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Innovative Solutions for Concrete with Reduced Environmental Impact

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<p>The aim of the final year project was to study the process of concrete production and its effects on the environment. The case study featured in this thesis focused on the environmental impacts caused by the production of concrete for a typical concrete panel residential building in Moscow. The estimations were based on a life cycle assessment of the building. The results of the LCA show that over 375 tons of carbon dioxide was released into the atmosphere, over 200 tons of water and over 3,4 GJ of energy were consumed by the production of the concrete for the building.</p> <p>The results of the study are important because the studied K7 building belongs to a group of typical panel buildings constructed widely during 1960's in the USSR. Therefore, the analysis of this building can help to estimate the hazardous impacts caused by industrial construction to the environment in almost any city around Russia and the post-Soviet territories. Two innovative solutions for concrete were studied in the thesis: organic concrete, and porous concrete. Both are based on replacing Portland cement with organic and nonorganic materials including burnt magnesia, fly ash, and slag. The innovative concretes are nearly carbon neutral compared to the regular one using Portland cement. However, none of them can be used alone in a building construction yet due to reduced strength, but both can be used for non-bearing elements such as elevations and roof tops.</p>	
Keywords	LCA, concrete, CO ₂ emissions, innovative concrete

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1 Introduction

Concrete is one of the most widely used building materials in the modern world – it has become an almost irreplaceable building material and it is difficult to imagine any modern construction without it. According to Concrete Sustainability Initiative (CSI), on the scale of popularity concrete is second after water. Furthermore, about a billion tons of concrete is used annually in the United States, Europe and Japan together. Not only does concrete impact the quality of constructed buildings and their durability, it also impacts human beings and the environment from the moment of its production, during its utilization, and even after the end of its life cycle. [1.] Certainly, concrete structures perform a protective role for human beings from the environment, in the first place. However, the environment often influences concrete in a bad way, causing its destruction and deterioration. Consequently, it is necessary to take action for its protection from the environment, too. So, what is the negative role of concrete in its relationship with humans and environment?

1.1 Background

In its basic form, concrete is a mix of water, cement and aggregates of different size, for example fine aggregate, such as sand, and coarse aggregate, such as crushed rock. Modern concretes include various chemical additives and admixtures in their compositions; depending on what additional properties they are supposed to have. For example, to withstand difficult environments, such as seawater, typical admixtures are pozzolans like fly ash, blast furnace slag and silica fume. [2.]

In fact, concrete structures are generally seen as rather time-stable and, during their operation, do not impact the environment, including potable water, in a bad way. Moreover, concrete structures can act as protection from radiation and harmful chemicals.

Modern innovative solutions for reducing of the negative impact of concrete include organic concrete and porous concrete. Both of the innovative solutions, presented in the thesis, are based on new types of cements, which are nearly carbon neutral. The innovative concretes – porous concrete and organic concrete have great potential and

can become carbon sink. However, currently these concretes cannot be used alone in building construction, as they are more suitable for non-bearing structural elements as elevations, rooftops, and pavements. [3.]

1.2 Aims

The aim of the thesis is to study the process of concrete production and the harm caused by it to the environment. The thesis also focuses on modern innovative solutions helping to reduce the impacts of concrete production. Life cycle assessment (LCA) of concrete as one of the main construction materials for modern buildings is used as the main instrument in the research of the impacts of concrete production on the environment at each step of its life cycle.

The case study described in chapter 4 below focuses on the LCA of concrete needed for the construction of a typical panel residential building located in Moscow. Based on the results of the LCA, suggestions on innovative solutions for concrete will be made.

2 Concrete as Construction Material

Concrete industry is one of the most well developed industries in the construction sector. Concrete is used in construction of multi-storey residential and office buildings, airports, schools, shopping centers, etc. All of the listed structures consist of elements which are either precast, produced at a factory, or cast-in-place, which means that the shape of a desired structure element is made using wood, and concrete is poured inside. The cast-in-place method is suitable for such structural elements as foundation footings and other relatively large structural elements, which are difficult to transport. Concrete is a versatile construction material, it is rather durable and fireproof. In addition, it is possible to change its characteristics by using various admixtures. [2.]

However, besides all the advantages of concrete, there is also a disadvantage, which cannot be solved using admixtures. It is relatively low tensile strength of concrete. The tensile strength of concrete is about ten times smaller than the compressive strength of concrete. In order for concrete to be able to withstand tension, reinforcement bars are used. Reinforcement bars, or rebars, take tensile forces on themselves preventing

concrete from cracking. This combination forms reinforced concrete, which is mainly used in construction. [2.]

2.1 Production Cycle

The production of concrete mixture is conducted at central mixing plants which provide construction sites, located at a distance that does not exceed technologically acceptable distances for transportation, with ready mixed concrete. Moreover, concrete mixture is also produced at on-site concrete mixing plants and in mixer trucks loaded with dry concrete mixture. Furthermore, free-standing concrete mixers are used as auxiliary equipment for the production of small portions of concrete mixture. [4,13.]

The production method depends on, for example, such factors as accessibility (road conditions), the amount of concrete mixture needed in a particular case, and requirements for homogeneity of concrete mixture. For example, in big cities and towns with well-developed road network, it is preferable to prepare the concrete mixture at central mixing plants. Generally, such production is more economically effective than a system of small on-site mixing plants. However, in remote areas and in case of impossible transportation of ready mixed concrete in local road conditions, it is more expedient to use small on-site concrete mixing plants. In case of low demand in concrete mixture on a remote construction site, located at a distance that exceeds technologically acceptable distances for transportation, it is more economically efficient to use mixer trucks than small on-site mixing plants. [4,13.]

2.2 Mixing

The process of preparation of concrete mixture starts from the loading of all the necessary components into a concrete mixer. The order in which the loading is carried out is highly important, and so is the duration of loading, which depends on two aspects – the duration of the mixing of dry components before water is added, and the speed of the loading of the components. The loading process starts with the first component added to the mixer and ends when all the components are in the mixer. Frequently, the loading process is divided into dry mixing or the mixing of dry components before the addition of water, and wet mixing, when water is added to the dry components while the

loading continues. Therefore, the components can be added to the mixer anytime and in the following ways: all dry components before water, water first and all dry components after, and in an alternating way. [5.] In the process of automated preparation of concrete mixture, the proportioning of the composites is done by mass, except for water [4,15]. Figure 1 below shows the stages of concrete mixing: loading period comprising dry mixing and wet mixing, followed by the mixing period and finally discharging.

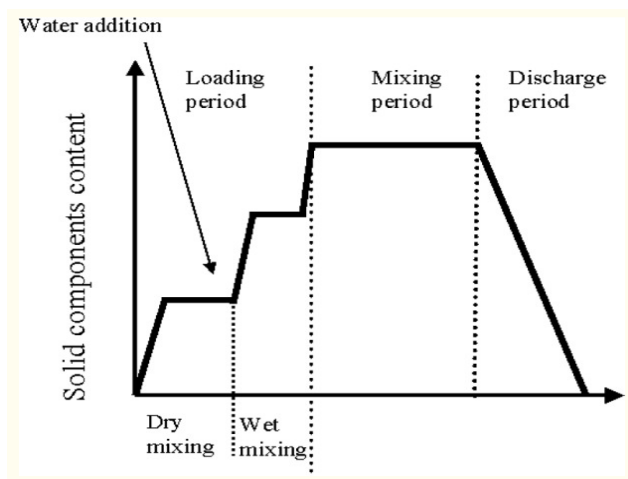


Figure 1. Concrete mixing stages. [5.]

