure. In order to do this a series of calculations for the structural elements will be done. Furthermore, additional design choices will be made regarding the reinforcement of those elements due to the different loads and properties that the materials provide. It is important to note that hempcrete will be placed on the exact places where there are currently ceramic brick walls and the dimensions of the walls will stay the same (see figure 13 in Appendix 11). Also wind, seismic and life loads are assumed to stay the same and only dead loads are considered.

The structural components of a building are floor slabs, columns and beams. However, the floor slabs in this building are beamless slabs with a thickness on 20 cm. This means that although there are a couple of beams, they do not provide as big structural support but instead, the applied loads are transferred directly to the slab and columns. This is why the following calculations will be for the most loaded slab section and column (figure 23).

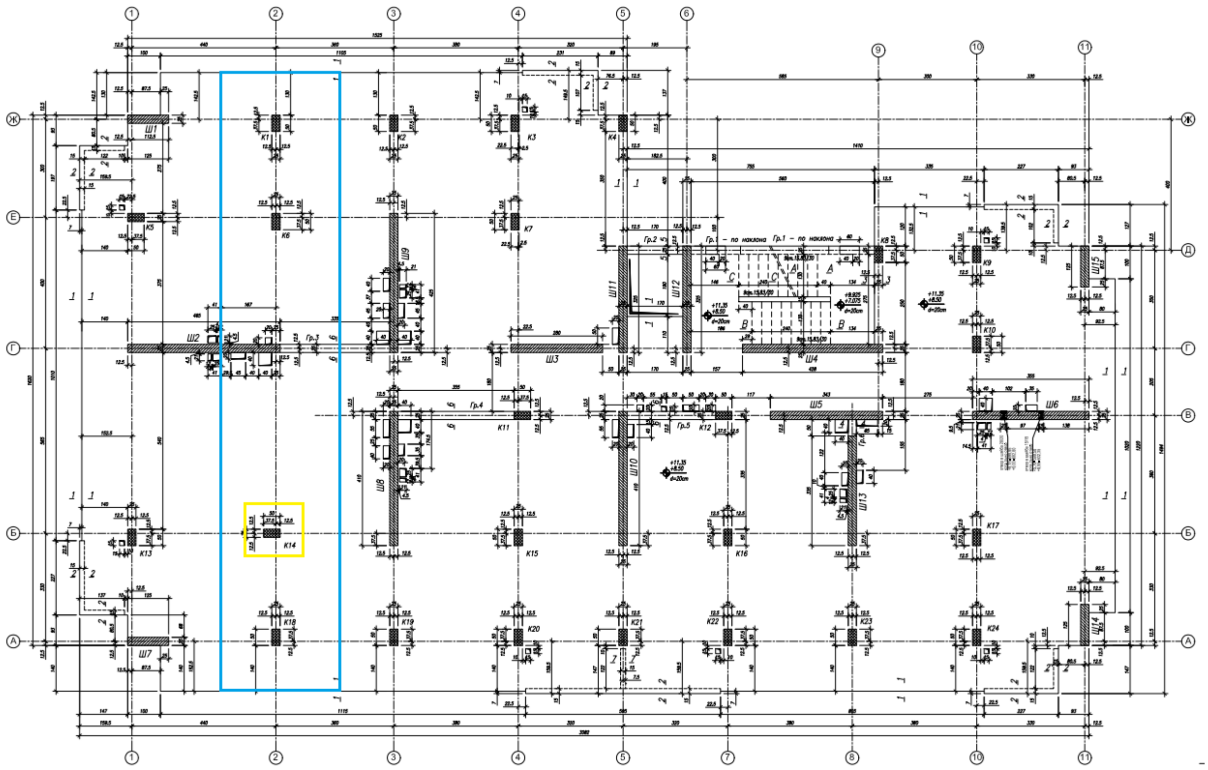
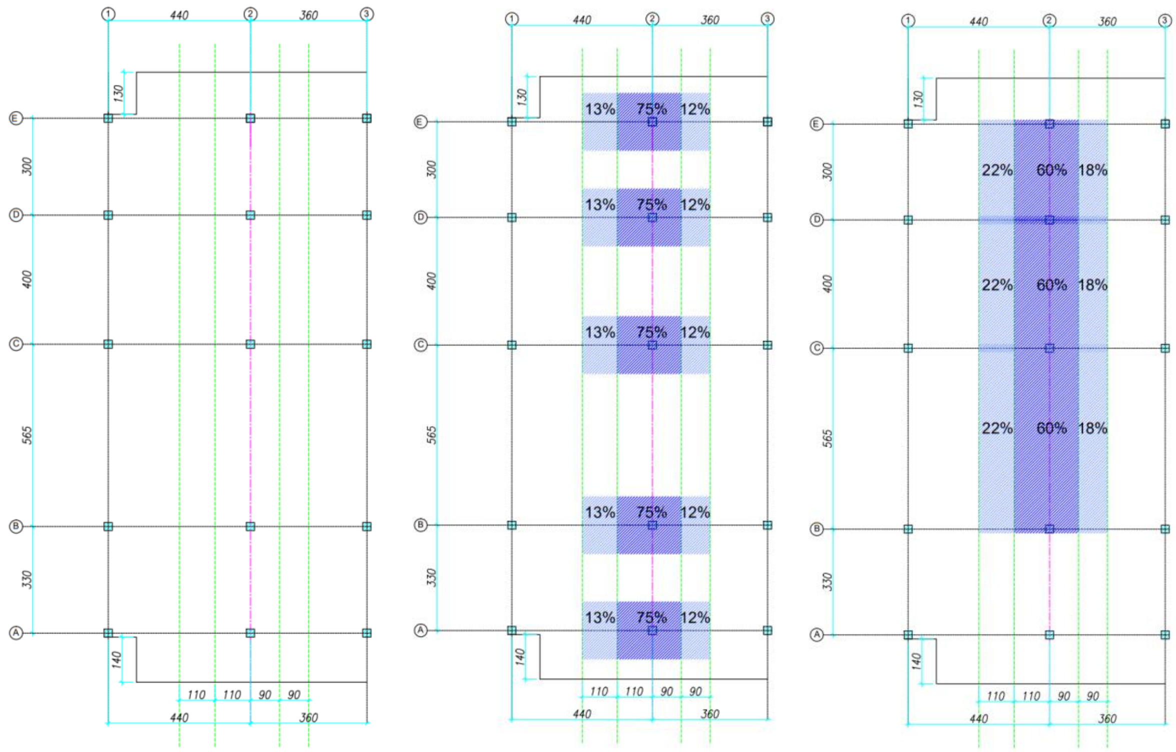


Figure 23. Blue represents the section of the slab. Yellow represents the column.

4.4.1 Slab calculations

Before the calculations there are several things to be noted. First, because the slab is a beamless slab the calculations will be done using the equivalent beam method. In this method a section of the slab is considered to have equivalent properties as a beam going through a central axis from one end of the slab to the other. When calculating the top and bottom reinforcement the effective width of the section distributes the top reinforcement at a ratio of 75% for the main and 25% divided between the rear sections and the bottom- 60% for the main and 40% divided between the rear sections (see figure 24). Second, for the purpose of the research only a section of the slab will be considered when calculating. The section in question is the one between axis 1 and 3 (figure 24). Third, the reinforcement only in one direction is to be considered in order to simplify the calculations and it is assumed, due to the similar dimensions in both directions of the slab that the results will prove similar. Fourth and last, when comparing the amount of reinforcement only the most critical points are considered, in this situation- the section between axis B and C on the figure below. In this section is the biggest length between two supports, so the maximum moments will be there. The point of the calculations is to show the difference when using both materials so even though simplified, the results will provide the needed information.



Section plan	Top reinforcement	Bottom reinforcement

Figure 24. Section of consideration.

Given for both materials:

Paramaeters	[mm]
l_{eff}	18650
d	164
h	200
b	1000
c	30
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
f_{yd}	435

The first step is to find the ULS for both materials which can be seen in the calculations made in the tables below.

ULS bricks:

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib load [kN/m²]
Bricks	-	18	2.85
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	9.55
Q	1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	56.07	<- decisive
1.2*G+1.5*Q	54.84	

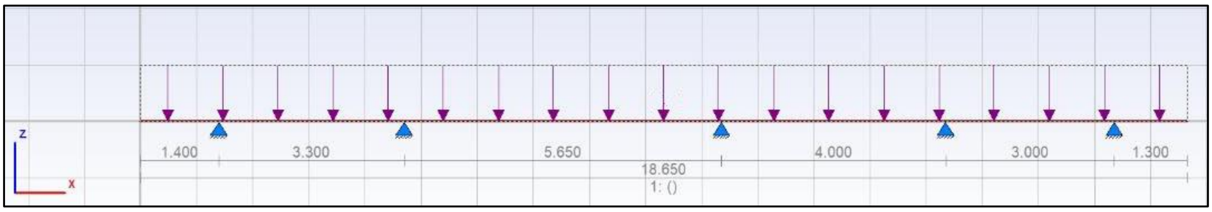
ULS hempcrete:

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib. load [kN/m²]
Hempcrete	-	3.4	0.6
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

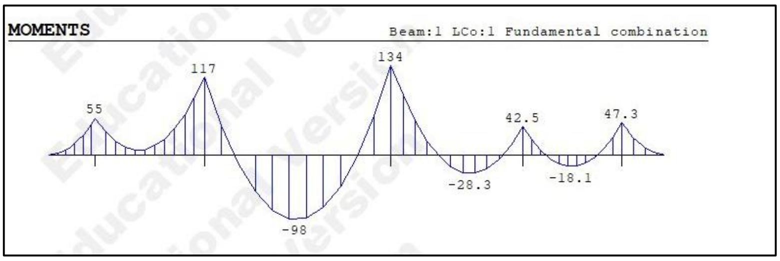
G	7.3
Q	1.5

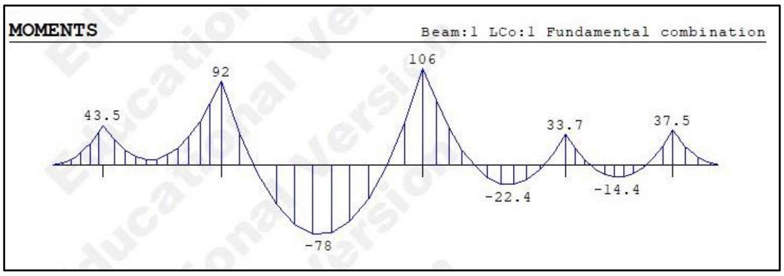
ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	43.92	
1.2*G+1.5*Q	44.04	<- decisive

The results for both ULS loads are then put into the Technosoft software to get the support reactions using the scheme below.



The Technosoft produced the following M-lines:

Bricks: 

Hempcrete: 

The amount of reinforcement is calculated by a series of calculations:

1) Calculating Med.
2) Calculating $\frac{\text{Med}}{\text{b}*\text{d}^2}$.
3) Using the GTB table for C25/30 to find ρ.
4) Calculate the required As.

When calculating the top reinforcement, the top values of the M-lines are considered and when calculating the bottom reinforcement- the bottom. As previously said only the highest top and bottom sections will be calculated to showcase the difference between the materials.

- Top reinforcement:

1) Med=$\frac{75\%*\text{M4}}{\text{width}}$

Med bricks= 50.25 kNm/m

Med hempcrete= 39.75 kNm/m

2) $\frac{\text{Med}}{\text{b}*\text{d}^2}$

bricks= 1868 kN/m²

hempcrete= 1478 kN/m²

3) GTB table for C25/30 to find ρ

ρ bricks= 0.46%

ρ hempcrete= 0.36%

4) Asreq.

Asreq.= ρ*b*d

Asreq. bricks= <u>755 mm²</u>

Asreq. hempcrete= <u>583 mm²</u>

This means that 30% less reinforcement will be used on the top when using hempcrete.

- Bottom reinforcement:

1) Med= $\frac{60\% * M3}{width}$

Med bricks= 36.75 kNm/m

Med hempcrete= 23.4 kNm/m

2) $\frac{Med}{b * d^2}$

bricks= 1366kN/m²

hempcrete= 870 kN/m²

3) GTB table for C25/30 to find ρ

ρ bricks= 0.33%

ρ hempcrete= 0,2%

4) Asreq.

Asreq.= ρ*b*d

Asreq. bricks= <u>541 mm²</u>

Asreq. hempcrete= <u>334.6 mm²</u>

This means that 40% less reinforcement will be used on the bottom when using hempcrete.

Now a design will be made for the reinforcement when using hempcrete with the required checks.

The calculation sequence is as follows:

1) Choosing reinforcement Ø.
2) Checking min and max reinforcement ratio.
3) Crack control.
4) Checking maximum spacing.

- Top reinforcement:

1) (Appendix10- Table 2): Ø12-165 => Asused= 685 mm²

2) $\rho = \frac{\text{Asused}}{b*d} = 0.42\%$

GTB table (Appendix 10- Tables 3 and 4): ρmin= 0.13% and ρmax= 1.54%

ρmin < ρ < ρmax => Satisfactory

3) $\sigma = \frac{\text{SLS}}{\text{ULS}} * \frac{\text{Asreq.}}{\text{Asused}} * \text{fyd} = 274.4 \text{ N/mm}^2$

4) Class XC1, w<= 0.4 (Appendix 10- Table 5)

Linier interpolate (Appendix 10- Table 6): smax= 202 mm > 165 mm => Satisfactory

- Bottom reinforcement:

1) (Appendix10- Table 2): Ø8-145=> Asused= 347 mm²

2) $\rho = \frac{\text{Asused}}{b*d} = 0.21\%$

GTB table (Appendix 10- Tables 3 and 4): ρmin= 0.13% and ρmax= 1.54%

ρmin < ρ < ρmax => Satisfactory

3) $\sigma = \frac{\text{SLS}}{\text{ULS}} * \frac{\text{Asreq.}}{\text{Asused}} * \text{fyd} = 315.5 \text{ N/mm}^2$

4) Class XC1, w<= 0.4 (Appendix 10- Table 5)

Linier interpolate (Appendix 10- Table 6): smax= 155 mm > 145 mm => Satisfactory

The rest of the bar were calculated and put in an excel table and are as follows:

Top reinforcement						
%	Parameter	M1	M2	M4	M6	M8
75%	Med	16.31	34.50	39.75	12.64	14.06
	Med/b*d^2	606.50	1282.72	1477.91	469.87	522.85
	ρ [%]	0.14	0.31	0.36	0.11	0.12
	As req.	231.73	502.73	583.16	181.97	204.29
	⌀	Ø8-185	Ø12-195	Ø12-165	Ø6-130	Ø8-200
	As used	272.00	580.00	685.00	217.00	251.00
	As/bd	0.17	0.35	0.42	0.13	0.15
	σ [N/mm²]	278.79	283.64	278.58	274.41	266.34
	smax [mm]	201.52	195.46	201.78	206.99	217.08
13%	Med	1.29	2.73	3.14	0.99	1.39
	Med/b*d^2	47.89	101.50	116.88	36.91	51.85
	q	0.02	0.02	0.02	0.02	0.02
	As req.	32.80	32.80	27.47	32.80	32.80
	⌀	Ø6-130	Ø8-215	Ø8-216	Ø6-130	Ø6-130
	As used	217.00	234.00	234.00	217.00	217.00
	As/bd	0.13	0.14	0.14	0.13	0.13
	σ [N/mm²]	49.46	45.87	38.42	49.46	49.46
	smax [mm]	300.00	300.00	300.00	300.00	300.00
12%	Med	1.45	3.08	3.55	1.12	1.57
	Med/b*d^2	54.04	114.52	131.87	41.64	58.50
	q	0.02	0.02	0.02	0.02	0.02
	As req.	32.80	25.92	37.30	32.80	32.80
	⌀	Ø6-130	Ø10-205	Ø10-206	Ø6-130	Ø6-130
	As used	217.00	245.00	245.00	217.00	217.00
	As/bd	0.13	0.15	0.15	0.13	0.13
	σ [N/mm²]	49.46	34.62	49.82	49.46	49.46
	smax [mm]	300.00	300.00	300.00	300.00	300.00

Bottom reinforcement				
%	Parameter	M3	M5	M7
60%	Med	23.40	6.72	4.32
	Med/b*d^2	870.02	249.85	160.62
	q	0.20	0.07	0.04
	As req.	334.57	114.70	62.62
	⌀	Ø8-145	Ø6-130	Ø6-130
	As used	347.00	217.00	217.00
	As/bd	0.21	0.13	0.13
	σ [N/mm²]	315.50	172.97	94.44
	smax [mm]	155.62	333.79	300.00
22%	Med	3.88	1.12	0.72
	Med/b*d^2	144.26	41.64	26.77
	q	0.03	0.02	0.02
	As req.	45.43	32.80	32.80
	⌀	Ø10-205	Ø6-130	Ø6-130
	As used	245.00	217.00	217.00
	As/bd	0.15	0.13	0.13
	σ [N/mm²]	60.68	49.46	49.46
	smax [mm]	300.00	300.00	300.00
18%	Med	3.88	1.12	0.72
	Med/b*d^2	144.26	41.64	26.77
	q	0.03	0.02	0.02
	As req.	45.43	32.80	32.80
	⌀	Ø10-206	Ø6-130	Ø6-130
	As used	245.00	217.00	217.00
	As/bd	0.15	0.13	0.13
	σ [N/mm²]	60.68	49.46	49.46
	smax [mm]	300.00	300.00	300.00

Detailed breakdown of the calculations can be found in Appendix 8 and drawings of the slab can be found in Appendix 11.

4.4.2 Column calculations

The column in consideration is column 14 (figure 23) because it is the one that is next to the biggest area between two supports therefore it is the most loaded which can also be seen in the M-lines.

Given for both materials:

Paramaeters	[mm]
l_{eff}	2650
h	250
b	500
c	30
stirrups	8
Ø	12
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
E	3600
f_{yd}	435
f_{cd}	16.7

The calculations for ULS for both materials can be seen in the tables below.

ULS bricks:

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib load [kN/m²]
Bricks	-	18	2.85
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	9.55
Q	1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	14	<- decisive
1.2*G+1.5*Q	13.71	

SLS [kN/m²]	
G+Q*Ψ1	10.6

ULS hempcrete:

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib. load [kN/m²]
Hempcrete	-	3.4	0.6
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	7.3
Q	1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	10.98	
1.2*G+1.5*Q	11.01	<- decisive

SLS [kN/m²]	
G+Q*Ψ1	8.35

The firs step is to find the loads that are applied to the column in both situations:

1) A floor
2) N
3) Ned

1) A floor= ((2.82+1.65)*(2.2+1.8)= 17.88 m^2
2) N bricks= ULS*A+column self-weight= 258.6kN
   N hempcrete=ULS*A+column self-weight =206.75kN
3) N_{ed} bricks= 258.6*5= 1293 kN
   N_{ed} hempcrete= 206.75*5= 1033.75 kN

Buckling stability:

2^{nd} order effects may be neglected if they are smaller than 10% of the first order effects.

$I= 1/12*b*h^3= 651041666.7\ mm^4$

$N_{cr}= \pi*EI/L_0^2= 10485$ kN

2^{nd} order effects:

n buckling= N_{cr}/N_{ed}= 8.1

n buckling/(n buckling-1)= 1.14 => Satisfactory

2^{nd} order effects in case of axial load:

If $\lambda \leq \lambda_{min}$, 2^{nd} order effects can be ignored.

$\lambda= L_0/i= 36.72$

$\lambda_{min}= 20*A*B*(C/\sqrt{n})= 13.9$

$\lambda>\lambda_{min}$ => Satisfactory, 2nd order can be considered

(Full calculations in Appendix 9)

Reinforcement:

$(N_{ed}/f_{cd}*A_c)*(e_t/h)$:

1) $N_{ed}/f_{cd}*A_c$
2) $e_t= e_0+e_1+e_2$

bricks:

1) $N_{ed}/f_{cd}*A_c$= <u>0.6</u>
2) $e_t= e_0+e_1+e_2 \geq e_{0;min}$:
   - $e_0= M_{0;Ed}/N_{ed}$= 0 (first order eccentricity)
   - $e_1= L_0/400$= 6.6

- $e_2 = K_r * K_\varphi * (L_0^2/\pi^2)*(\varepsilon_{yd}/0.45*d) = 19.67$

$e_t = e_0+e_1+e_2 = \underline{26.27}$

$(N_{ed}/f_{cd}*A_c)*(e_t/h) = 0.06$

(Full calculations in Appendix 9)

hempcrete:

1) $N_{ed}/f_{cd}*A_c = \underline{0.48}$
2) $e_t = e_0+e_1+e_2 \geq e_{0;min}$:
   - $e_0 = M_{0;Ed}/N_{ed} = 0$ (first order eccentricity)
   - $e_1 = L_0/400 = 6.6$
   - $e_2 = K_r * K_\varphi * (L_0^2/\pi^2)*(\varepsilon_{yd}/0.45*d) = 30.95$

   $e_t = e_0+e_1+e_2 = \underline{37.55}$

   $(N_{ed}/f_{cd}*A_c)*(e_t/h) = 0.07$

(Full calculations in Appendix 9)

Reinforcement ratio A_s/A_c:

Using Appendix 10- Table 9 to calculate the ratio for both materials it turns out that $\rho*(f_{yd}/f_{cd}) = 0$. What this means is that the loads in both cases are very small so the needed amount of reinforcement is the minimum required by the norms for structural stability therefore ρ is used as 0.4%. This means the reinforcement in the columns cannot be reduced but the calculations show that when using hempcrete the loads on the building will be smaller.

Never the less, a design is made for the reinforcement when using hempcrete.

$A_s = \rho*b*h = 0.004*500*200 = \underline{500\ mm^2}$

Using Appendix 10- Table 10:

Use 6Ø12 for main reinforcement.

Use Ø18 for stirrups.

Drawings of the column can be found in Appendix 11.

4.4.3 Effects of removing the bricks

1 ton of newly manufactured bricks is estimated to releases 258 kg of CO2 emissions. The following calculations will show how much emissions will be preserved from removing the ceramic bricks from the structure. As previously mentioned hempcrete will be placed on the exact positions where there are currently brick walls keeping the dimensions as they are.

Two types of walls:

- Exterior walls and between apartments and hallway- 0.25 m width, 2.65 m height, 81 m total length per floor. This equals to 54 m^3 bricks per floor, 270 m^3 in total. 1 m^3 of these bricks weighs around 570 kg, so in total there are roughly 154 tons of bricks in the building which from the information above shows that 40 tons of CO2 will be preserved.

- Interior walls between rooms- 12 cm width 2.65 m height, 91 m total length per floor. This equals to 29 m^3 bricks per floor, 145 m^3 in total. 1 m^3 of these bricks weighs around 485 kg, so in total there are roughly 70 tons of bricks in the building which from the information above shows that more than 18.5 tons of CO2 will be preserved.

In total from both types of bricks 58.5 tons of CO2 will be preserved from releasing into the atmosphere.

5. Discussion, conclusion and recommendations

5.1 Discussion

The outcome of this research provides an alternative to the current construction materials for Bulgarian residential buildings. There are several points proving that the current construction materials are not good for the environment and their production is not sustainable long term. To concur this a dive into environmentally beneficial construction materials was made using literature sources and professional advices.

The research produced several solutions for materials and methods that not only minimized the unfortunate bad effects of constructing but also decreased them and help to better the environment. The methods in questions are EcoCocon panels, Hempcrete and Mycelium which have their own properties and provide different benefits.

After thoughtful consideration and evaluation, the Hempcrete solution was selected based on a Multi criteria analysis comparison between the three for the criteria of sustainability, safe and healthy environment, durability, climate, availability and cost. Hempcrete has many environmental benefits, some of which include- capture of CO2 emissions, energy savings, reducing the need for additional insulation and more; and structural advantages like better earthquake resistance, lighter loads and reduction of the reinforcement. When it comes to reducing the reinforcement it is important to say that it can only be done to the floor slabs due to the facts that the loads that it provides are so little that in the other structural elements the minimum amount will be used. This means that besides the benefits that the material itself provides, there will be additional benefits like lower CO2 emissions from the lower amount of reinforcement needed and the liquidation of the bricks.

Furthermore, the client was also pleased with the results. The aim set by them was to make their building more sustainable and to increase its efficiency and longevity and exactly this is achieved. One concern worth mentioning is costs due to the fact that using this material proves pricier than the current ones but the value of the property increases significantly and the energy savings makes the investment worth it in the long run in their opinion.

Additionally, to the client's opinion the project was shown to a professional hempcrete builder. Their opinion on the matter is that this solution is feasible even though the scale of the building is much bigger than the ones that are currently in construction in the country.

5.2 Conclusion

This final thesis assignment was mainly focused on providing different alternative sustainable construction materials for residential building in Sofia, Bulgaria. The idea is to find the most suitable material for the climate, structure of the building, client requirements and it also has to meet all technical and functional requirements.

The report aims to shows the problem with traditional construction material and causes of manufacturing them. Moreover, presenting the possibility of natural materials, not only in relation to ecological qualities, but also in relation to mechanical and functional qualities. A Multi-Criteria Analysis is used to sieve through all the proposed alternatives and to find the most suitable one.

The results of the MCA indicate that a hempcrete material is by far the best possible alternative to the current structural design while also meeting all the requirements.

The positive parts of this material are explained and it was decided to leave the structure of the building, which is reinforced concrete, and to replace the ceramic bricks with hempcrete, which is installed using formwork.

These changes lead to several improvements in ecological way. The use of hempcrete will decrease moisture and preventing erosion. Furthermore, using hempcrete will decrease manufacturing of traditional non sustainable construction material, which produce huge CO2 emissions.

The mechanical properties of hempcrete increase its value. First of all, hempcrete has low density, making it an attractive alternative to areas prone to earthquakes. Moreover, it has great moisture-resistant, better thermal conductivity than ceramic bricks with insulation, fire-resistant and it is fully recyclable material which can be reused for making fertilizers.

In addition to ecological benefits using hempcrete will affect the structural elements. The loads of the hempcrete are far less than the ones from the ceramic bricks. This in the case of the floor slabs means that reinforcement can be reduced by 30% for the top reinforcement and 40% for the bottom. Less emissions will be emitted when producing the needed reinforcement for this building and as another bonus- the price will be lower. The removal of the bricks will also decrease the emissions for their production by 58.5 tons and the building will be lighter. This leads to huge positive changes because it will prove beneficial in case of an earthquake. It is important to note that Bulgaria is in the 9th earthquake zone and this will make things much better if strong earthquakes erupt. In such case the bricks will fall and get damaged, while in the new case the impact of the earthquakes on the non-bearing wall will not cause damage.

In conclusion, the suggested alternative offers a creative way to improve residential construction, and by using this material, many environmental and health issues can be lessened.

5.3 Recommendation

The first recommendation is to commercialize this kind of buildings. In order to optimize the use of hempcrete and to better benefit from the positive features it has to be applied in more projects. If its use becomes a standard practice the construction process can be optimized and solutions for further problems can be resolved.

The second recommendation is to substitute the concrete structure with hempcrete. Removing reinforced concrete all together will be a huge improvement to the building sector in terms of environmental footprint. For the purpose of this paper the task of changing the whole structure was too big, but with further work with the material and professional knowledge the goal is achievable.

The biggest limitation of using the material is that it is not produced locally. The hemp sawdust has to be transported from Romania where the near factory is located. In order to start using hempcrete as a mass material, its production in Bulgaria will have to be ensured. This can happen after the legalization of industrial hemp. The positive feature is that, as negotiations are under way for legalization and growth in Bulgaria.

Furthermore, quality workers have to be hired. It is not possible to apply this material if the builders are not familiar with building with it. According to the only hempcrete company in Bulgaria, there are very few builders who can work with it. However, the technique of work is not difficult so more people can be taught.

As a final recommendation, the outcome of this research can be used as a base for professional engineers, investors and builders. More people have to be introduced to the benefits of using hempcrete as a material. Furthermore, in order to improve the entire residential building, future research regarding complete improvement of the structure of the building to be designed in way that it can be fully sustainable. And as an added bonus design for sustainable techniques and features for ventilation, reducing water waste and electricity can be added to create circularity and further improve the building.

References

A fast plant for rapid shifts in construction – how the ancient supercrop Hemp can help build low carbon homes. (2020). Retrieved June 4, 2022, from Rapidtransition.org website: https://www.rapidtransition.org/stories/a-fast-plant-for-rapid-shifts-in-construction-how-the-ancient-supercrop-hemp-can-help-build-low-carbon-homes/

Arrigoni, A., Pelosato, R., Melià, P., Ruggieri, G., Sabbadini, S., & Dotelli, G. (2017). Life cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. Journal of Cleaner Production, 149, 1051–1061. https://doi.org/10.1016/j.jclepro.2017.02.161

Author. (2020, September 28). Article headline. Retrieved June 7, 2022, from Aranca.com website: https://www.aranca.com/knowledge-library/articles/business-research/the-need-for-sustainable-building-material

Bailey, M. (2022, January 24). Building a viable hemp plant industry in Europe. Retrieved June 4, 2022, from Health Europa website: https://www.healtheuropa.com/building-a-viable-hemp-plant-industry-in-europe/113012/

Bcci.bg website: https://www.bcci.bg/bulgarian/infobusb/year2010/number12/item8.htm

Block, M., & Bokalders, V. (2010). The Whole Building Handbook. Routledge. https://doi.org/10.4324/9781849774833

Bozsaky, D. (2019). Nature-Based Thermal Insulation Materials From Renewable Resources – A State-Of-The-Art Review. Slovak Journal of Civil Engineering, 27(1), 52–59. https://doi.org/10.2478/sjce-2019-0008

Budds, D. (2019, September 19). How buildings contribute to climate change. Retrieved June 4, 2022, from Curbed website: https://archive.curbed.com/2019/9/19/20874234/buildings-carbon-emissions-climate-change

Building with EcoCocon. (2020). Retrieved June 4, 2022, from EcoCocon website: https://ecococon.eu/bg/blog/2020/building-with-ecococon-panels

Building with Hempcrete. (2020, October 16). Retrieved June 4, 2022, from Rise website: https://www.buildwithrise.com/stories/building-with-hempcrete

C. (2020, November 3). PSCI. Retrieved June 4, 2022, from PSCI website: https://psci.princeton.edu/tips/2020/11/3/cement-and-concrete-the-environmental-impact

Catalysing Science-Based Policy Action on SCP Analysis of the Construction Value Chain Understanding the value chain & identifying hotspots. (2021). Retrieved from https://www.oneplanetnetwork.org/sites/default/files/value-chain_analysis_-_construction_-_210210.pdf

Catalysing Science-Based Policy Action on SCP Analysis of the Construction Value Chain Understanding the value chain & identifying hotspots. (2021). Retrieved from https://www.oneplanetnetwork.org/sites/default/files/value-chain_analysis_-_construction_-_210210.pdf

Demir, İ., & Doğan, C. (2020). Physical and Mechanical Properties of Hempcrete. *The Open Waste Management Journal*, *13*(1). Retrieved from https://openwastemanagementjournal.com/VOLUME/13/PAGE/26/

Demir, İ., & Doğan, C. (2020). Physical and Mechanical Properties of Hempcrete. *The Open Waste Management Journal*, *13*(1). Retrieved from https://openwastemanagementjournal.com/VOLUME/13/PAGE/26/FULLTEXT/

Different Concrete Grades and How They're Used | Concrete Columbia SC. (2018, July 30). Retrieved June 4, 2022, from Knightscompanies.com website: https://www.knightscompanies.com/blog/concrete/different-concrete-grades-and-what-they-are-used-for/

Eco-Friendly Alternatives To Traditional Concrete. (2019). Retrieved June 4, 2022, from Specify Concrete website: https://www.specifyconcrete.org/blog/eco-friendly-alternatives-to-traditional-concrete

Environmental benefits. (2022). Retrieved June 4, 2022, from EIHA website: https://eiha.org/environmental-benefits/

Environmental Impact of Brick Kilns | Habla Zig Zag Kilns. (2021). Retrieved June 4, 2022, from Hablakilns.com website: https://hablakilns.com/environment/environmental-impact/