There are two main types of concrete mixers: gravity concrete mixers and fixed drum concrete mixers. Fixed drum concrete mixers are recommended for the preparation of harsh mixes, mixes with porous aggregates and concrete mixes with high cement content (over 350 kg/m^3). Gravity concrete mixers are cheaper and easier in operation. Moreover, they are usually used to prepare concrete mixtures with larger size aggregate than fixed drum mixers. [4,20.]

2.3 Separation

Separation of concrete occurs when concrete is young and has uniform consistency. Stability is the criterion that determines the degree of homogeneity of concrete. Stable concrete does not separate at any stage of the process of concrete hardening. Basically, the separation of concrete can be divided into three main types: stone, water and mortar separation. [6,15.]

The separation of greater sized aggregates from the concrete mixture is called stone separation. This type of separation may happen during the logistics of a ready-made concrete mixture or due to a lack of vibration when casting. This causes an uneven distribution of strength over the whole volume of concrete. In order to avoid stone separation, it is important to provide vibration so that the aggregate can distribute evenly in the concrete mass. In addition, aggregate of suitable size should be chosen. [6,15.]

Water separation begins if there is not enough small particle aggregate in the concrete mixture, which leads to inability of concrete to absorb the water that it contains. Consequently, water starts gathering on top of concrete mass. [6,15.]

When concrete is excessively loose mortar separation takes place, causing concrete mixture to split into two different layers. Furthermore, in mortar separation each individual layer has distinctive features, which therefore means that each of the layers becomes a different kind of substance. [6,15.]

3 Assessing environmental impacts with LCA

One of the most modern and far-reaching ways to figure out the degree of sustainability of a building is life cycle assessment (LCA). The purpose of LCA is to factually analyze the complete life cycle of a product and assess to what extent it is sustainable. In other words, LCA helps to figure out in what ways a product impacts the environment from the beginning of its life cycle till the end of its life cycle. LCA analyses each phase of the life cycle individually, so that one phase follows another. [7.]

The diagram in figure 2 below shows a simplified life cycle of concrete as a construction material. The first phase, raw materials, is quite complex and consists of a series of processes, such as the mining of limestone and extraction of clay, then grinding and producing clinker. Later on, gypsum, clinker and possibly other raw materials are grinded to produce cement. [6.] In the second phase, manufacturing, all the necessary raw materials, including cement, aggregate, water and admixtures, as well as steel, need to be obtained in order to manufacture a concrete mixture and reinforcement bars. The third phase of the life cycle is construction. Concrete can be precast at a factory or it can be cast-in-place on a construction site. The fourth phase, use or utilization, means the

operation of a building, constructed from the concrete produced during the earlier stages. This is a long-term phase, which can last decades or centuries if appropriate maintenance and service take place. When a building ends its life cycle, it is demolished or reconstructed in some cases. Afterwards, construction waste is either recycled or taken to landfill. [8.]



Figure 2. Life cycle of a building product. [8.]

The life cycle of concrete includes inputs and outputs, besides the phases mentioned above. The inputs are raw materials necessary for concrete production, and energy needed for transportation and automatization of the production process. The outputs are negative impacts, like air and water pollution, solid waste, byproducts and other harmful discharges, caused by each phase of the life cycle of concrete contributing to environmental pollution. In order to be able to qualitatively analyze the impact caused by a concrete building to the environment, it is essential to take into account each phase of the life cycle. [9.]

3.1 Methodology

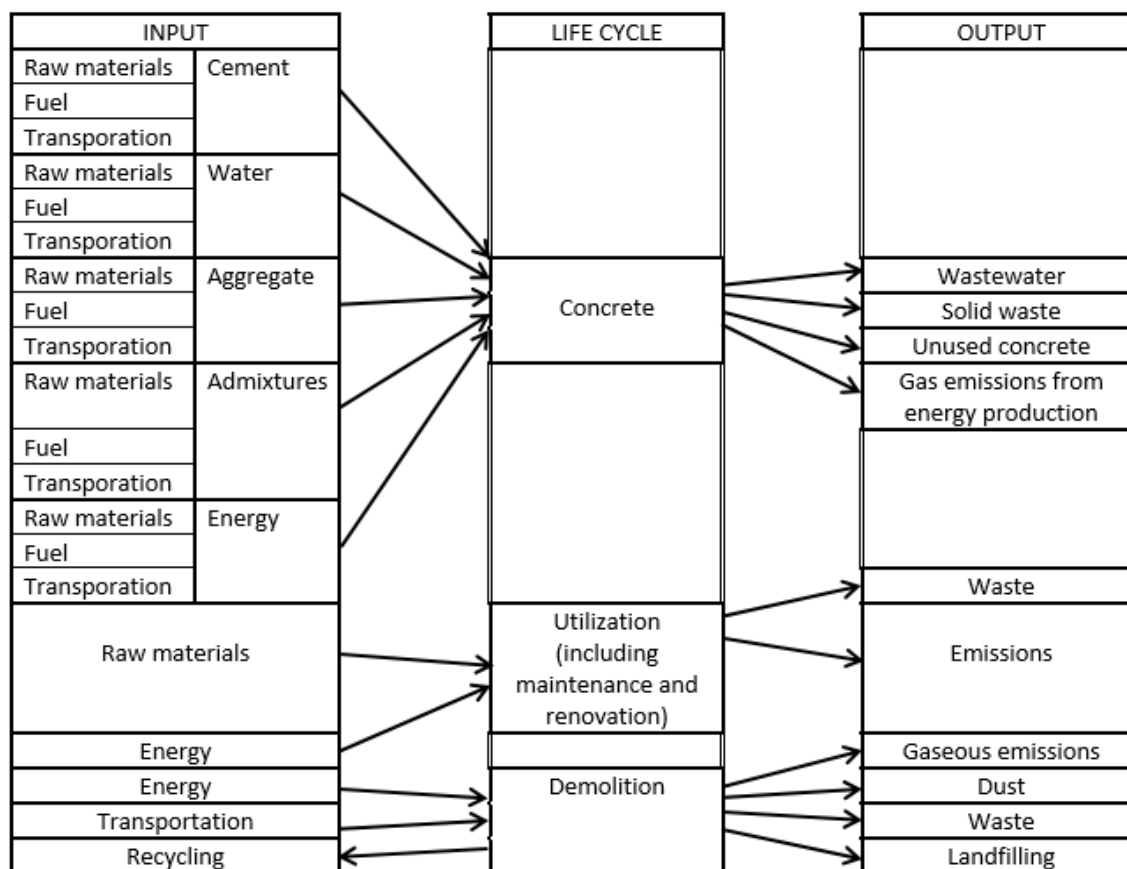
The reliability and clarity of LCA are provided by a standardized methodology. The principles and core for LCA are explained in ISO14040:2006, whereas the requirements and guidance are explained in ISO14044:2006. The four essential phases of LCA, according to the standards are: description of the goal and scope of the LCA, the life cycle inventory analysis (LCI), the life cycle impact assessment (LCIA), and the life cycle interpretation. [10.] The explanation of the phases is provided below.

1. Description of the goal and scope of the LCA – this phase focuses on characterization of the object of the analysis, the product. [9.]
2. Life cycle inventory analysis (LCI) – at this phase it is important to figure out the identity and quantity of the materials, water and energy required for the manufactory of the product. In addition, all the possible environmental impacts should be considered at this phase, too. In practice it is often difficult to determine all inputs and outputs related to a specific product, as well as measuring the emissions released to the environment, which can be rather costly. [9.]
3. Life cycle impact assessment (LCIA) – this phase involves the analysis of the probable harm caused by the extraction of raw materials, production of wastewater and energy usage during the production process, including the emissions released during the process. This phase is particularly complicated because it is necessary to compare the emissions released to the environment and analyze their possible influence on humans and the environment. [9.]
4. Life cycle interpretation – the final phase focuses on the analysis of the outcomes and on making decisions on what product to choose. [9.]

3.2 Environmental Impacts

In order to qualitatively assess the environmental impacts caused by concrete production, this chapter focuses on the analysis of the impacts according to each phase of concrete's life cycle: production of cement and raw material extraction, production of concrete, construction and utilization phase, demolition and recycling or landfilling. Table 1 below demonstrates the life cycle of concrete, including its inputs and outputs.

Table 1. Life cycle of a concrete building. [11.]



The outputs are the environmental impacts of concrete production. They include, among others, wastewater, unused concrete, hazardous emissions, and dust.

3.3 Raw Material Extraction and Cement Production

In environmental assessment, it is important to consider the reserves of a raw material extracted. The reserves are determined on the basis of the economical, technical and ecological factors for a particular region. For some types of raw materials, it is already known that their reserves are going to deplete in a short period of time if their extraction continues on the current level. The process of the extraction of such raw materials as clay and limestone often damages ecosystems, through deforestation and destruction of the top soil layer, releases of harmful emissions, as well as frequent catastrophes during extraction and transportation of oil, and coal extraction. Figure 3 below demonstrates the

consequences of open extraction of raw materials. What is more, approximately 30% of the materials are wasted according to statistics. [11.]



Figure 3. Consequences of open extraction of raw materials.

Furthermore, the process of industrial production of cement employs a vast amount of energy. Almost 1.8 kWh of energy is required to produce a ton of cement. The figure includes the direct usage of fuel for the excavation of raw materials and their conveyance. Most of the energy used in the production process, including electricity, is still made using fossil fuels, mainly coal, and this results in excessive emissions of carbon dioxide, sulphur and nitrous oxide as well as other hazardous chemical compounds. [12,31.]

Among the stages of cement production, two stages cause special concern because they make up most of the emissions of carbon dioxide associated with the process. The most remarkable of the causes is coal combustion to run the rotary kiln. During this stage, approximately 800 kg of carbon dioxide is produced per 1 ton of cement. Furthermore, carbon dioxide is also produced by the chemistry of limestone calcination, taking place

in the cement kiln to form lime. Combined, both of the sources produce approximately 1,250 kg of carbon dioxide per each 1,000 kg of cement generated. [12,31-32.]

In addition to carbon dioxide emissions, both cement and concrete productions contribute to air pollution. One of the most common contaminants is dust [12,32]. As seen in table 2 below, cement production generates approximately 53 million tons of dust per year.

Table 2. Comparison of dust emissions during production of construction materials. [11.]

Type of production process	Dust emissions, million t/year
Coal burning	93.600
Iron smelting	20.210
Copper smelting (no purification)	6.230
Zinc smelting	0.180
Tin smelting (no purification)	0.004
Lead smelting	0.130
Cement production	53.370

Table 2 also shows how much dust is generated by other industrial processes compared to cement production. Dust as a waste product is generated throughout the whole process of cement production starting with the processing of raw materials till the bundling and storing of cement [12,32].

Apart from energy, another highly consumed resource involved in concrete production is fresh water. Moreover, water is an essential ingredient of concrete and it is absolutely necessary at different stages of concrete production, starting from mixing together all the ingredients of concrete and finishing with the curing of concrete. Additionally, in the ready mixed concrete industry water is used to wash the trucks after the transportation of the concrete mixture, which leads to the generation of large amounts of wastewater. [13.]

3.4 Construction and Utilization

The construction phase of the life cycle of concrete produces different kinds of waste, such as unused concrete mixture, pieces of hardened concrete, wood from framework,

and plastics from the unpacking of various construction elements and products. In addition, due to the fact that the construction phase involves the usage of machinery, this process also produces CO₂ and dust, which are released into the atmosphere. However, during the construction phase recycled concrete waste grinded to a necessary size is widely used. [11.]

In the utilization phase the ecological load is defined by the choices made during the previous phases, and on this stage it is essential to figure out the material maintenance costs to preserve its properties and quality. [11.]

3.5 Demolition

Demolition phase marks the end of the life cycle of a concrete building, meaning that the building is deconstructed. The process of demolition produces various types of construction waste and air contaminants, such as solid waste, gaseous emissions and dust. Frequently, concrete solid waste is recycled and reused in many different sectors of the construction industry, such as the production of concrete, or road and pavement construction. Approximately 150 million tons of concrete waste is recycled every year in the United States. [14.]

The process of concrete recycling starts from the transportation of waste concrete to a recycling terminal. The first step is the removing of reinforcement bars, and the second step is the crushing of waste concrete into appropriate aggregate size according to what it will be used for later on. In some cases, large fragments of concrete waste are not crushed in order to reuse them as embankment stones. This way the recycling of concrete waste contributes to the reduction of the depletion of natural raw materials like rock, sand, and stone. [6,11.]

4 K7 Building in Moscow

The building studied in this thesis is a type panel residential building of series K7 constructed in Moscow. The studied K7 building belongs to a series of buildings constructed massively all over USSR in the 1960's. Such buildings are located in almost every district of Moscow, where the first buildings of the K7 series were constructed

already in 1958. The fastest way of building construction in the industry is construction out of reinforced concrete panels. However, due to the unavailability of such technologies in some regions, many buildings at the time were still constructed out of brick or silicate blocks.