Environmental Impact of Brick Kilns | Habla Zig Zag Kilns. (2021). Retrieved June 8, 2022, from Hablakilns.com website: https://hablakilns.com/environment/environmental-impact/

FAQ. (2014). Retrieved June 8, 2022, from EcoCocon website: https://ecococon.eu/faq

Firstcitizen. (2018, December 21). *Кононен Бетон / Hempcrete – 7 пъти по-здрав от бетон*. Retrieved June 4, 2022, from Медицински Канабис България - Българска канабис общност website: https://grysti.com/2018/12/21/%D0%BA%D0%BE%D0%BD%D0%BE%D0%BF%D0%B5%D0%BD-%D0%B1%D0%B5%D1%82%D0%BE%D0%BD-hempcrete-7-%D0%BF%D1%8A%D1%82%D0%B8-%D0%BF%D0%BE-%D0%B7%D0%B4%D1%80%D0%B0%D0%B2-%D0%BE%D1%82-%D0%B1%D0%B5%D1%82/

Franzoni, E. (2011). Materials Selection for Green Buildings: which Tools for Engineers and Architects? *Procedia Engineering*, *21*, 883–890. https://doi.org/10.1016/j.proeng.2011.11.2090

Greenspek (2013). Retrieved June 4, 2022, from https://www.greenspec.co.uk/building-design/steel-products-and-environmental-impact/

Guide. (2014). *Sheeps Wool & Hemp Insulation Properties, Benefits, IAQ questions*. Retrieved June 4, 2022, from Inspectapedia.com website: https://inspectapedia.com/insulation/Sheeps-Wool-Insulation-in-Buildings.php

Happhoadmin7. (2021, June 17). *An Emerging Sustainable Construction Material - Mycelium Bricks - Happho*. Retrieved June 8, 2022, from Happho website: https://happho.com/an-emerging-sustainable-construction-material-mycelium-bricks/

Hemp Building: Using Hemp For Construction Materials - Cleveland School of Cannabis. (2020, June 24). Retrieved June 4, 2022, from Cleveland School of Cannabis website: https://csceducation.com/blog/hemp-building-using-hemp-for-construction-materials

Hemp Concrete: A High Performance Material for Green-Building and Retrofitting. (2016). Retrieved June 4, 2022, from Urbannext.net website: https://urbannext.net/hemp-concrete/

Hemp in Romania | Cavvas. (2022). Retrieved June 8, 2022, from Cavvas.com website: https://cavvas.com/?page_id=73

Hemp lime: An introduction to low-impact building materials Downloadable Version : BREbookshop.com. (2021). Retrieved June 7, 2022, from Brebookshop.com website: https://www.brebookshop.com/details.jsp?id=326819

Hemp. (2022). Retrieved June 4, 2022, from European Commission website: https://ec.europa.eu/info/food-farming-fisheries/plants-and-plant-products/plant-products/hemp_en

Hemp. (2022). Retrieved June 8, 2022, from European Commission website: https://ec.europa.eu/info/food-farming-fisheries/plants-and-plant-products/plant-products/hemp_en

Hempcrete buildings - thermal performance and costs - UK Hempcrete. (2014, August 8). Retrieved June 4, 2022, from UK Hempcrete website: https://www.ukhempcrete.com/hempcrete-buildings-thermal-performance-and-costs/

Hempcrete buildings - thermal performance and costs - UK Hempcrete. (2014, August 8). Retrieved June 4, 2022, from UK Hempcrete website: https://www.ukhempcrete.com/hempcrete-buildings-thermal-performance-and-costs/

Hempcrete: Creating Holistic Sustainability With Plant-Based Building Materials. (2015). Retrieved June 4, 2022, from Hempitecture Inc. website: https://www.hempitecture.com/post/hempcrete-creating-holistic-sustainability-with-plant-based-building-materials

Hoffmann, C., Michel Van Hoey, & Benedikt Zeumer. (2020, June 3). *Decarbonization challenge for steel.* Retrieved June 4, 2022, from McKinsey & Company website:

https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

Home - HempFlax - Solutions from nature! (2020, June 25). Retrieved June 4, 2022, from HempFlax - Solutions from nature! website: https://www.hempflax.com/en/

Home - StoneCycling. (2022, May 30). Retrieved June 4, 2022, from StoneCycling website: https://www.stonecycling.com/

Illankoon, I. M. C. S., Tam, V. W. Y., & Le, K. N. (2021). Sustainable development and green buildings. Life-Cycle Cost Models for Green Buildings, 13–44. https://doi.org/10.1016/b978-0-12-820062-9.00002-5

Ilvy Bonnefin. (2017). Emerging Materials: Mycelium Brick. Retrieved June 4, 2022, from Certifiedenergy.com.au website: https://www.certifiedenergy.com.au/emerging-materials/emerging-materials-mycelium-brick

INTEGRATED ENERGY AND CLIMATE PLAN OF THE REPUBLIC OF BULGARIA 2021-2030 REPUBLIC OF BULGARIA Ministry of Energy Ministry of the Environment and Water. (n.d.). Retrieved from https://ec.europa.eu/energy/sites/default/files/documents/bg_final_necp_main_en.pdf

Integrated Insulation Systems > Hempcrete Walls : About this Product. (2022). Retrieved June 4, 2022, from Rise website: https://www.buildwithrise.com/products/building-envelope-and-structure/insulation/integrated-insulation-systems/hempcrete-walls

Jami, T., Karade, S. R., & Singh, L. P. (2019). A review of the properties of hemp concrete for green building applications. Journal of Cleaner Production, 239, 117852. https://doi.org/10.1016/j.jclepro.2019.117852

Let's Talk about Hempcrete – OzHemp. (2014). Retrieved June 4, 2022, from Ozhemp.com.au website: https://ozhemp.com.au/lets-talk-about-hempcrete/

Li, C., Gong, X. Z., Cui, S. P., Wang, Z. H., Zheng, Y., & Chi, B. C. (2011). CO_2 Emissions due to Cement Manufacture. Materials Science Forum, 685, 181–187. https://doi.org/10.4028/www.scientific.net/msf.685.181

Lightweight framing | YourHome. (2015). Retrieved June 6, 2022, from Yourhome.gov.au website: https://www.yourhome.gov.au/materials/lightweight-framing

Lomite, H., & Kare, S. (2009). Impact of Construction Material on Environment (Steel & Concrete). Retrieved from http://www.diva-portal.org/smash/get/diva2:1311265/FULLTEXT01.pdf

Lucon, O., Brazil, D., Ürge-Vorsatz, Zain, A., Akbari, H., Usa, … Eyre, N. (2014). 9 Buildings Coordinating Lead Authors: Lead Authors: Contributing Authors: Review Editors: Chapter Science Assistants. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter9.pdf

Manufacturing of Hemp concrete block - Vibrating press Quadra. (2021, March 9). Retrieved June 4, 2022, from Quadra Concrete website: http://www.quadra-concrete.com/company-description/manufacturing-of-hemp-block-vibrating-press-quadra/?lang=en

MME | Home Page. (2018). Retrieved June 8, 2022, from Myceliummaterials.nl website: https://www.myceliummaterials.nl/

New Society Publishers. (2022, June 6). Retrieved June 7, 2022, from New Society Publishers website: https://newsociety.com/

Price. (2014). Build With Nature. Retrieved June 8, 2022, from Build With Nature website: https://www.buildwithnature.us/price

Putting the construction sector at the core of the climate change debate | Deloitte Central Europe. (2020, April 27). Retrieved June 4, 2022, from Deloitte website: https://www2.deloitte.com/ce/en/pages/real-estate/articles/putting-the-construction-sector-at-the-core-of-the-climate-change-debate.html

Reilly, A., & Kinnane, O. (2017, December 19). The Thermal Behaviour and Embodied Energy of Hemplime Construction. Retrieved June 4, 2022, from ResearchGate website: https://www.researchgate.net/publication/322065270_The_Thermal_Behaviour_and_Embodied_Energy_of_Hemplime_Construction

Shraddha Erandole. (2020, October 6). 8 things to consider while choosing the materials for your project - RTF | Rethinking The Future. Retrieved June 4, 2022, from RTF | Rethinking The Future website: https://www.re-thinkingthefuture.com/rtf-fresh-

perspectives/a1824-8-things-to-consider-while-choosing-the-materials-for-your-project/

Sia Magazin. (2021, November 23). Lego-Style HEMP BLOCKS Make Building a House Quick Easy And Sustainable. Retrieved June 4, 2022, from Sia Magazin website: https://siamagazin.com/amazing-lego-style-hemp-blocks-make-building-a-house-quick-easy-and-sustainable/

Smith, A. (2021). Exploring the Marketing Potential of Hemp-based Paper Products. (6). Retrieved from https://digitalcommons.kennesaw.edu/cgi/viewcontent.cgi?article=1559&context=ama_proceedings

Sparrow, A. (2014). Building With Hempcrete (Hemp-Lime): Essential Tips For The Beginner (Part 1) – The Last Straw. Retrieved June 4, 2022, from Thelaststraw.org website: https://www.thelaststraw.org/building-with-hempcrete-part-1/

Sparrow, A. (2014). Building With Hempcrete (Hemp-Lime): Essential Tips For The Beginner (Part 1) – The Last Straw. Retrieved June 4, 2022, from Thelaststraw.org website: https://www.thelaststraw.org/building-with-hempcrete-part-1/

Steel, concrete and climate change - The Institution of Structural Engineers. (2019, December 11). Retrieved June 4, 2022, from Istructe.org website: https://www.istructe.org/resources/blog/steel-concrete-and-climate-change/

Sustainable and Green Building Construction Materials - Conserve Energy Future. (2020, September 11). Retrieved June 4, 2022, from Conserve Energy Future website: https://www.conserve-energy-future.com/sustainable-construction-materials.php

Technical information for HCB hempcrete blocks. (n.d.). Retrieved from https://www.ukhempcrete.com/wp-content/uploads/2016/09/UK-Hempcrete-price-list-hempcrete-blocks-20-Sept-2016.pdf

Tradical - Building lime innovation. (2022). Retrieved June 4, 2022, from Tradical.com website: https://www.tradical.com/hemp-lime.html

UN environment programme. (2020). Building sector emissions hit record high, but low-carbon pandemic recovery can help transform sector – UN report. Retrieved June 4, *2022, from UN Environment website: https://www.unep.org/news-and-stories/press-release/building-sector-emissions-hit-record-high-low-carbon-pandemic*

Venkatarama Reddy, B. V. (2009). Sustainable materials for low carbon buildings. International Journal of Low-Carbon Technologies, 4(3), 175–181. https://doi.org/10.1093/ijlct/ctp025

Wall Solutions: Porotherm Smart Bricks. (2019, December 16). Retrieved June 4, 2022, from India website: https://www.wienerberger.in/products/wall/porotherm-smart-bricks.html

What exactly is 1 tonne of CO2? We make it tangible. - Climate Neutral Group. (2022, March 30). Retrieved June 4, 2022, from Climate Neutral Group website: https://www.climateneutralgroup.com/en/news/what-exactly-is-1-tonne-of-co2/

Wikipedia Contributors. (2022, June 2). R-value (insulation). Retrieved June 4, 2022, from Wikipedia website: https://en.wikipedia.org/wiki/R-value_(insulation)

Wiley. (2020, June 9). Discover the Sustainable Characteristics of Metal. Wiley.com. https://www.wiley.com/network/professionals/sustainability/discover-the-sustainable-characteristics-of-metal

Wilson, C. (n.d.). The Future for Hemp. Retrieved from https://ec.europa.eu/environment/forests/pdf/respondents-additional-inputs/European%20Industrial%20Hemp%20Association%20(EIHA).pdf

Yang, K.-H., Jung, Y.-B., Cho, M.-S., & Tae, S.-H. (2015). Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete. Journal of Cleaner Production, 103, 774–783. https://doi.org/10.1016/j.jclepro.2014.03.018

Керамичен блок Porotherm 12. (2022, July 4). Retrieved August 7, 2022, from Masterhaus.bg website: https://www.masterhaus.bg/bg/product/7296-keramichen-blok-porotherm-12

Керамичен блок Porotherm 25. (2020, June 26). Retrieved August 7, 2022, from Masterhaus.bg website: https://www.masterhaus.bg/bg/product/7297-keramichen-blok-porotherm-25

Къща от конoп • БАИС. (2019, December 4). Retrieved June 4, 2022, from БАИС website: https://bais.bg/%D0%BA%D1%8A%D1%89%D0%B0-%D0%BE%D1%82-%D0%BA%D0%BE%D0%BD%D0%BE%D0%BF/

Къща от конoп • БАИС. (2019, December 4). Retrieved June 4, 2022, from БАИС website: https://bais.bg/%D0%BA%D1%8A%D1%89%D0%B0-%D0%BE%D1%82-%D0%BA%D0%BE%D0%BD%D0%BE%D0%BF/

Панел. (2019). Retrieved June 4, 2022, from EcoCocon website: https://ecococon.eu/bg/%D0%9F%D0%B0%D0%BD%D0%B5%D0%BB

Устойчивото строителство – състояние, проблеми и перспективи. (2014). Retrieved June 4, 2022, from vestnikstroitel.bg website: https://vestnikstroitel.bg/analysis/93941_ustojchivoto-stroitelstvo-sstoyanie-problemi-i-perspektivi

Устойчивото строителство – състояние, проблеми и перспективи. (2022). Устойчивото строителство и България - 12/2010. (2020). Retrieved March 30, 2022,from

Харбич ООД – Стил и качество за Вашия бъдещ дом! (2019). Retrieved June 4, 2022, from Stroitelstvo-harbich.com website: https://www.stroitelstvo-harbich.com/

Appendix 1: Energy efficiency

The compliance with the requirements for energy efficiency of the buildings shall be considered fulfilled when the value of the integrated indicator - specific annual cost of primary energy in kWh / m², corresponds at least to the following class of energy consumption:

"B" - for new buildings, which are put into operation for the first time, and for existing buildings, which are put into operation after 1 February 2010;

"C" - for existing buildings that have been put into operation by February 1, 2010 inclusive; "A"

- for buildings with close to zero energy consumption;

"A +" - for buildings exceeding the national requirements for buildings with close to zero energy consumption.

The scale of energy consumption classes for residential buildings is defined in Figure 1. The scale of energy consumption classes is developed for their purpose in accordance with BDSEN 15217 and the requirements of the methodological framework of the Delegated

Regulation. (EC) № 244/2012 of 2012 Commission supplementing Directive 2010/31 / EU on the energy performance of buildings by establishing a comparative methodological framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building components (OJ L 81/18 of 21 March 2012)

Клас	EPmin, kWh/m²	EPmax, kWh/m²	ЖИЛИЩНИ СГРАДИ
A+	<	48	A+
A	48	95	A
B	96	190	B
C	191	240	C
D	241	290	D
E	291	363	E
F	364	435	F
G	>	435	G

Figure 1. The scale of energy consumption classes for residential buildings.

According to the documentation provided by the company, the windows are PVC windows with heat transfer coefficient U= 1.4W/m²K, g= 0.52 and doors U= 1.7W/m²K, g= 0.01.

Floor above the ground

Floor above the ground consist of Glossy cement screed, Reinforced concrete slab, Reverse embankment, Foundation slab, Waterproofing, Substrate concrete, Soil.

The thickness of the floor is d=2.05m.

The "R" value, which shows used to grade insulation products or a material's insulating properties is equal to 1.17 m2K/W

The "U" value, measure of the rate of heat loss, is equal to 0.447 W/m2K

Floors of rooms adjacent to outside air

Floors of rooms adjacent to outside air consist of Flooring and underlay, Cement screed, Reinforced concrete slab, Cement base adhesive, EPS thermal insulation, Exterior plaster

The thickness of the floor is d=0.4m. R=3.66 m2K/W U=0.258 W/ m2K

The roof

The roof consists of waterproofing - 2 layers, reinforced cement screed, thermal insulation of stone wool, vapor barrier, reinforced concrete, internal gypsum plaster for machine application.

The thickness of the roof is d=0.46m. R=4.631 m2K/W U=0.225 W/ m2K

External wall adjacent to external air with masonry of repetitive bricks

The wall consists of facade plaster with reinforcing mesh, heat insulation EPS, cement-based adhesive, masonry of repetitive bricks, internal gypsum plaster for machine application

The thickness of the wall is d=0.40m. R=3.69 m2K/W U=0.25 W/ m2K

External wall adjacent to external air with reinforced concrete

The wall consists of facade plaster with reinforcing mesh, heat insulation EPS, cement-based adhesive, reinforced concrete, internal gypsum plaster for machine application

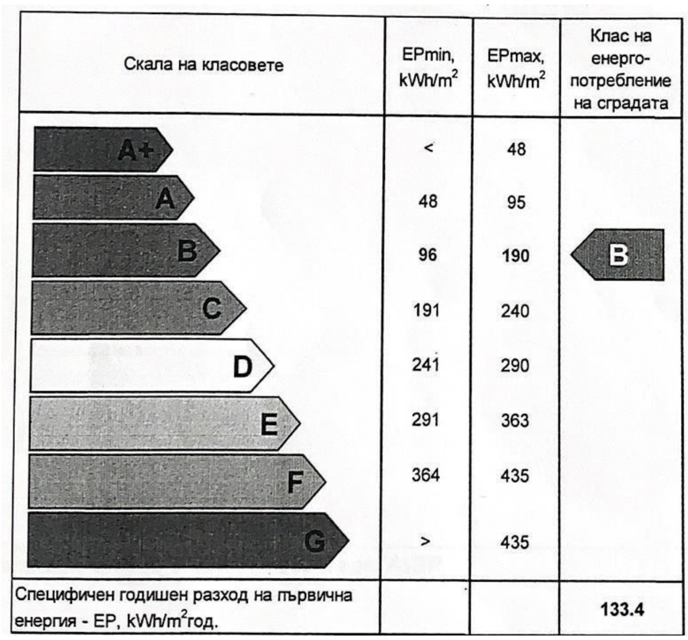
The thickness of the wall is d=0.40m. R=3.11 m2K/W U=0.305 W/ m2K

A model study was performed on the building, with the software product EAB Software v. 1.00 HC, to calculate the integrated energy performance. The calculations from the software product are shown in Figure 1.

The affiliation of the building to a specific class of energy consumption is shown graphically in the form below, calculated accordingly:

EP = 133.4 kWh / m² - energy consumption for the building, defined as primary energy

EP = 68.42 tons of CO_2 generated. These calculations show that the energy consumption class of the building is ,,B''.(Figure 2)

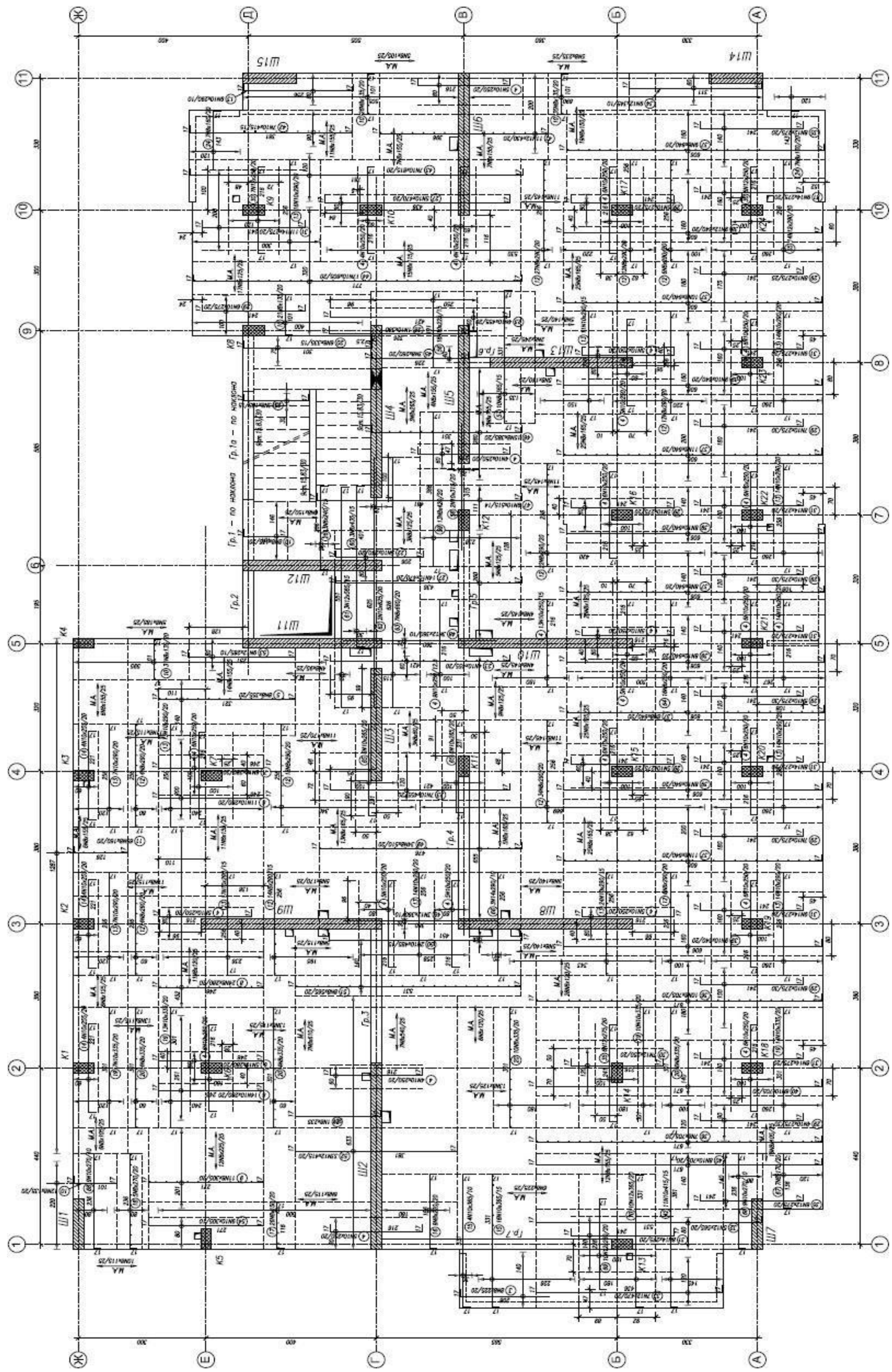


Скала на класовете	EPmin, kWh/m^2	EPmax, kWh/m^2	Клас на енерго-потребление на сградата
A+	<	48	
A	48	95	
B	96	190	B
C	191	240	
D	241	290	
E	291	363	
F	364	435	
G	>	435	
Специфичен годишен разход на първична енергия - EP, kWh/m^{2}год.			133.4

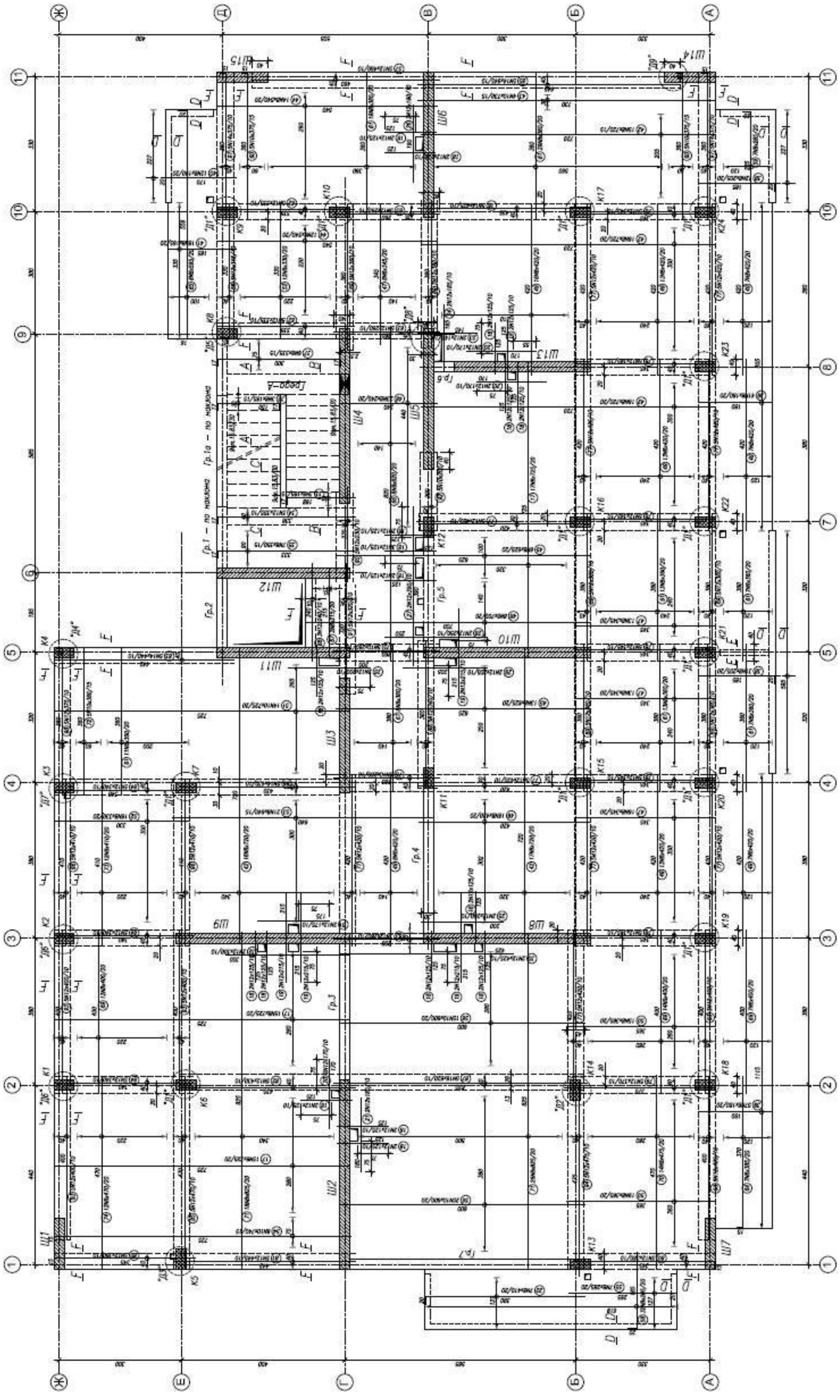
Figure 2. Energy performance

Appendix 2: Structural elements

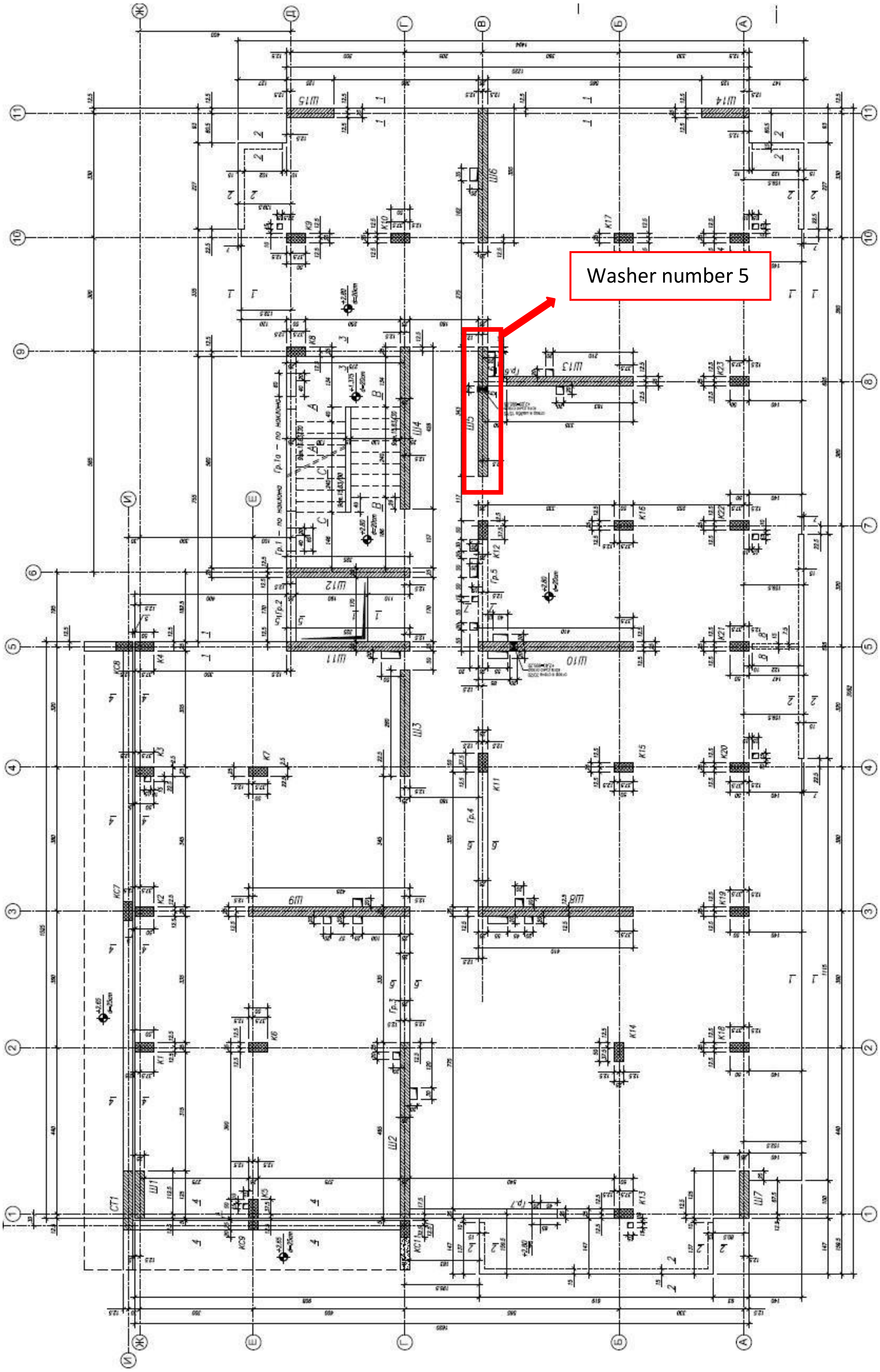
Reinforcement plan on slab elevation +2.80 on upper reinforcement.



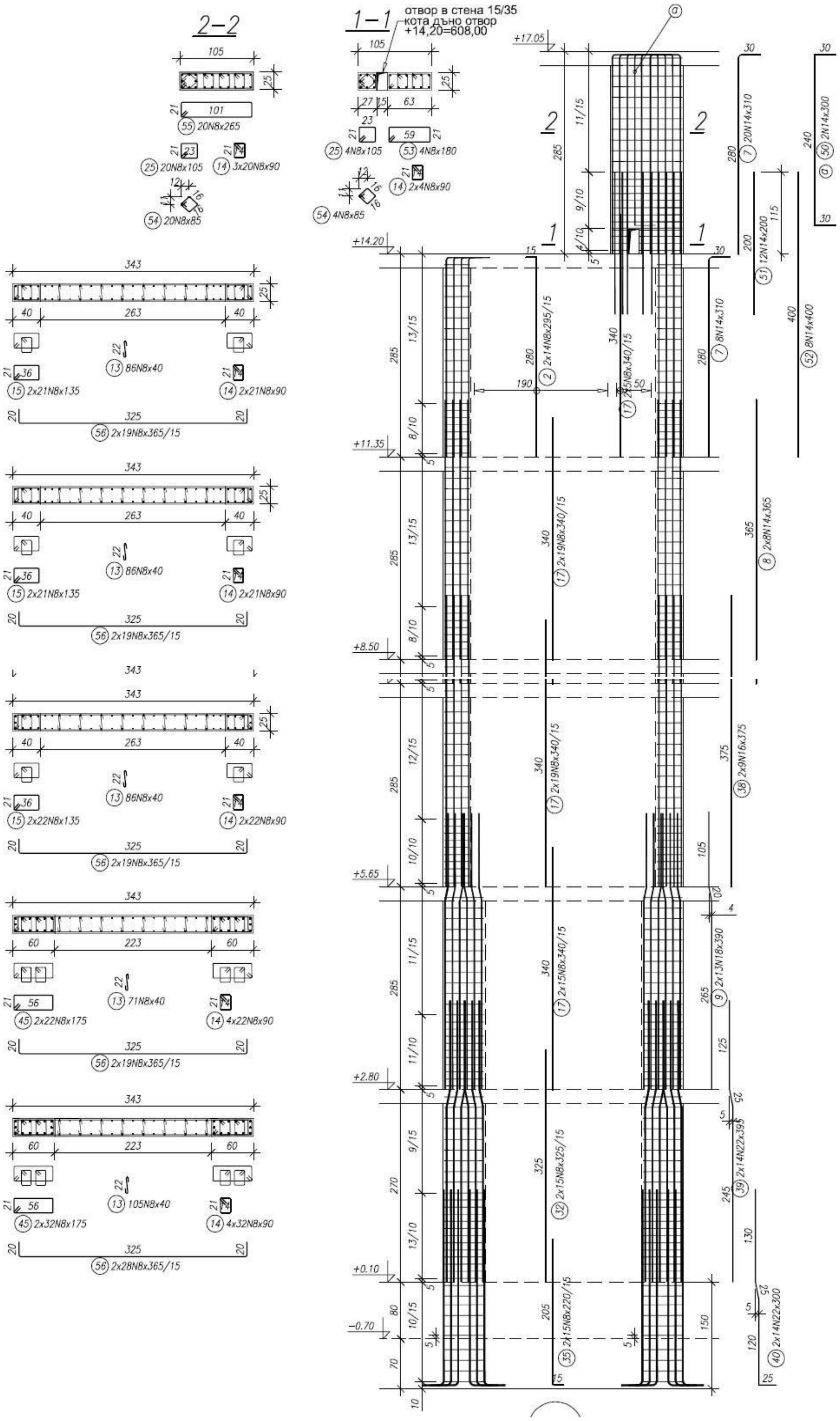
Reinforcement plan on slab elevation +2.80 on lower reinforcement.