The point of the vast construction of type buildings was to get rid of the housing shortage all over the USSR in a short period of time and to provide all families with modern and comfortable housing. The main advantages of the K7 buildings were that they were rather cheap and easy to construct. Furthermore, the buildings were constructed rapidly. What is more, the construction of new modern housing solved the problem of densified living of people especially in Moscow, where several families could share one apartment with many rooms. However, the main disadvantage of the new panel buildings was that they were only meant to be temporary housing in a transition of the society from socialism to communism, and they were only designed for a lifetime of 25-50 years. What is more, most of the buildings had poor thermal insulation and panel connections. The original idea was to later demolish all the temporary buildings and construct better and more comfortable housing instead. The characteristics of the K7 series include:

- Building type: frame – panel.
- Number of floors: five.
- Apartment types: 1, 2 and 3 room apartments.
- Room height: 2.59 m.

External walls of the K7 buildings were composed of reinforced concrete panels with a light foam material as thermal insulation. The total thickness of the external walls was 30 cm. The load bearing walls were internal reinforced concrete shear walls with an H-section where the thickness of the vertical wall was 40 mm, with the upper and lower parts of the wall panel being 240 mm and 170 mm, respectively. The living rooms of adjacent apartments were separated by two shear walls with a channel section with a gap of 40 mm. The slabs were composed of precast ribbed panels. [15.]

The study of the K7 series is of special interest because it represents the first generation of industrially constructed concrete buildings in the USSR. According to a new renovation program in Moscow, initiated by the government of Russian Federation, all type panel buildings of the first generation of industrial construction are to be demolished by 2022 and replaced by modern buildings which fulfill all the modern norms for residential

housing. Furthermore, according to the city council of Moscow, the buildings are to be demolished in a smart way. All the construction waste is to be sorted and recycled to produce construction materials for new housing. The smart demolition of the concrete panel buildings seriously improves the ecological situation in the region. It, for example, reduces the need for raw materials and decreases hazardous emissions related to the excavation of them.



Figure 4. Concrete panel residential building of series K7. [15.]

Figure 4 above demonstrates the studied concrete panel residential building of the K7 series located in Moscow. The condition of the building is unsatisfactory; designed for a lifetime of 25 years, built in 1960's, it was in use in 2018. This seriously impacts the quality of living and the environment. Due to low energy efficiency the buildings consume great amounts of energy for heating. [15.]

The mass production of prefabricated concrete elements and start of industrial construction in Moscow was initiated in 1961 when the first integrated building construction factory (IBCF) was constructed. It included several factories around Moscow, as well as two installation departments. Table 3 below demonstrates the types

of concrete that were mainly used in all of the initial series of concrete panel buildings, including series K7.

Table 3. Concrete types used in K7 buildings. [16,43.]

	Class	Mix Ratio	Pure Compression Stress	Bending Compression	Shrinkage factor
Foundation concrete	3	1:3:5	40 kg/cm	50 kg/cm	1.54 -1.57
Concrete for structural elements	2	1:2:4	45 kg/cm	50 kg/cm	1.54 -1.57

As seen in table 3, the concrete used for foundations is class 3 concrete with mix ratio 1:3:5, pure compression stress of 40 kg/cm and bending compression of 50 kg/cm, whereas the concrete for structural elements like columns, beams, slabs and stair carriages is class 2 concrete with mix ratio 1:2:4, pure compression stress of 45 kg/cm, bending compression of 50 kg/cm and shear fracture of 4 kg/cm. The shrinkage factor for both classes of concrete is approximately 1.54 -1.57.

5 Life Cycle Analysis of the K7

The late 1950's marked the start of massive use of concrete in USSR, when thousands of buildings of the K7 series were constructed all over Moscow, Moscow region and other cities [16,43]. The need for concrete at that time was extremely high, which means extremely high rates of concrete production. This fact has, certainly, greatly influenced the environment in many different ways, including releases of carbon dioxide and other hazardous emissions, water pollution, and solid waste creation. Therefore, it is extremely important to assess the environmental impacts of concrete production at the beginning of the mass construction of concrete panel buildings in order to minimize or avoid their negative impacts on the environment in the modern world.

Even though the design lifetime of a K7 concrete panel building is 25 to 50 years, the LCA in this thesis is done for a period of 50 years because most of the buildings seriously

exceeded the lifetime of 25 years and were utilized up to 2018 when they were finally demolished in Moscow. The K7 series as well as some other early series were included in the federal renovation program in 2017, and sentenced to demolition. They are to be substituted by modern and comfortable buildings. According to the government of Moscow one of targets is smart demolition of the buildings, including sorting construction waste, followed by recycling and further usage to produce concrete for new buildings, pavements and other purposes.

5.1 Goal and Scope

The main goal of the LCA is to identify and quantify environmental impacts, including carbon dioxide emissions, consumption of fresh water and energy, caused during the *raw materials* and *manufacturing* phases of the lifecycle of concrete that was used in 1960's in construction of the K7 buildings in Moscow. After the estimation of the environmental impacts, the potential areas for improvement in terms of concrete sustainability are suggested.

The LCA in this thesis focuses on the manufacturing phase of concrete, and the resources used, such as water and energy, as well as the carbon dioxide emissions related to the production of concrete for the studied K7 building. In addition, the LCA does not take into account the reinforcement steels inside the concrete, nor thermal insulation.

5.2 Life Cycle Inventory Analysis and Impact Assessment

This chapter focuses on the analysis of the resources needed to produce concrete elements for the studied K7 building, such as cement, water and electricity. Concrete hardening is an extremely important process in concrete production and it releases heat due to a chemical reaction (see chapter 4.4.1 below). Another important concept in concrete production, which determines the relationship between the amount of water and cement used in the production of a particular concrete mixture, is the water-cement ratio (see chapter 4.4.2 below).

5.2.1 Concrete Hardening

Mixing cement and water produces a hydration reaction. This reaction progresses from an initial condition to an end condition of concrete. Basically, hydration reaction is the reaction of water with components, which include calcium oxide, also known as quicklime. As a result of the reaction, calcium hydroxide is formed and because the reaction is exothermic, heat is released as well. In fact, the process of concrete hardening produces heat, up to 250 kJ per kilogram of cement in a period of a day, that is 24 hours. After the one-day period, the heat release starts descending. To sum up, roughly 330 kJ of energy per kilogram of cement is released into atmosphere as a result of the hydration reaction. The amount of energy released depends on the type of cement used in the preparation of a particular concrete mixture. [6,8.]

Concrete hardening consists of four stages; green concrete, young concrete, hardening and hardened concrete [5,14]. As seen in figure 5 below, the first two stages – green concrete and young concrete – are the states of concrete during the first 1-3 days, followed by a strength growth phase or hardening phase. The strength growth continues until the age of 28 days when concrete is considered hardened.

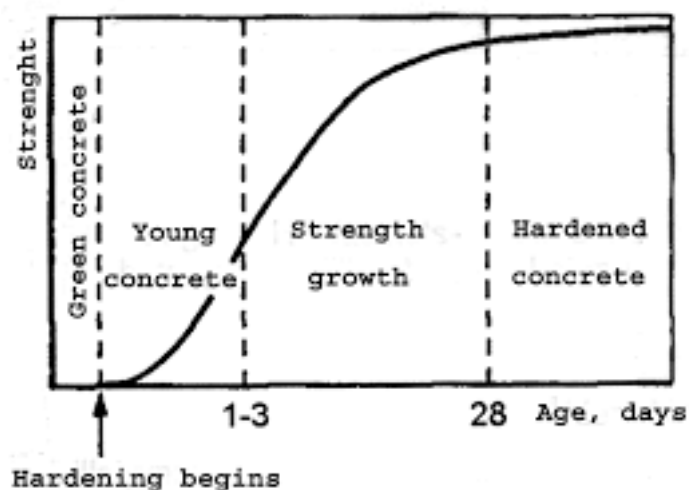


Figure 5. Stages of concrete hardening. [6,14.]