Formwork plan of the slab.



Reinforcement of washer №5.



Appendix 3: Tables of construction and installation work

N	Types of construction and installation work	measure	amount
2	*CONCRETE WORKS - BUILDING*		
2.1	Substrate concrete C10/15 - under the foundations	m^3	71
2.2	Concrete for foundation slab C25/30	m^3	334
2.3	Concrete C30/35 for vertical elements up to elevation -0.05	m^3	28
2.4	Concrete C30 for reinforced pavement at elevations -0.05, -0.30 and +0.10	m^3	83
2.5	Concrete C30/35 for vertical elements up to elevation +2.80	m^3	41
2.6	Concrete C30/35 for slab and stairs at elevation +2.80	m^3	102
2.7	Concrete C30/35 for vertical elements up to elevation +5.65	m^3	42
2.8	Concrete C30/35 for slab and stairs at elevation +5.65	m^3	106
2.9	Concrete C3/35 for vertical elements up to elevation +8.50	m^3	42
2.10	Concrete C30/35 for slab and stairs at elevation +8.50	m^3	106
2.11	Concrete C30/35 for vertical elements up to elevation +11.35	m^3	42
2.12	Concrete C30/35 for slab and stairs at elevation +11.35	m^3	106
2.13	Concrete C30/35 for vertical elements up to elevation +14.20	m^3	42
2.14	Concrete C30 for slab and stairs at elevation +14.20	m^3	115
2.15	Concrete C30 for vertical elements to roof level	m^3	27
2.16	Concrete C30 for slab and roof beams	m^3	65
	TOTAL QUANTITY OF CONCRETE	**m^3**	**1352**

Figure 3. Concrete works for the building.

N	Types of construction and installation work	measure	amount
3	CORRAGE WORK – BUILDING		
3.1	Formwork for foundations	m^2	73
3.2	Formwork for vertical elements up to elevations -0.05, -0.30 and +0.10	m^2	154
3.3	Formwork for reinforced concrete flooring at elevations -0.05, -0.30 and +0.10	m^2	20
3.4	Formwork for vertical elements up to elevation +2.80	m^2	386
3.5	Formwork for slab and stairs at elevation +2.80	m^2	565
3.6	Formwork for vertical elements up to elevation +5.65	m^2	390
3.7	Formwork for slab and stairs at elevation +5.65	m^2	560
3.8	Formwork for vertical elements up to elevation +8.50	m^2	390
3.9	Formwork for slab and stairs at elevation +8.50	m^2	560
3.10	Formwork for vertical elements up to elevation +11.35	m^2	390
3.11	Formwork for slab and stairs at elevation +11.35	m^2	560
3.12	Formwork for vertical elements up to elevation +14.20	m^2	390
3.13	Formwork for slab and stairs at elevation +14.20	m^2	655
3.14	Formwork for vertical elements to the roof elevation	m^2	245
3.15	Formwork for slab and roof elevation beams	m^2	420
	TOTAL QUANTITY OF FORMWORK	m^2	**5758**

Figure 4. Formwork for the building.

N	Types of construction and installation work	measures	amount
4	ARMORIAL WORKS - BUILDING		
4.1	Reinforcement for foundations and basement walls	kg.	30931
4.2	Reinforcement for vertical elements to the roof	kg.	35572
4.3	Reinforcement for slab and slabs at elevation +2.80	kg.	8376
4.4	Reinforcement for slab and slabs at elevation +5.65	kg.	9127
4.5	Reinforcement for slab and slabs at elevation +8.50	kg.	9155
4.6	Reinforcement for slab and slabs at elevation +11.35	kg.	9155
4.7	Reinforcement for slab and slabs at elevation +14.20	kg.	9779
4.8	Reinforcement for slab and roof elevation beams	kg.	4865
	TOTAL AMOUNT OF REINFORCEMENT	**kg.**	**116960**

Figure 5. Reinforcement for the building.

Appendix 4: Meetings information with specialists in the field of environmentally friendly materials

MEETING INFORMATION			
Meeting Date	14.3.2022		
Meeting Time	10:00-13:00		
Meeting Location	Exhibition for sustainable materials in Inter Expo Centre Sofia		
Minutes issued by	Andzhelika Nakova		
ATTENDANCE			
Name	**Function**	**Attended**	**Reason**
Andzhelika Nakova	Trener	Yes	N.A.
Dimitar Mihaylov	Specialists in the field of environmentally friendly materials	Yes	N.A.

Picture of the creator of hemp concrete for Bulgaria

AGENDA				
No.	**Decision**	**Action points**	**Owner(s) of the action points**	**Time [min]**
1	Discussing the environmentally friendly materials in Bulgaria	Discussing the current situation of the use of the materials in Bulgaria.	Dimitar Mihaylov and Andzhelika	20
2	Presentation of my project for residential building	Asking questions about possible alternatives for residential buildings.	Dimitar Mihaylov and Andzhelika	30
3	Introducing the of characteristics of hempcrete as construction material.	Detailed explanation for mechanical properties of hempcrete	Dimitar Mihaylov	30
4	Introducing the characteristics of EcoCocon Straw Panels	Detailed explanation for mechanical properties of EcoCocon Panels	Dimitar Mihaylov	30
5	Discussing the differences in prices	Comparing prices with traditional materials in Bulgaria	Dimitar Mihaylov	20
6	Discussing the need for change	Advantages of using natural materials	Dimitar Mihaylov and Andzhelika	20

Appendix 5: Meeting information with specialists in the field of construction engineering

MEETING INFORMATION			
Meeting Date	07.04.2022		
Meeting Time	11:00-13:00		
Meeting Location	Harbich office		
Minutes issued by	Andzhelika Nakova		
ATTENDANCE			
Name	**Function**	**Attended**	**Reason**
Andzhelika Nakova	Trener	Yes	N.A.
Stefan Harbov	Specialists in the field of construction engineering	Yes	N.A.

AGENDA				
No.	**Decision**	**Action points**	**Owner(s) of the action points**	**Time [min]**
1	Discussing the structures	Discussing the different structures for residential building in Bulgaria	Stefan Harbov and Andzhelika	10
2	Discussing concrete-steel structure	Discussing how concrete-steel structure will affect with sustainable materials.	Stefan Harbov and Andzhelika	15
3	Discussing wooden structure	Discussing how concrete-steel structure will affect with sustainable materials and especially hempcrete.	Stefan Harbov and Andzhelika	15
4	Discussing steel structure	Discussing how concrete-steel structure will affects with hempcrete and EcoCocon Panels	Stefan Harbov and Andzhelika	15
5	Discussing the differences in prices of structures	Comparing prices with traditional concrete-steel structure	Stefan Harbov and Andzhelika	20
6	Discussing the advantages and disadvantages of all of three structures	Summarize which structure would be most appropriate in the case of this research.	Stefan Harbov and Andzhelika	20

Appendix 6: Regulation and standard for construction

ORDINANCE № 3 OF JULY 21, 2004 ON THE BASIC PROVISIONS FOR THE DESIGN OF STRUCTURAL STRUCTURES AND THE IMPACTS ON THEM

Issued by the Minister of Regional Development and Public Works

Art. 3. The design of structures and the determination of the impacts on them may also be performed according to the European design standards of the "Constructive Eurocodes" system, introduced as BDS EN 1990 or as parts of Eurocode 1, provided that their reliability is equal to or greater than greater than that specified in the relevant design regulations.

Art. 6. (1) The construction shall be designed and executed in such a way that during the design operational term:

1. to withstand all influences and influences, which may be manifested during its implementation and operation;

2. to remain fit during the envisaged period of operation.

(2) The bearing capacity of the structure shall be ensured by checks of strength and stability.

(3) In case of fire the construction shall be provided for the required period of time (degree of fire resistance).

(4) The structure shall be designed and executed in such a way that it is not damaged to a degree that is disproportionately large in relation to the root cause of events such as explosions, blows or consequences of human intervention.

(5) The prevention or limitation of the damages under par. 4 may be implemented by appropriate selection of one or more of the following measures:

1. avoidance, elimination or reduction of the dangers to which the construction may be exposed;

2. selection of such type of construction, which is less vulnerable than the possible dangers;

3. selection of such type of construction, respectively of a method for its design, which will allow it to preserve its integrity in case of accidental destruction of its separate element or of a limited part of it, as well as in the cases of admissible local damages;

4. avoid, as far as possible, of structural systems in which sudden destruction may occur;

5. ensuring the joint work of the parts of the structure.

(6) The constructions shall be provided also by choosing appropriate:

1. construction products;

2. methods for calculation and construction;

3. regulated procedures for control during the design, production, implementation and operation, which shall be in compliance with the specific project.

(7) The structures shall be designed by persons with full design qualification according to the Law for the Chambers of Architects and Engineers in the investment design and the by-laws on its application.

DESIGN OF CONSTRUCTIONS AND DETERMINATION OF IMPACTS ACCORDING TO EUROPEAN EUROCODE STANDARDS 1

Art. 119. (1) The building constructions of buildings and facilities under the system "Constructive Eurocodes" shall be designed in accordance with BDS EN 1990: 2002 "Fundamentals of the design of building constructions".

(2) The standard BDS EN 1990 shall be applied together with the respective parts of Eurocodes 1 to 9.

Art. 120. (1) The impacts on the structures shall be determined according to the respective parts of Eurocode 1 (BDS EN 1991 - ... and BDS ENV 1991 - ...).

(2) The recommended values in brackets under par. 1 in the preliminary European standards BDS ENV - parts 1 to 5 of Eurocode 1, are considered as minimum necessary (or as maximum if it is in favor of security).

(3) Until the introduction of the national annexes to the standards BDS ENV 1991-, which will regulate the methods for determining climatic effects, the necessary meteorological data in the design of construction shall be provided by the National Institute of Meteorology and Hydrology at the Bulgarian Academy of Sciences (NIMH). - BAS).

Art. 121. The impact of own weight and operating loads on building structures is determined according to BDS EN 1991-1-1 "Eurocode 1: Impact on building structures - Part 1.1: Volume and own weights and operating loads".

Art. 122. The effects of fire on the building structures of the constructions are determined according to BDS EN 1991-2-2: (2002) "Eurocode 1: Impact on building structures - Part 1.2: Impact on structures, fire exposure".

Art. 123. Impacts of snow on building structures are determined according to BDS ENV 1991-2-3: (2001) "Eurocode 1: Basic principles for design and effects on structures. Impacts on structures - Part 2.3: Snow load".

Art. 124. The effects of wind on building structures are determined according to BDS ENV 1991-2-4: (2001) "Eurocode 1: Basic principles for design and effects on structures. Impacts on structures - Part 2.4: Wind effects".

Art. 125. The temperature effects (excluding the effects of fire) on the building structures of the constructions are determined according to BDS ENV 1991-2-5: (2001) "Eurocode 1: Basic principles for design and effects on the building structures. Impacts on the building structures - Part 2.5: Temperature effects ".

Art. 126. The impacts of building structures during the use of construction works are determined according to BDS ENV 1991-2-6: (2001) "Eurocode 1: Basic principles for design and impacts of building structures. Impacts on building structures - Part 2.6: Impacts on time level ".

Art. 127. Accidental impacts of impacts and explosions on building structures are determined according to BDS ENV 1991-2-7: (2001) "Eurocode 1: Basic principles for design and effects of building structures. Impacts on building structures - Part 2.7: Cases impact and explosion effects'.

Art. 128. Impacts of moving loads on bridge structures are determined according to BDS ENV 1991-3: (2001) "Eurocode 1: Basic design principles and effects on structures. Impacts on structures - Part 3: Mobile loads on bridges".

Art. 129. The effects of bulk materials and liquids on the construction of silos and tanks are determined according to BDS ENV 1991-4: (2002) "Eurocode 1: Basic principles for design and effects on structures. Impacts on structures - Part 4: Impacts in silos and tanks'.

Art. 130. The effects of cranes and machinery on building structures are determined according to BDS ENV 1991-5: (2003) "Eurocode 1: Basic principles for design and effects on structures. Impacts on structures - Part 5: Effects on cranes and impacts other machines ".

Appendix 7: Hempcrete construction methods

Hempcrete can be made in three ways, similar to normal concrete: prefabricated blocks, molded in place, and spraying.

- **Prefabricated hempcrete blocks**

Hempcrete blocks are composed of hemp shives, lime, and water- the same formula as hempcrete, but in ready-to-use, lightweight blocks with the amazing heating qualities of hemp fiber. This material is highly sturdy, breathable, and long-lasting. Ideal for creating a healthy and enjoyable living environment.

Figure 6. Laying pre-cast hempcrete blocks.

Hempcrete block is a product that can be very easily installed, generally requiring mortar to be applied between the blocks. Hempcrete block walls can be left without any covering and insulation or can be covered with finishing plasters, using the same mixture in different proportions. Blocks can be manufactured on the construction site or through an industrial process. Industrial blocks usually have more regular dimensions and a higher quality thanks to an automated manufacturing process and to the employment of more complex mixtures. *(Arrigoni et al., 2017)*

The installation of rectangular shaped blocks needs staggered and keyed joints, as with other masonry structures. Furthermore, since a vegetal component is included in the mixture, the blocks must be protected from water and rising damp. The joints between the wall and the ground are therefore designed in order to avoid capillary rising as well as water runoff at the wall base. For the same reason, hempcrete blocks are to be installed above the ground level. External walls should be protected by the rain gale with sand and lime plasters in order to avoid rotting of shives. Typically, hempcrete blocks are inserted into wood frames, but they can be used also in metal or reinforced concrete structures. Internal partitions made with hempcrete blocks need to be carefully jointed with the external walls. They will normally be thicker than typical internal brick walls (at least 15 cm instead of 10 cm). *(Arrigoni et al., 2017)*

- **Molding in place**

Hempcrete is typically cast on site as shuttering (formwork) over a structural timber frame in new structures, but it can also be cast against existing masonry walls as a retro-fit solid wall insulation. The material is mechanically mixed before being delivered to the shuttering in big tubs, where it is manually put.

When using cast in situ hempcrete, keep drying times in mind from the beginning, as they are a major cause of delays before finishes can be applied, and therefore a major source of conflicts with clients and/or primary contractors.

The drying time can be drastically reduced by using the right materials, mixing and placing them correctly, and using good "drying management" on site, so it's important to be aware of this from the start; both to ensure good construction practice and to manage everyone's expectations from the start of the project. *(Sparrow, 2014)*

- **Spraying**

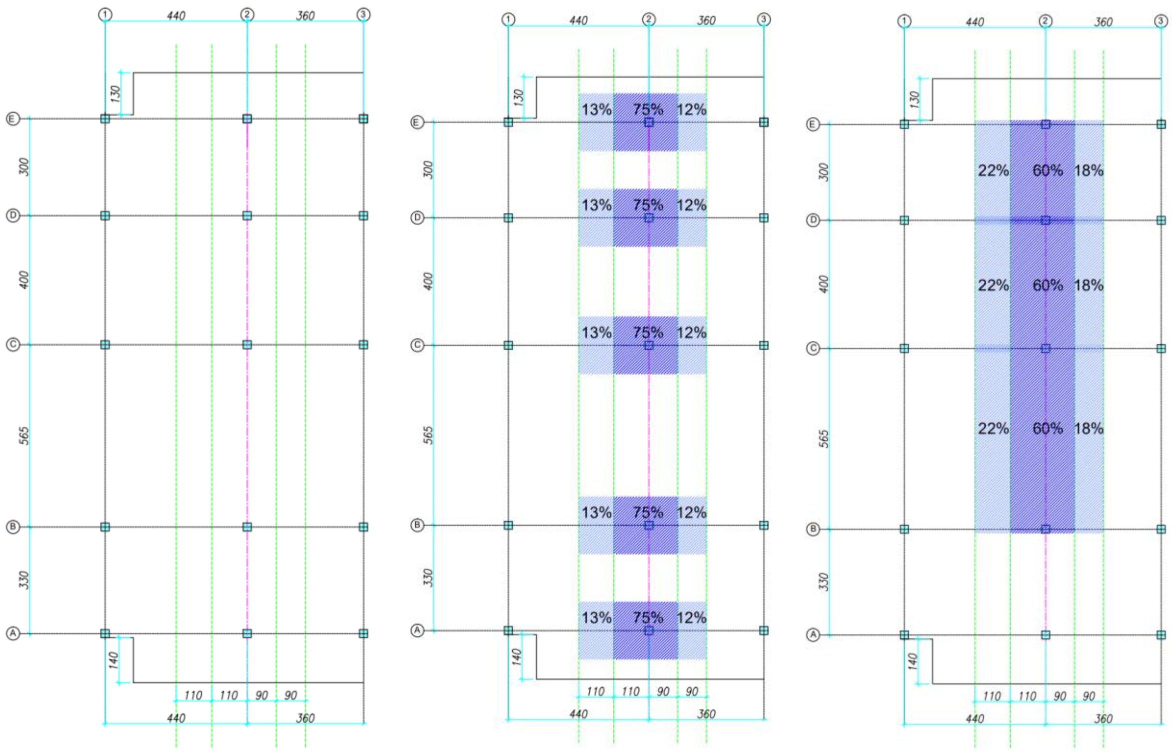
The approach that is more approachable and low-tech is hand-placing. Hempcrete sprayers aren't easy to come by, and they're expensive to acquire, store, transport, clean, and maintain. The sprayers produce a more binder-rich hempcrete, increasing the material's density and carbon embodied. Despite the fact that the completed material is still a net carbon sink, storing more CO2 over the building's lifetime than was utilized in its creation. Spraying necessitates the use of a vapor permeable plaster carrier board as permanent shuttering on one side of the wall (to spray against), which introduces another highly processed, high embodied energy material to the wall build-up, as well as an additional cost.

While spraying decreases the number of personnel on site, it has no effect on the time it takes to complete a project of this magnitude. Spraying is a noisy, filthy job that necessitates the use of heavy-duty safety masks, and it takes away from the social aspect of hand-placing hempcrete in a larger group. Because of the spraying process, a large amount of material ends up on the floor (up to 10% wastage), although this can be addressed by collecting it and using it to cast a hempcrete floor slab if one is needed. Finally, the surface of a sprayed hempcrete wall is uneven and unconsolidated as opposed to the flat, even surface of a hand cast wall once the shuttering is removed. This means that the wall absorbs more plaster in the basecoat, increasing the expense of finishing. Nevertheless, when casting larger buildings, the efficiencies achieved mean that spray-application really comes into its own.

All fittings within the hemp-lime wall should be stainless steel or hot dip galvanized because to the high alkali environment. Other structural fixings that aren't available in stainless or hot dip galvanized versions can be coated to preserve them before being cast in hempcrete. *(Sparrow, 2014)*

Figure 7. Spraying of hempcrete.

Appendix 8: Slab calculations



Section plan

Top reinforcement

Bottom reinforcement

Figure 8. Section of consideration.

Brick calculations:

Given:

Paramaeters	[mm]
l_{eff}	18650
d	164
h	200
b	1000
c	30
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
f_{yd}	435

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib load [kN/m²]
Bricks	-	18	2.85
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	9.55
Q	1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	56.07	<- decisive
1.2*G+1.5*Q	54.84	

SLS [kN/m²]	
G+Q*Ψ_1	42.4

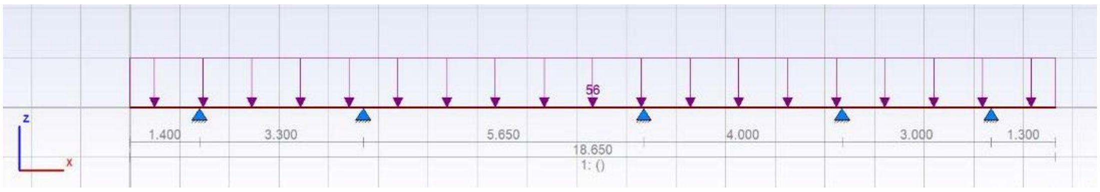


Figure 9. Mechanical scheme.

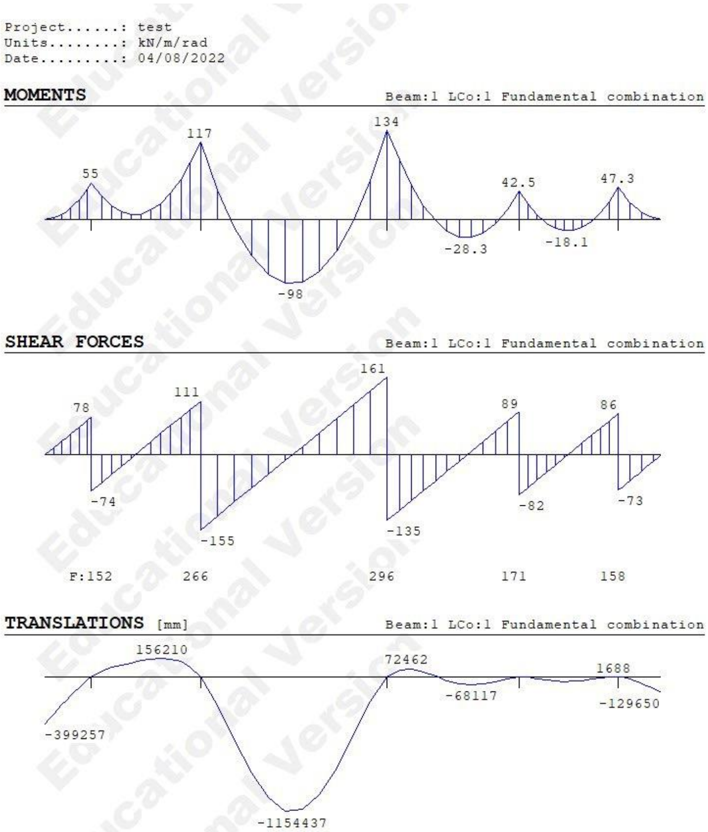


Figure 10. Moment, Shear and Translation lines.

- Top reinforcement

Looking at M4= 134 kNm

Med= $\frac{75\%*\mathrm{M4}}{\mathrm{width}}$= $\frac{75\%*134}{2}$= 50.25 kNm/m

Stress= $\frac{\mathrm{Med}}{\mathrm{b}*\mathrm{d}^2}$= $\frac{50.25}{1*0.164^2}$= 1868 kN/m²

Using GTB table for C25/30 (Appendix 10- Table 1): ρ= 0.46%

Asreq.= ρ*b*d= 0.46%*1000*164= <u>755 mm²</u>

- Bottom reinforcement

Looking at M3= 98 kNm

Med= $\frac{60\%*\mathrm{M3}}{\mathrm{width}}$= $\frac{60\%*98}{2}$= 36.75 kNm/m

Stress= $\frac{\mathrm{Med}}{\mathrm{b}*\mathrm{d}^2}$= $\frac{36.75}{1*0.164^2}$= 1366 kN/m²

Using GTB table for C25/30 (Appendix 10- Table 1): ρ= 0.33%

Asreq.= ρ*b*d= 0.33%*1000*164= <u>541 mm²</u>

Hempcrete calculations:

Given:

Paramaeters	[mm]
l_{eff}	18650
d	164
h	200
b	1000
c	30
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
f_{yd}	435

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib. load [kN/m²]
Hempcrete	-	3.4	0.6
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2
			G 7.3
			Q 1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	43.92	
1.2*G+1.5*Q	44.04	<- decisive

SLS [kN/m²]	
G+Q*Ψ_1	33.4

Figure 11. Mechanical scheme.

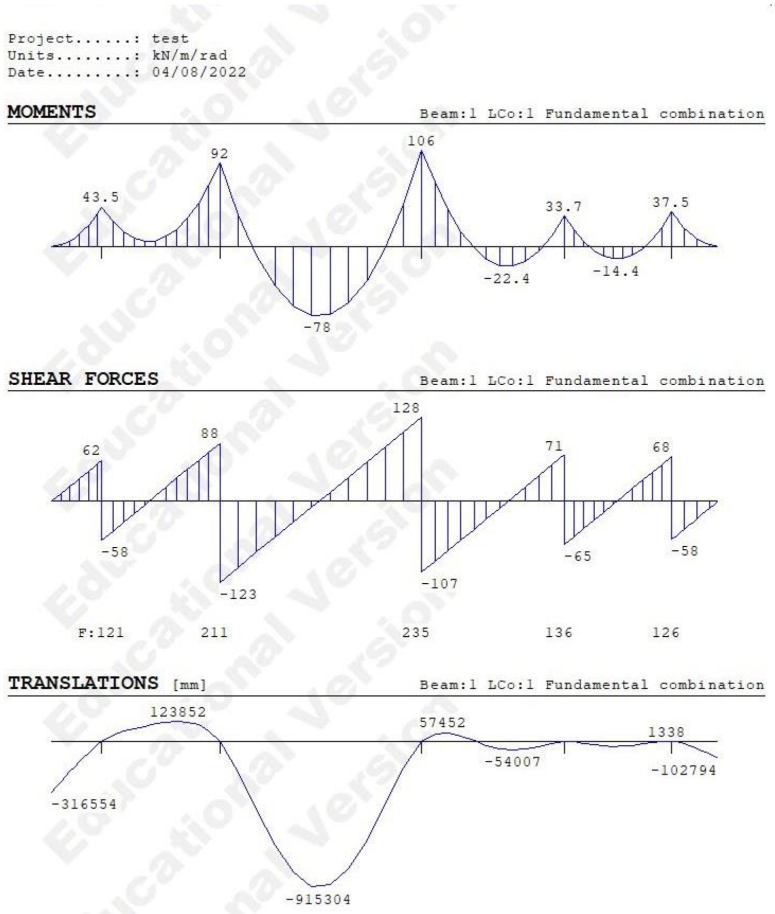


Figure 12. Moment, Shear and Translation lines.

- Top reinforcement

Looking at M4= 106 kNm

Med= $\frac{75\%*M4}{width}$= $\frac{75\%*106}{2}$= 39,75 kNm/m

Stress= $\frac{Med}{b*d^2}$= $\frac{1478}{1*0.164^2}$= 1478kN/m²

Using GTB table for C25/30 (Appendix 10- Table 1): ρ= 0,36%

Asreq.= ρ*b*d= 0,37%*1000*164= <u>583 mm²</u> => 30% less reinforcement will be used when using hempcrete

Design of reinforcement:

Use Ø12-165 for the based reinforcement (Appendix10- Table 2)

Asused= 685 mm² > Asreq. => Satisfactory

Checking min and max reinf. ratio:

$\frac{\text{Asused}}{\text{b}*\text{d}} = \frac{685}{1000*164}$= 0.42%

GTB table (Appendix 10- Tables 3 and 4): ρmin= 0.13% and ρmax= 1.54%
ρmin < ρ < ρmax => Satisfactory

Crack control:

σ= $\frac{\text{SLS}}{\text{ULS}} * \frac{\text{Asreq.}}{\text{Asused}}$*fyd= $\frac{33.4}{44.4} * \frac{583}{685}$*= 274.4 N/mm²

Spacing:

Class XC1, w<= 0.4 (Appendix 10- Table 5)

Linier interpolate (Appendix 10- Table 6): smax= 202 mm > 165 mm => Satisfactory

- Bottom reinforcement

Looking at M3= 78 kNm

Med= $\frac{60\%*\text{M3}}{\text{width}}$= $\frac{60\%*78}{2}$= 23.4 kNm/m

Stress= $\frac{\text{Med}}{\text{b}*\text{d}^2}$= $\frac{23.4}{1*0.164^2}$= 870 kN/m²

Using GTB table for C25/30 (Appendix 10- Table 1): ρ= 0.2%

Asreq.= ρ*b*d= 0.2%*1000*164= <u>334.6 mm²</u> => 29.5% less reinforcement will be used when using hempcrete

Design of reinforcement:

Use Ø8-145 for the based reinforcement (Appendix10- Table 2)

Asused= 347 mm² > Asreq. => Satisfactory

Checking min and max reinf. ratio:

$\frac{\text{Asused}}{\text{b}*\text{d}} = \frac{347}{1000*164}$= 0.21%

GTB table (Appendix 10- Tables 3 and 4): ρmin= 0.13% and ρmax= 1.54%
ρmin < ρ < ρmax => Satisfactory

Crack control:

$\sigma = \frac{SLS}{ULS} * \frac{Asreq.}{Asused}$*fyd= $\frac{33.4}{44.4} * \frac{334.6}{347}$*= 315.5 N/mm²

Spacing:

Class XC1, w<= 0.4 (Appendix 10- Table 5)

Linier interpolate (Appendix 10- Table 6): smax= 155 mm > 145 mm => Satisfactory

Appendix 9: Column calculations

Bricks:

Given:

Paramaeters	[mm]
l_{eff}	2650
h	250
b	500
c	30
stirrups	8
Ø	12
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
E	3600
f_{yd}	435
f_{cd}	16.7

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib load [kN/m²]
Bricks	-	18	2.85
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	9.55
Q	1.5

ULS [kN/m²]		
1.35*G+1.5*Q*Ψ_0	14	<- decisive
1.2*G+1.5*Q	13.71	

SLS [kN/m²]	
G+Q*Ψ_1	10.6

A floor= ((2.82+1.65)*(2.2+1.8)= 17.88 m²

N= ULS*A+ column self-weight= 14*17.88+(25*0.25*0.5*2.65)= 258.6kN

N_{ed}= 258.6*5= 1293 kN

Buckling stability:

*2nd order effects may be neglected if they are smaller than 10% of the first order effects.

I= 1/12*b*h³= 1/12*500*250³= 651041666.7 mm⁴

N_{cr}= π*EI/$L_0$²= π*36000*651041666,7/2650²= 10485 kN

*2nd order effect

n buckling= N_{cr}/N_{ed}= *10485*/1293 = 8.1

n buckling/(n buckling-1)= 8.1/(8.1-1)= 1.14 => Satisfactory

*2nd order effects in case of axial load

If $\lambda \leq \lambda_{min}$, 2nd order effects can be ignored.