Stability and workability are the most valuable features of green concrete – due to these qualities, concrete has the ability to take any particular shape and to keep an even or homogenous texture. The degree of workability of concrete is determined by such aspects as the water-cement ratio and composition of concrete, including size and type of

aggregate and admixtures used. At this stage of the process of concrete hardening, strength starts growing. [6,14.]

As soon as the process of strength growing starts, the stage of young concrete begins. It lasts up to the age of 28 days. It is important to note that on this stage concrete is rather susceptible to moisture loss and variations of temperature due to, on one hand, the chemical reactions taking place and, on the other hand, the quick strength growth and, consequently, the changes in the features of concrete. In order to maintain the concrete in a suitable condition and to avoid any damage to the strength of hardened concrete, it is essential to keep the concrete hydrated for the initial period after casting, for approximately one to three days. After this period, the concrete is fairly resistant to the outside conditions and changes. In addition to keeping the concrete moisturized during the initial period, it is also important to monitor its surface temperature. It should not rise over 60°C. [6,14.]

5.2.2 Water-cement ratio

Generally, there are two main criteria set for concrete produced in the construction industry, design compressive strength and the maximal water-cement ratio (w/c). The relationship between these two criteria is inverse. Hence, as the compressive strength decreases, the water-cement ratio increases. However, in addition to compressive strength, water-cement ratio greatly affects such important aspects as the durability and permeability of concrete. They play a crucial role in concrete's ability to resist corrosion and freeze-thaw circumstances, and help to achieve water tightness in concrete structures. [17.]

Due to the fact that various aggregates, cements and their components typically generate different strengths at an equal water-cement ratio (w/c), it is absolutely necessary to establish the relation between strength and w/c for the specific components intended to be used. The instructions on how to select the w/c for a case in which the concrete contains Type I Portland cement are provided by the American Concrete Institute (ACI) Committee. Table 4 below demonstrates the strengths which should be produced by the given figures of w/c. The results provided in the table are established on the basis of 28-day tests of samples cured in normal laboratory conditions. [18.]

Table 4. Relationship between compressive strength and water-cement ratio. [18.]

Compressive strength at 28 days, psi*	Water-cement ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000	0.41	—
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

The specific strength, essentially, ought to have an acceptably higher value than that of the average strength. [18,9.]

5.3 Life Cycle Impact Assessment

Among all emissions released by construction material enterprises, over 40% is generated by the cement industry, 18-20% by the production of insulation materials, 10% by the production of asbestos, 15% by the production of non-metallic building materials, and less than 10% by the production of concrete and reinforced concrete structures and products. [19,85.]

The production of cement is a large source of carbon dioxide: per 1 ton of cement, 1 ton of carbon dioxide, per 1 ton of clinker, 1.5 to 9.5 kg of nitrous oxide, solid particles with flue gases approximately 0.3 to 1.0 kg/t. However, most of the cement dust is trapped by filters and then directed to the furnace. [19,85.]

5.3.1 The amount of cement used in class 2 and class 3 concrete

On average, the demolition of a K7 building with four sections creates up to 4 thousand tons of large sized solid waste. Since the building is built mainly out of concrete, it is assumed that the amount of concrete waste is approximately 3,000 tons.

The K7 building is constructed of class 2 and class 3 concrete, grades C25 and C10, respectively. It is assumed that 1/3 of the building (1,000 t) is constructed of class 3

concrete and 2/3 (2,000 t) of class 2 concrete. In both cases it is assumed that 1 m³ of concrete equals to 2,400 kg.

For class 2 concrete, the amount of cement needed to produce 2,000 tons of concrete is assumed to have a 1:2:4 mixture. This indicates that the mixture has one part of cement, two parts of sand and four parts of coarse aggregate. The first step is to calculate the size of the parts for 1 m³ of concrete.

$$\text{Ratio sum} = 1+2+4 = 7 \quad (1)$$

Taking into consideration the shrinkage factor of 1.57, the volume of wet class 2 concrete should be 1.57 m³. The calculation is done by multiplying the part of the particular component from the ratio sum by the volume of wet class 2 concrete.

$$V_{\text{cement}} = 1/7 \times 1.57 \text{ m}^3 = 0.224 \text{ m}^3 \quad (2)$$

$$V_{\text{sand}} = 2/7 \times 1.57 \text{ m}^3 = 0.449 \text{ m}^3 \quad (3)$$

$$V_{\text{coarse aggregate}} = 4/7 \times 1.57 \text{ m}^3 = 0.897 \text{ m}^3 \quad (4)$$

Having found the volume of cement, it is now possible to find its mass. The density of cement is 1,450 kg/m³.

$$\text{Mass of cement} = V \times \text{density} = 0.224 \text{ m}^3 \times 1,450 \text{ kg/m}^3 = 325 \text{ kg} \quad (5)$$

The calculation shows that approximately 325 kg of cement is required per 1 m³ of concrete. It was assumed above that 2,000 tons of class 2 concrete was used in the K7 building. Since 1 m³ of concrete is 2,400 kg of concrete and 325 kg of cement makes 2,400 of concrete, the following amount of cement is required to produce 2,000,000 kg of class 2 concrete:

$$X = (325 \text{ kg} \times 2,000,000 \text{ kg}) / 2,400 \text{ kg} = 270,833 \text{ kg of cement} \quad (6)$$

Based on the calculations, approximately 270 tons of cement is required to produce 2,000 tons of class 2 concrete.

For class 3 concrete, the amount of cement needed to produce 1,000 ton of concrete is assumed to have a 1:3:5 mixture. This indicates that the mixture has one part of cement, three parts of sand and five parts of coarse aggregate. The first step is to calculate the size of the parts for 1 m³ of concrete.

$$\text{Ratio sum} = 1+3+5 = 9 \quad (2)$$

Taking into the consideration the shrinkage factor of 1.57, the volume of wet class 3 concrete should be 1.57 m³. The calculation is done by multiplying the part of the particular component from the ratio sum by the volume of wet class 3 concrete.

$$V_{\text{cement}} = 1/9 \times 1.57 \text{ m}^3 = 0.174 \text{ m}^3 \quad (2)$$

$$V_{\text{sand}} = 3/9 \times 1.57 \text{ m}^3 = 0.523 \text{ m}^3 \quad (3)$$

$$V_{\text{coarse aggregate}} = 5/9 \times 1.57 \text{ m}^3 = 0.872 \text{ m}^3 \quad (4)$$

Having found the volume of cement, it is now possible to find its mass. The density of cement is 1,450 kg/m³.

$$\text{Mass of cement} = V \times \text{density} = 0.174 \text{ m}^3 \times 1,450 \text{ kg/m}^3 = 252 \text{ kg} \quad (5)$$

The calculation shows that approximately 252 kg of cement is required to make 1 m³ of class 3 concrete. It was assumed above that 1,000 ton of class 3 concrete was used in the K7 building. Since 1 m³ of concrete is 2,400 kg of concrete and 252 kg of cement makes 2,400 of concrete, the following amount of cement is required to produce 1,000,000 kg of class 3 concrete:

$$X = (252 \text{ kg} \times 1,000,000 \text{ kg}) / 2,400 \text{ kg} = 105,000 \text{ kg of cement} \quad (6)$$

Based on the calculations, approximately 105 tons of cement is required to produce 1,000 tons of class 3 concrete.

To sum up, the production of concrete for the studied K7 building in the amount of 3,000 tons required about 375 tons of cement.

5.3.2 Consumption of fresh water by class 2 and 3 concrete

This chapter focuses on the calculation of the amount of water involved in production of the 3,000 tons of concrete used in the K7 building. For class 2 concrete with mixture 1:2:4 it is typical to have water-cement ratio 0.55, which means that 0.55 t of water is required to produce 1 t of cement. As it was estimated above, 270 t of cement was used to produce the concrete for the K7 building, therefore:

$$0,55\text{t}/1\text{t} = X\text{t}/270\text{t} \quad (3)$$

$$X = (0,55\text{t} \times 270\text{t})/1\text{t} = 148 \text{ t} \quad (2)$$

In the calculation above, X stands for the amount of water used for the production of class 2 concrete. Based on the calculations, in order to produce 2 000 t of class 2 concrete for the K7 building, 148 t of water should have been used.

For class 3 concrete with a mixture of 1:3:5 it is typical to have water-cement ratio of 0.50. According to the estimation above, 105 t of cement is required to produce 1,000 t of class 3 concrete for the K7 building, therefore:

$$0,55\text{t}/1\text{t} = X\text{t}/105\text{t} \quad (4)$$

$$X = (0.50\text{t} \times 105\text{t})/1\text{t} = 52.5 \text{ t} \quad (2)$$

In the calculation above, X stands for the amount of water used for production of class 3 concrete. The calculation shows that in order to produce 1,000 t of class 3 concrete for the given K7 building 52.5 t of water should have been used.

To sum up, the production of class 2 concrete requires approximately 148 tons of water, and production of class 3 concrete requires approximately 52.5 tons of water. Therefore, about 200 t of water is required to produce 3,000 t of concrete for the K7 building.

5.3.3 Energy consumption in the cement production for the K7 building

The focus of this chapter is to find out the amount of energy used in production of cement for class 2 and class 3 concrete for the K7 building. The calculations will include the amount of energy needed to produce 3,000 tons of concrete for the K7 building as well. The first step is to convert the amount of concrete used in the K7 building from tons to m³. Since 1 m³ of concrete equals 2,400 kg of concrete, therefore 3,000,000 kg of concrete equals:

$$X = (3,000,000\text{kg} \times 1 \text{ m}^3)/2,400\text{kg} = 1,250 \text{ m}^3$$

The result shows that 3,000,000 kg of concrete used in the K7 buildings is 1,250 m³.

The second step is to estimate the amount of energy needed to produce 1,250 m³ of concrete. In this calculation it is assumed that both class 2 and class 3 concrete require the same amount of energy for the production. Since 1 m³ of concrete requires 2.7 MJ of energy, therefore 1,250 m³ require:

$$X = (1,250 \text{ m}^3 \times 2.7\text{MJ})/1\text{m}^3 = 3,375 \text{ MJ} = 3.375 \text{ GJ}$$

Based on the calculation, approximately 3 GJ of energy is required to produce 3,000 tons or 1,250 m³ of concrete for the K7 building.

The third step is to calculate the energy used in the production of 1 m³ of cement. On average, 1 ton or 0.66 m³ of cement requires 1.8 kWh of electricity, therefore 1 m³ of cement requires:

$$X = (1.8 \text{ kWh} \times 1 \text{ m}^3)/0.66\text{m}^3 = 2.727 \text{ kWh}$$

The result shows that 1 m³ of cement requires about 2.727 kWh of electricity. Converting the result in kWh to MJ gives the amount of energy required for the production of 1 m³ of cement:

$$2.727 \text{ kWh} = 10.5 \text{ MJ}$$

Based on the calculations, 10.5 MJ of energy is required to produce 1 m³ of cement.

The next step is to find out the energy required to produce cement for both class 2 and class 3 concrete. Since the amount of cement used in class 2 concrete is 0.325 t and 1 ton of cement equals 0.66 m³ of cement, conversion of 0.325 t of cement to m³ gives:

$$X = (0.325\text{t} \times 0.66 \text{ m}^3)/1\text{t} = 0.2145 \text{ m}^3$$

The result shows that 0.2145 m³ or 0.325 t of cement was used in the class 2 concrete of the K7 building. Because 1 m³ of cement requires 10.5 MJ of energy to produce it, 0.2145 m³ of cement requires:

$$X = (10.5 \text{ MJ} \times 0.2145 \text{ m}^3)/1\text{m}^3 = 2.252 \text{ MJ}.$$

Based on the calculations above, 2.252 MJ of energy is required to produce cement in the amount of 325 kg contained in 1 m³ of concrete class 2.

Similarly, the energy used to produce 0.252 t of cement contained in class 3 concrete of the K7 building is calculated. Converting 0.252 t of cement to m³ gives:

$$X = (0.252\text{t} \times 0.66 \text{ m}^3)/1\text{t} = 0.1663 \text{ m}^3$$

The result of the conversion shows that 0.252 t of cement of class 3 concrete equals 0.1663 m³. Because 1 m³ of cement requires 10.5 MJ of energy to produce it, 0.1663 m³ of cement requires:

$$X = (10.5 \text{ MJ} \times 0.1663 \text{ m}^3)/1\text{m}^3 = 1.746 \text{ MJ}$$

Based on the calculations above, 1.746 MJ of energy is required to produce cement in the amount of 252 kg contained in 1 m³ of concrete class 3.

To conclude, this chapter answers several important questions about the environmental impacts of the concrete used in the K7 building, such as: how much cement is needed to produce 3,000 tons of concrete? How much energy was used in the production of 3,000 tons of concrete and 1 m³ of cement? How much carbon dioxide was released during the cement production? What is the electricity and water consumption involved in the production of 3,000 tons of concrete? The results are provided in table 5 below.

Table 5. The results of the calculations for class 2 and 3 concrete.