λ= L_0/i:

i= $\sqrt{(I/A_c)}$= $\sqrt{(651041666.7 /125000)}$= 72.16

λ= L_0/i= 2650/72.16= 36.72

λ_{min}= 20*A*B*(C/$\sqrt{n}$):

n= $N_{ed}/(A_c*f_{cd})$= 1293*1000/125000*16.7= 0.6

Appendix 10- Table 7: A=0.7; B=1.1; C=0.7

λ_{min}= 20*A*B*(C/$\sqrt{n}$)= 20*0.7*1.1*(0.7/$\sqrt{0.6}$)= 13.9

$\lambda > \lambda_{min}$

36.72>13.9 => Satisfactory, 2nd order can be considered

Reinforcement:

($N_{ed}/f_{cd}*A_c$)*(e_t/h):

1) a/h
2) $N_{ed}/f_{cd}*A_c$
3) d
4) $e_t= e_0+e_1+e_2 \geq e_{0;min}$

3) a= c+stirrups+Ø/2= 30+8+12/2= 44
   a/h= 44/250= 0.17 => Satisfactory

4) $N_{ed}/f_{cd}*A_c$= 1293*1000/125000*16.7= 0.6

5) $d= h-c-stirrups-Ø= 250-30-8-12= 200$ mm

6) $e_t= e_0+e_1+e_2 \geq e_{0;min}$:

- $e_0= M_{0;Ed}/N_{ed}= 0$ (first order eccentricity)
- $e_1= L_0/400= 2650/400= 6.6$
- $e_2= K_r*K_\varphi* (L_0^2/ \pi^2)*(\varepsilon_{yd}/0.45*d)$

$e_2= K_r*K_\varphi* (L_0^2/ \pi^2)*(\varepsilon_{yd}/0.45*d)$:

- ➢ $\varepsilon_{yd}= 2.175*10^{-3}$

- ➢ $K_r= (1+w-n)/(0.6+w) \leq 1$:

$w= (A_s*f_{yd})/(A_c*f_{cd})= (0.02*435)/16.7= 0.5$

Reinforcement ratio As/Ac is still unknown therefore needs to be estimated. As a first estimate 2% is taken.

$K_r= (1+w-n)/(0.6+w)= (1+0.5-0.6)/(0.6+0.5)= 0.8$

- ➢ $K_\varphi= 1+ \beta*\varphi_{ef} \geq 1$:

$\beta= 0.35+(f_{ck}/200)-(\lambda/150)= 0.35+(25/200)-(36.72/150)= 0.23$

$\varphi_{ef}= \varphi_{(\infty,to)}*(M_{0E,qv}/M_{0E,d})$:

$M_{0E,qv}/M_{0E,d}=$ SLS/ULS$= 10.6/14= 0.75$

$\varphi_{(\infty,to)}$:

$h_0=2*A_c/O=2*(250*500/250+500)= 333$ mm

Age of concrete when loaded = 28 days. This is because with concrete, the compressive strength is most likely at its highest after 28 days.

Appendix 10- Table 8: $\varphi_{(\infty,to)}= 2.5$

$\varphi_{ef}= \varphi_{(\infty,to)}*(M_{0E,qv}/M_{0E,d})= 2.5*0.75= 1.87$ =>Satisfactory

$K_\varphi= 1+ \beta*\varphi_{ef}= 1+0.23*1.87= 1.43 \geq 1.0$ => Satisfactory

$e_2= K_r*K_\varphi* (L_0^2/ \pi^2)*(\varepsilon_{yd}/0.45*d)$

$e_2= 0.8*1.43*(2650^2/ \pi^2)*(2.175*10^{-3}/0.45*200)$

$e_2= 19.67$

$e_t = e_0 + e_1 + e_2 = 0 + 6.6 + 19.67 = 26.27$

$(N_{ed}/f_{cd} * A_c) * (e_t/h) = 0.6 * (26.27/250) = 0.06$

Reinforcement ratio A_s/A_c:

Appendix 10- Table 9:

$\rho * (f_{yd}/f_{cd}) = 0$ => the reinforcement needed is only the minimum required for structural stability => $\rho = 0.4\%$

$A_s = \rho * b * h = 0.004 * 500 * 200 =$ <u>500 mm²</u>

Hempcrete:

Given:

Paramaeters	[mm]
l_{eff}	2650
h	250
b	500
c	30
stirrups	8
Ø	12
Ψ_0	0.5
Ψ_1	0.7
Concrete class	C25/30
Consequence class	CC2
Exposure class	XC1
Reinforcement	B 500
E	3600
f_{yd}	435
f_{cd}	16.7

Component	Thickness [cm]	Vol. weight [kN/m³]	Distrib. load [kN/m²]
Hempcrete	-	3.4	0.6
Arch. flooring	1	30	0.3
Floor screaning	6	20	1.2
Floor slab 20 cm	20	25	5
Ceiling plaster	1	20	0.2

G	7.3
Q	1.5

ULS [kN/m²]		
$1.35*G+1.5*Q*\Psi_0$	10.98	
$1.2*G+1.5*Q$	11.01	<- decisive

SLS [kN/m²]	
$G+Q*\Psi_1$	8.35

A floor= ((2.82+1.65)*(2.2+1.8)= 17.88 m²

N= ULS*A+ column self-weight = 11.1*17.88+(25*0.25*0.5*2.65)= 206.75 kN

$N_{ed} = 206.75 * 5 = 1033.75$ kN

Buckling stability:

*2nd order effects may be neglected if they are smaller than 10% of the first order effects.

$I = 1/12 * b * h^3 = 1/12 * 500 * 250^3 = 651041666.7$ mm⁴

$N_{cr} = \pi * EI/L_0^2 = \pi * 36000 * 651041666.7/2650^2 = 10485$ kN

*2nd order effect

n buckling= N_{cr}/N_{ed}= 10485/1033.75= 10.14

n buckling/(n buckling-1)= 10.14/(10.14-1)= 1.1 => Satisfactory

*2nd order effects in case of axial load

If $\lambda \leq \lambda_{min}$, 2nd order effects can be ignored

$\lambda = L_0/i$:

$i = \sqrt{(I/A_c)} = \sqrt{(651041666.7/125000)} = 72.16$

$\lambda = L_0/i = 2650/72.16 = 36.72$

$\lambda_{min} = 20*A*B*(C/\sqrt{n})$:

$n = N_{ed}/(A_c*f_{cd}) = 1033.75*1000/125000*16.7 = 0.48$

Appendix 10- Table 9: A=0.7; B=1.1; C=0.7

$\lambda_{min} = 20*A*B*(C/\sqrt{n}) = 20*0.7*1.1*(0.7/\sqrt{0.48}) = 15.5$

$\lambda > \lambda_{min}$ => Satisfactory, 2nd order can be considered

Reinforcement:

$(N_{ed}/f_{cd}*A_c)*(e_t/h)$:

1) a/h
2) $N_{ed}/f_{cd}*A_c$
3) d
4) $e_t = e_0+e_1+e_2 \geq e_{0;min}$

1) a= c+stirrups+Ø/2= 30+8+12/2= 44
   a/h= 44/250= 0.17 => Satisfactory

2) $N_{ed}/f_{cd}*A_c$= 1033.75*1000/125000*16.7= 0.48

3) d= h-c-stirrups-Ø= 250-30-8-12= 200 mm

4) $e_t = e_0 + e_1 + e_2 \geq e_{0;min}$:
   - $e_0 = M_{0;Ed}/N_{ed} = 0$ (first order eccentricity)
   - $e_1 = L_0/400 = 2650/400 = 6.6$
   - $e_2 = K_r * K_\varphi * (L_0^2/\pi^2) * (\varepsilon_{yd}/0.45*d)$:

$e_2 = K_r * K_\varphi * (L_0^2/\pi^2) * (\varepsilon_{yd}/0.45*d)$:

- $\varepsilon_{yd} = 2.175*10^{-3}$

- $K_r = (1+w-n)/(0.6+w) \leq 1$:

$w = (A_s * f_{yd})/(A_c * f_{cd}) = (0.02*435)/16.7 = 0.5$

Reinforcement ratio As/Ac is still unknown therefore needs to be estimated. As a first estimate 2% is taken.

$K_r = (1+w-n)/(0.5+w) = (1+0.5-0.48)/(0.6+0.5) = 0.9$

- $K_\varphi = 1 + \beta * \varphi_{ef} \geq 1$:

$\beta = 0.35 + (f_{ck}/200) - (\lambda/150) = 0.35 + (25/200) - (36.72/150) = 0.23$

$\varphi_{ef} = \varphi(\infty,t_o) * (M_{0E,qv}/M_{0E,d})$:

$M_{0E,qv}/M_{0E,d}$ = SLS/ULS = 8.35/11.1 = 0.75

$\varphi(\infty,t_o)$:

$h_0 = 2*A_c/O = 2*(250*500/250+500) = 333$ mm

Age of concrete when loaded = 28 days. This is because with concrete, the compressive strength is most likely at its highest after 28 days.

Appendix 10- Table 8: $\varphi(\infty,t_o) = 2.5$

$\varphi_{ef} = \varphi(\infty,t_o) * (M_{0E,qv}/M_{0E,d}) = 2.5*0.75 = 4.37$

$K_\varphi = 1 + \beta * \varphi_{ef} = 1 + 0.23*4.37 = 2$

$e_2 = K_r * K_\varphi * (L_0^2/\pi^2) * (\varepsilon_{yd}/0.45*d)$

$e_2 = 0.9*2*(2650^2/\pi^2)*(2.175*10^{-3}/0.45*200)$

$e_2 = 30.95$

$e_t = e_0 + e_1 + e_2 = 0 + 6.6 + 30.95 = 37.55$

$(N_{ed}/f_{cd} * A_c) * (e_t/h) = 0.48 * (37.55/250) = 0.07$

Reinforcement ratio A_s/A_c:

Appendix 10- Table 9:

$\rho * (f_{yd}/f_{cd}) = 0$ => the reinforcement needed is only the minimum required for structural stability => $\rho = 0.4\%$

$A_s = \rho * b * h = 0.004 * 500 * 200 =$ <u>500 mm²</u>

Appendix 10- Table 10:

Use 6Ø12 for main reinforcement.

Use Ø18 for stirrups.

Appendix 10: GTB tables

GTB 2010 - 11.4

buiging zonder normaalkracht
bij rechthoekige doorsneden

C25/30 B500

$\frac{M_{Ed}\,(kNm)}{b\,d^2\,(m^3)}$	k_s	$100\,\rho_l$	k_x	k_z
100	0,433	0,02	0,008	0,997
200	0,432	0,05	0,016	0,994
300	0,431	0,07	0,024	0,991
400	0,429	0,09	0,032	0,987
500	0,428	0,12	0,041	0,984
600	0,427	0,14	0,049	0,981
700	0,425	0,16	0,057	0,978
800	0,424	0,19	0,066	0,974
900	0,422	0,21	0,074	0,971
1000	0,421	0,24	0,083	0,968
1100	0,419	0,26	0,091	0,965
1200	0,418	0,29	0,100	0,961
1300	0,416	0,31	0,109	0,958
1400	0,415	0,34	0,117	0,954
1500	0,413	0,36	0,126	0,951
1600	0,412	0,39	0,135	0,947
1700	0,410	0,41	0,144	0,944
1800	0,409	0,44	0,153	0,940
1900	0,407	0,47	0,162	0,937
2000	0,406	0,49	0,171	0,933
2100	0,404	0,52	0,181	0,930
2200	0,403	0,55	0,190	0,926
2300	0,401	0,57	0,199	0,922
2400	0,399	0,60	0,209	0,919
2500	0,398	0,63	0,219	0,915
2600	0,396	0,66	0,228	0,911
(0,7)2700	0,395	0,68	0,238	0,907
2800	0,393	0,71	0,248	0,904
2900	0,391	0,74	0,258	0,900
3000	0,389	0,77	0,268	0,896
3100	0,388	0,80	0,278	0,892
3200	0,386	0,83	0,288	0,888
3300	0,384	0,86	0,299	0,884
3400	0,383	0,89	0,309	0,880
3500	0,381	0,92	0,320	0,876
(0,8)3600	0,379	0,95	0,330	0,871
3700	0,377	0,98	0,341	0,867
3800	0,375	1,01	0,352	0,863
3900	0,373	1,04	0,363	0,859
4000	0,371	1,08	0,375	0,854
4100	0,370	1,11	0,386	0,850
4200	0,368	1,14	0,397	0,845
4300	0,366	1,18	0,409	0,841
4400	0,364	1,21	0,421	0,836
(0.9)4500	0,362	1,24	0,433	0,832
4600	0,360	1,28	0,445	0,827
4700	0,357	1,31	0,457	0,822
4800	0,355	1,35	0,470	0,817
4900	0,353	1,39	0,483	0,812
5000	0,351	1,42	0,495	0,807
5100	0,349	1,46	0,509	0,802
5200	0,347	1,50	0,522	0,797
(1,0)5300	0,344	1,54	0,536	0,792
5400	0,342	1,58	0,549	0,786
5500	0,340	1,62	0,563	0,781
5600	0,337	1,66	0,578	0,775
5700	0,355	1,70	0,593	0,770
5800	0,332	1,75	0,608	0,764
5861	0,330	1,77	0,617	0,760

Table 1. Bending without axial normal force.

afstand h.o.h. (mm)	aantal staven per m	$\varnothing_k$ (mm)									
		6	8	10	12	14	16	20	25	32	40
70	14,29	404	718	1122	1616	2199	2872	4488	7012	11489	17952
75	13,33	377	670	1047	1508	2051	2681	4189	6545	10723	16755
80	12,50	353	628	982	1414	1923	2513	3927	6136	10053	15708
85	11,76	333	591	924	1331	1809	2365	3696	5775	9462	14784
90	11,11	314	559	873	1257	1709	2234	3491	5454	8936	13963
95	10,53	298	529	827	1190	1620	2116	3307	5167	8466	13228
100	10,00	283	503	785	1131	1539	2011	3142	4909	8042	12566
105	9,52	269	479	748	1077	1465	1915	2992	4675	7660	11968
110	9,09	257	457	714	1028	1399	1828	2856	4462	7311	11424
115	8,70	246	437	683	983	1339	1748	2732	4268	6993	10927
120	8,33	236	419	654	942	1282	1676	2618	4091	6702	10472
125	8,00	226	402	628	905	1231	1608	2513	3927	6434	10053
130	7,69	217	387	604	870	1183	1547	2417	3776	6187	9666
135	7,41	209	372	582	838	1140	1489	2327	3636	5957	9308
140	7,14	202	359	561	808	1099	1436	2244	3506	5745	8976
145	6,90	195	347	542	780	1062	1387	2167	3385	5547	8666
150	6,67	188	335	524	754	1026	1340	2094	3272	5362	8378
155	6,45	182	324	507	730	992	1297	2027	3167	5189	8107
160	6,25	177	314	491	707	962	1257	1963	3068	5027	7854
165	6,06	171	305	476	685	932	1219	1904	2975	4874	7616
170	5,88	166	296	462	665	905	1183	1848	2887	4731	7392
175	5,71	162	287	449	646	879	1149	1795	2805	4596	7181
180	5,56	157	279	436	628	855	1117	1745	2727	4468	6981
185	5,41	153	272	425	611	832	1087	1689	2653	4347	6793
190	5,26	149	265	413	595	809	1058	1653	2584	4233	6614
195	5,13	145	258	403	580	789	1031	1611	2517	4124	6444
200	5,00	141	251	393	565	769	1005	1571	2454	4021	6283
205	4,88	138	245	383	552	751	981	1532	2395	3923	6130
210	4,76	135	239	374	539	732	957	1496	2337	3830	5984
215	4,65	132	234	365	526	715	935	1461	2283	3741	5845
220	4,55	129	228	357	514	700	914	1428	2231	3656	5712
225	4,44	126	223	349	503	683	894	1396	2182	3574	5585
230	4,35	123	219	341	492	669	874	1366	2134	3497	5464
235	4,26	120	214	334	481	655	856	1337	2089	3422	5347
240	4,17	118	209	327	471	642	838	1309	2045	3351	5236
245	4,08	115	205	321	462	628	821	1282	2004	3283	5129
250	4,00	113	201	314	452	615	804	1257	1963	3217	5027

Table 2. Tables for selection of reinforcement steel used to select bars for a floor section.

C12/15	C16/20	C20/25	C25/30	C28/35	C30/37	C35/45	C40/50
0.08	0.10	0.11	0.13	0.14	0.15	0.16	0.18

C45/55	C50/60	C53/65	C55/67	C60/75	C70/85	C80/95	C90/105
0.19	0.21	0.22	0.22	0.23	0.24	0.25	0.26

Table 3. ρ_{min} table.

C12/15	C16/20	C20/25	C25/30	C28/35	C30/37	C35/45	C40/50
0.74	0.98	1.23	1.54	1.70	1.85	2.15	2.46

C45/55	C50/60	C53/65	C55/67	C60/75	C70/85	C80/95	C80/95
2.77	3.08	3.01	3.03	3.01	3.10	3.31	3.55

Table 4. ρ_{max} table.

Max. crack-width	Exposure class (*)
W<=0.4 mm	XC0, XC1
W<=0.3 mm	XC-2, XC-3, XC-4; XD1, XD2; XS-1, XS-2, XS-3
W<=0.2 mm	All other classes

Table 5. Max. crack width.

Steel stress σ_s [SLS]	Max. bar spacing W_{crack}=0.4 mm	Max. bar spacing W_{crack}=0.3 mm	Max. bar spacing W_{crack}=0.2 mm
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

Table 6. Max bar spacing for control of crack width.

$\lambda = L_o/i \qquad (i=\sqrt{I/A_c})$

$\lambda_{\lim} = 20 \cdot A \cdot B \cdot C / \sqrt{n}$

These are used!

Simplified

$A = 1/(1+0{,}2\phi_{ef})$ ← Influence of creep ← A = 0,7

$B = \sqrt{1+2\omega}$ ← Influence of reinforcement ← B = 1,1

$C = 1{,}7 - r_m$ ← Influence of end moments ← C = 0,7

$n = N_{Ed}/(A_c * f_{cd})$ (**Mind: this is not $n_{buckling}$!!**)

Table 7. 2nd order effects in case of axial load.

Volgorde: lijn 1: horizontaal voor $t_{(0)}$ = 15 dagen naar lijn S (= CEM32,5)
lijn 2. hulplijn vanuit 0 met snijpunt lijn 1 op lijn S
lijn 3: h_0 = 170 naar lijn C25/30
lijn 4: horizontale naar hulplijn 2
lijn 5: vanaf snijpunt lijn 4 en hulplijn 2: verticale lijn naar beneden: aflezen φ(∞,t₀) = 3,3

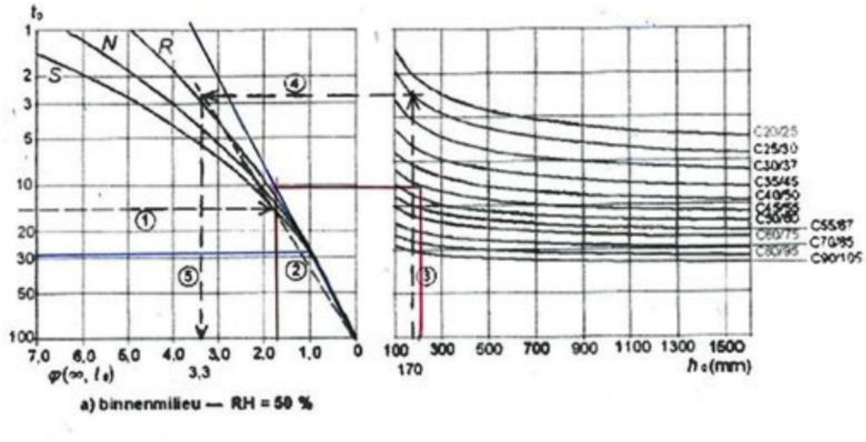


Table 8. ϕ(∞,to)

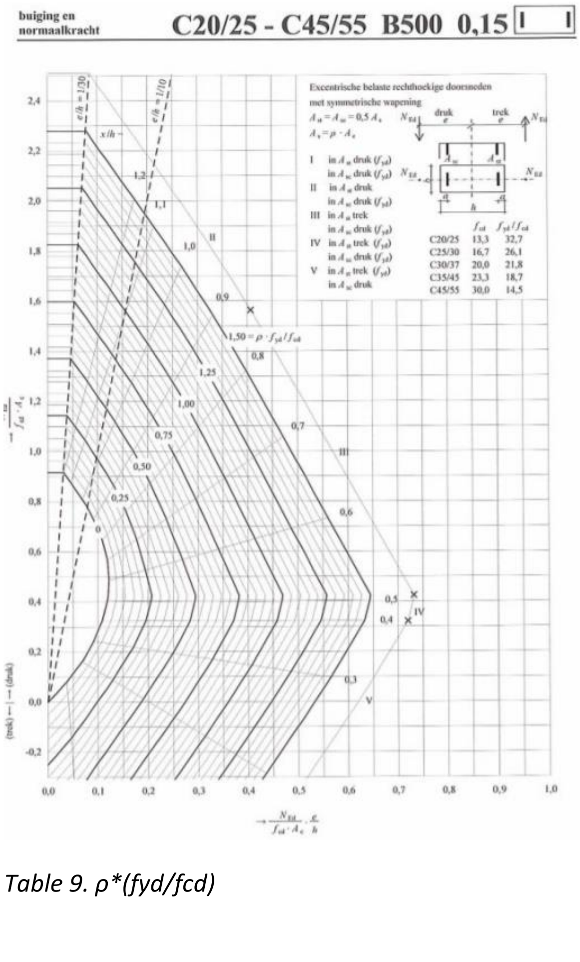


Table 9. ρ(fyd/fcd)*

betonstaal reinforcement steel

cross-sectional area of reinforcing steel $\Sigma \varnothing_k$

• **doorsnede betonstaalstaven**

Table 1: Total (cross-sectional) area of number of bars in mm2)

First column: diameter of bars. Second column: mass of 1 bar per m1 (kg/m1);remaining columns: total cross sectional area of bars in mm2

Gezamenlijke doorsnede van betonstaalstaven in mm²

Ø$_k$	massa per staaf (kg/m)	aantal staven									
		1	2	3	4	5	6	7	8	9	10
6	0,222	28	57	85	113	141	170	198	226	254	283
8	0,395	50	101	151	201	251	302	352	402	453	503
10	0,617	79	157	236	314	393	471	550	628	707	785
12	0,888	113	226	339	452	565	679	792	905	1018	1131
14	1,208	154	308	462	615	769	923	1077	1231	1385	1539
16	1,578	201	402	603	804	1005	1206	1407	1608	1810	2011
20	2,466	314	628	942	1257	1571	1885	2199	2513	2827	3142
25	3,853	491	982	1473	1963	2454	2945	3436	3927	4418	4909
32	6,313	804	1608	2413	3217	4021	4825	5630	6434	7238	8042
40	9,865	1257	2513	3770	5027	6283	7540	8796	10053	11310	12566
50	15,406	1962	3925	5887	7850	9812	11775	13737	15700	17662	19625

Table 10. Tables for selection of reinforcement steel used to select bars for a floor section.

Appendix 11: Drawings

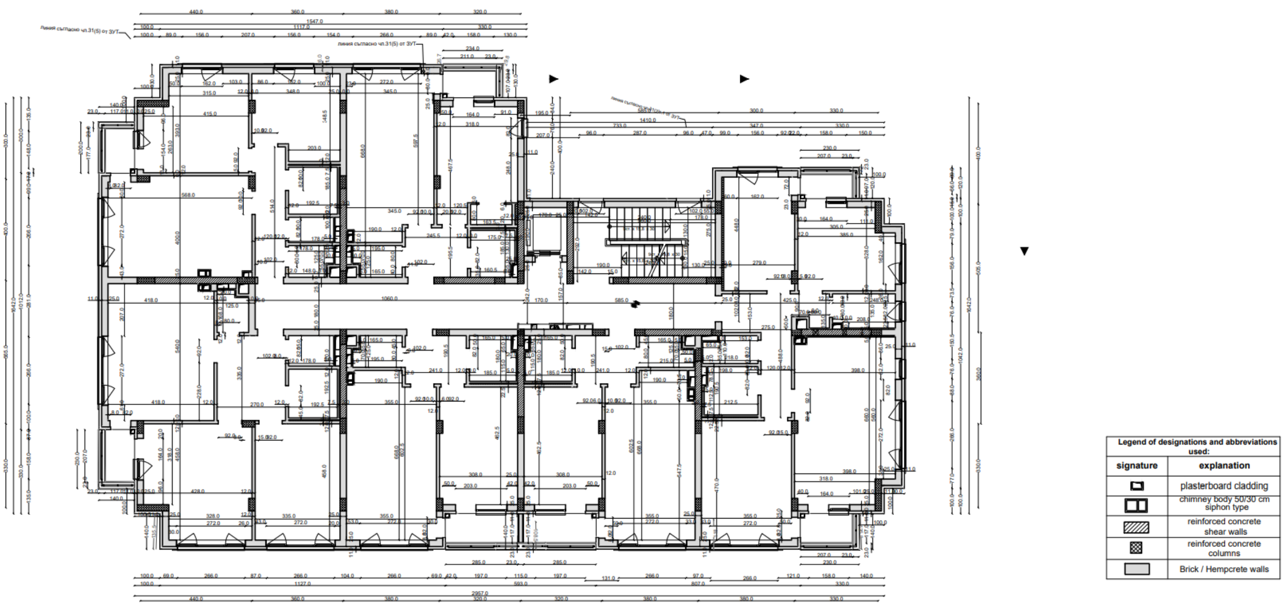


Figure 13. Brick/ Hempcrete layout.

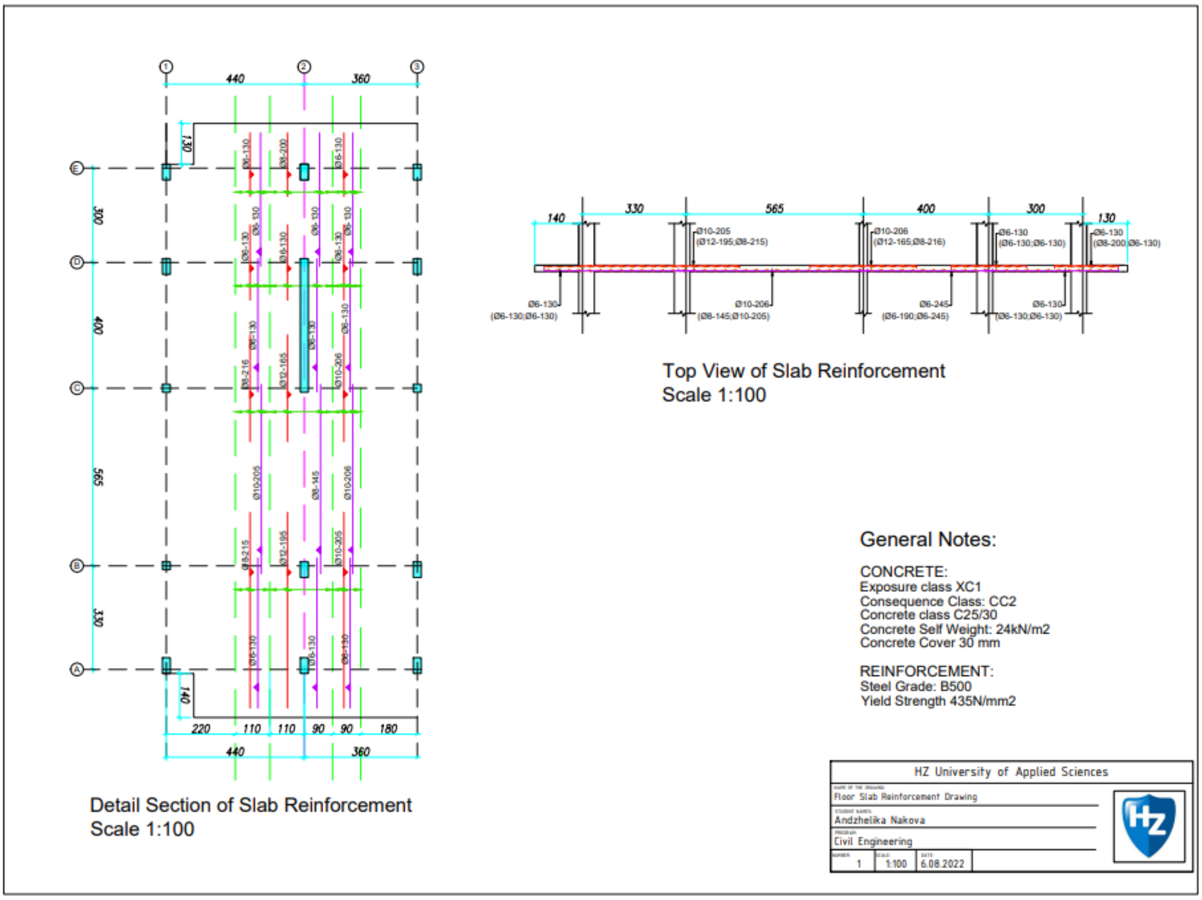


Figure 14. Floor slab reinforcement drawing.

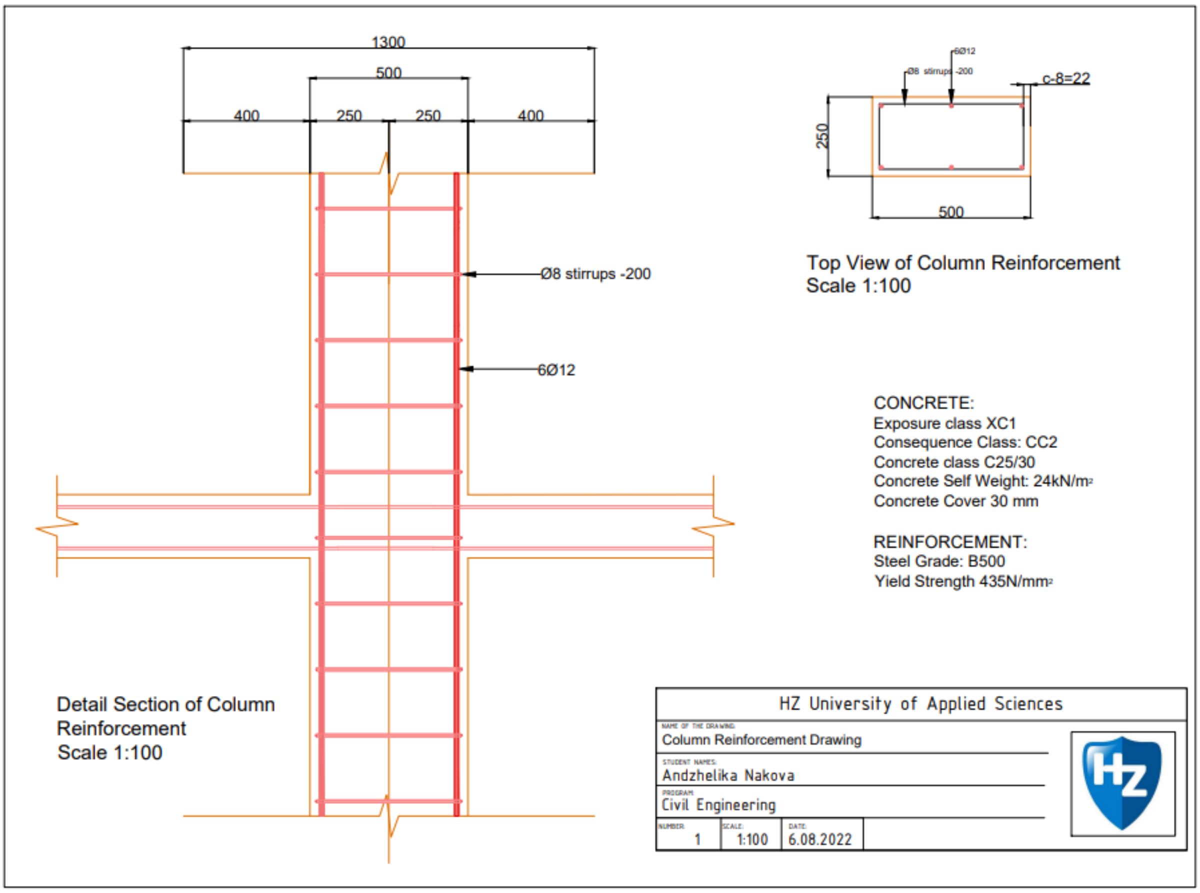


Figure 15. Column reinforcement drawing.