	Amount of cement required	CO ₂ emissions of cement production	Fresh water consumption of the concrete production	Electricity consumption during cement production (per 1m ³)	Electricity consumption during concrete production
Class 2 Concrete	270 t	270 t	148 t	2,3 MJ	--
Class 3 Concrete	105 t	105 t	52,5 t	1,7 MJ	--
Total	375 t	375 t	200 t	4,0 MJ	3,4 GJ

The quantities of the amount of cement required for class 2 and 3 concrete are 270 tons and 105 tons, respectively. The values for the CO₂ emissions released as a result of the cement production of each of the classes of concrete are the same as the amount of cement required for each of the classes, given that 1 ton of cement produces 1 ton of carbon dioxide. The fresh water consumption of the production of class 2 and 3 concrete is 148 tons and 52.5 tons, respectively. The values of electricity consumption in cement production for class 2 and 3 concrete are given for 1 m³ and are 2.3 MJ and 1.7 MJ, respectively.

5.3.4 Carbon dioxide emissions

Due to the fact that the production of 1 ton of Portland cement, which was used at the time when the K7 building was constructed, produced approximately 1 ton of CO₂ and according to the calculation results above, the following results were obtained: 270 tons of cement, required to produce 2,000 tons of class 2 concrete, release 270 tons of CO₂, whereas 105 tons of cement, required to produce 1,000 tons of class 3 concrete, release 105 tons of CO₂.

In this thesis the carbon dioxide emissions released by the cement production only are considered. Due to unavailability of data it was not possible to calculate the carbon dioxide emissions for the concrete production too.

5.4 Life Cycle Interpretation

The water-cement ratio and mixture ratio are the important criteria in the calculation of the amount of cement and water used for the studies K7 building. Since the actual records of such aspects as the amount of water, cement and electricity used to construct the K7 building are not widely available, the calculations are partially based on the data from archives and partially on assumptions. Therefore, the results are estimates of the minimum values and the real values were most probably higher.

The results of the concrete LCA for the studied K7 building are shown in table 6.

Table 6. LCA results for the K7 building

Type of resources used and emissions released	Amount
Cement	≥ 375 t
CO ₂	≥ 375 t
Water	≥ 200 t
Electricity	≥ 3.4 GJ

Because cement plays one of the biggest roles in a concrete mixture and its percentage among the man-made materials used in concrete is the highest, other additives were not considered in the calculations. In addition, the calculations do not consider emissions of carbon dioxide released during the transportation of concrete panels, water needed to wash the concrete trucks, and other related processes.

According to the Government of Moscow, all type concrete panel buildings are demolished in a smart way, that is, the construction waste is sorted and then recycled [20]. The studied K7 building belongs to the group of buildings being demolished in Moscow, therefore the information is applicable to it, too. Thus, the concrete used for its construction is recycled and reused. A major benefit of concrete waste recycling is the reduction of raw materials needed to produce new concrete buildings, which are to replace the old buildings around Moscow.

The influence of concrete used in the studied K7 building is assessed according to the following scale on the basis of the level of hazard to the environment and humans: 1 – low, 2 – medium, 3 – high. Table 7 below demonstrates the hazard levels of each of the LCA outcomes.

Table 7. Levels of hazard to the environment of the LCA results.

	1 – low	2-medium	3 - high
CO2 emissions			✓
Water consumption		✓	
Electricity consumption			✓

Based on the estimation that 1 ton of cement produces 1 ton of carbon dioxide released into the atmosphere, the hazard level of the calculated carbon dioxide emissions is judged as high. The 1960's, when the K7 building was built was the era of the industrial building construction, and Portland cement was used to produce concrete in large amounts. Although Portland cement is nowadays considered to be the least environmentally friendly cement and avoided, it was the most widely available good quality product at the time.

The hazard level of the water consumption of the concrete production for the K7 building is judged as medium, due to the fact that the amount of water used in concrete production depends on the water-cement ratio – 0.50-0.55 in the case of the K7 building.

The hazard level of electricity consumption in the construction of the K7 building is judged as high due to the fact that vast amounts of electricity was spent on the production of the 1,250 m³ of concrete for the K7 building. What is more, large amounts of electricity were used at every stage of the concrete production. However, the use of recycled materials could minimize the amount of electricity needed in the production process.

During the lifetime of the K7 building, its concrete structure required no special maintenance and, therefore, no emissions were released during the utilization period of the building. Most of the emissions are related to production of concrete for the building and to its demolition. The data on the emissions related to the demolition is not

considered in this thesis, because it is not widely available. A summary of the LCA for 1 m³ of concrete of classes 2 and 3 used in the K7 building is provided in tables 8 and 9 below.

Table 8. Summary of the LCA for 1 m³ of class 2 concrete of the K7 building.

INPUTS	LCA phase	OUTPUTS
Excavation - neglectable	Raw materials and cement production	Dust emissions - neglectable
		Destruction of ecosystems
2.3 MJ of energy		Gas emissions – no data available
<hr/>		
325 kg of cement	Concrete production (1 m ³ class 2 concrete)	325 kg of CO ₂ released
1.32 t of water		Wastewater
2.7 MJ of energy		Other gas emissions – no data available
<hr/>		
Transportation emissions - neglectable	Construction and utilization	Solid waste
Energy – no data available		Gas emissions – no data available
<hr/>		
Energy - neglectable	Demolition (1 m ³ of class 2 concrete)	Dust emissions
		Solid waste
<hr/>		
Concrete waste separated from steel	Recycling	Aggregate
Energy - neglectable		Gas emissions

The summary does not include any data on the amount of energy used in the construction and utilization phases, or the demolition phase due to unavailability. However, it can be assumed that the energy is neglectable. The main focus was drawn to the raw materials and manufacturing phases because these phases have the major

impacts on the environment due to a large number of processes involved and large energy consumption, and, consequently, carbon dioxide emissions. Due to a close location of the concrete factory where all of the concrete panels were made for the K7 building, the emissions related to transportation are neglectable.

Table 9. Summary of the LCA for 1 m³ of class 3 concrete of the K7 building.

INPUTS	LCA phase	OUTPUTS
Excavation - neglectable	Raw materials of cement production	Dust emissions - neglectable
1.8 MJ of energy		Destruction of ecosystems
		Gas emissions – no data available
252 kg of cement	Concrete production (1 m ³ class 3 concrete)	252 kg of CO ₂ released
1.24 t of water		Wastewater
2.7 MJ of energy		Other gas emissions – no data available
Transportation emissions - neglectable	Construction and utilization	Solid waste
Energy – no data available		Gas emissions – no data available
Energy - neglectable	Demolition (1 m ³ of class 3 concrete)	Dust emissions
		Solid waste
Concrete waste separated from steel	Recycling	Aggregate
Energy - neglectable		Gas emissions - neglectable

To sum up, the weak aspects of the LCA of the K7 building are mainly concentrated in the raw material and cement production phase and concrete production phase. The negative impact from these phases could have been reduced if the K7 building was

constructed nowadays by using less concrete, using different cement in concrete production or replacing cement with other materials.

6 Innovative Solutions for Concrete with Reduced Environmental Impact

Since the 1960's when the K7 building was built in Moscow, the methods of concrete production have developed radically and a lot of new types of concrete have appeared on the market. Some of the most modern innovations in the reduction of environmental impacts of concrete are based on concepts of replacing Portland cement with other cements or materials that require less energy for production, and on the absorption of carbon dioxide by concrete. Examples of such innovative solutions for concrete are described below in chapters 6.1 and 6.2.

Already the improvements made in the industry are rather significant. Due to the advancement in energy-efficiency of modern power stations and the introduction of waste as fuel for power stations, the typical amount of carbon dioxide release per ton of cement has decreased by 18% in a period of a few decades. [21.]

6.1 Organic concrete

Back in 2005 a group of Portuguese designers and architects developed “organic concrete” (betão organico) which combines organic and nonorganic materials. The innovative mixture of the hybrid concrete allows for tiny plants like grass to grow on its surface. The ability of the organic concrete to retain water inside it maintains plants growing on its surface, especially during dry periods. [21,11.]

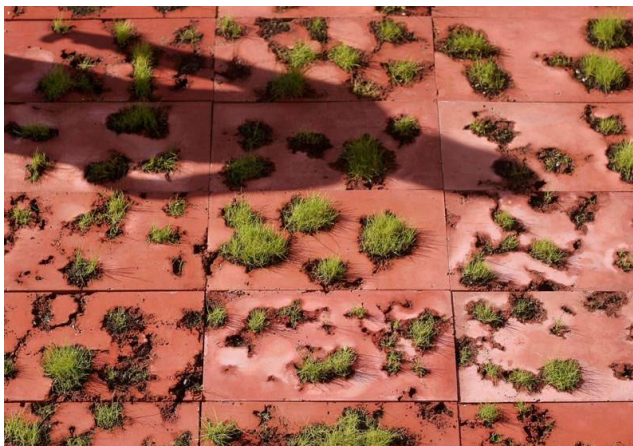


Figure 6. Grass growing on the organic concrete roof top. [22.]

The organic concrete could change any city dramatically: the usage of this innovation for roofs and elevations of buildings could introduce extra greenness and sustainability. Plants growing on green roofs (figure 6) and elevations would partially absorb carbon dioxide from the outside air, which would work best for large cities, where the percentage of nature is reduced almost to a minimum. What is more, it is an ideal solution for cities with dense development where not much space is left for green areas like parks. Furthermore, green roof terraces could play a positive role in sustainable community development.

6.2 Porous concrete

One of the most interesting innovative concrete types is Porecocrete, porous concrete developed by an Australian company, TecEco. The product is an ecological concrete composite based on eco-cement, which is able to absorb carbon dioxide from the environment, also developed by TecEco. Moreover, due to the presence of large amount of pores in the concrete, it is able to retain cool and it is more preferable during hot weather than concrete based on Portland cement. [21,12.]

The most important ingredient in the porous concrete is chemically active dead burnt magnesia. The addition of magnesia to the concrete mixture initiates the regular absorption of carbon dioxide and water followed by concrete hardening. Other additives beneficial for the ecological concrete besides magnesia are, for example, fly ash, slag,

plastic, that do not affect the ability to absorb carbon dioxide. Porous concrete, in turn, may become the main end product of eco-cement. [21,12.] Figure 6 below demonstrates the emissions of carbon dioxide per kg of different types of cements.

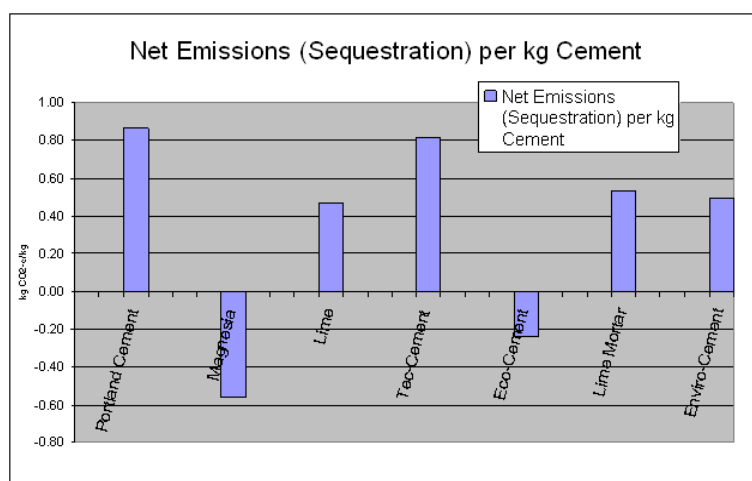


Figure 7. Comparison of CO₂ emissions released by various concretes. [23.]

As seen in figure 7 above, magnesia and eco-cement are completely carbon neutral, whereas Portland cement and Tec-cement are approximately on the same level of 0.85 kg CO₂ per kg of cement. In addition, lime, lime mortar and Enviro-cement are also on approximately same level of 0.50 kg CO₂ per kg of cement.

According to experts, the main sector where Poreconcrete will be used in the close future is various road applications like pedestrian lanes and sidewalks. However, perhaps in a bit further future it will be adapted in building construction, or, perhaps, it is already possible to use Poreconcrete for external walls of buildings.

7 Conclusions

Concrete production is a rather complicated and demanding process. It involves a lot of processes from the production of cement to the mixing of the concrete mixture. Each of the stages influences the technical properties of the future concrete, such as the compressive strength, durability, and permeability. The right performance of the

processes in the necessary order can save the wet concrete mass from separation, and, consequently, loss of the essential technical properties of hardened concrete.

A K7 building located in Moscow was used in order to estimate the amount of carbon dioxide released during the production of concrete for the building, as well as the amount of water and electricity consumed by the process. The method used in the study is LCA, and it usually considers the harmful influence of every stage of a process on the environment. However, because the LCA is a rather modern tool for environmental assessment, not all of the stages of concrete production for the K7 building were considered in the thesis due to absence of data. Therefore, the LCA was based on the production stage of the concrete's life cycle only. The results of the LCA show a high level of carbon dioxide emissions, 375 t, medium level of water consumption, 200 t, and a high level of electricity consumption, 3.4 GJ. Based on the results of the LCA, it can be said that the industrial construction of K7 buildings has influenced the environment in a significant way, especially considering that K7 buildings were designed for a lifetime of 25 years.

Considering the suggested innovative solutions for concrete, the negative impact of concrete production can be reduced dramatically. Both solutions, organic concrete and porous concrete are based on innovative cements used in their mixtures. Replacing Portland cement with eco-cement containing for example magnesia, fly ash, or slag, leads to lower energy required during the production process, and, therefore, to a reduction in hazardous emissions of carbon dioxide and other gases.

Both of the innovative solutions discussed above, organic concrete and porous concrete, are implementable in practice and can even be used in tandem. However, the innovative concretes cannot be used in all structural elements of buildings, such as load bearing structures like foundations, columns and beams. On the other hand, considering the amounts of concrete used to construct an average residential building like the K7 studied in this thesis, the use of either one of the innovative solutions mentioned above could make a significant difference in the CO₂ emissions since the difference in the amount of CO₂ emissions per ton of cement between Portland cement and eco-cement is approximately 800 kg, which is a considerable amount on the large scale.

In conclusion, the aims set at the beginning were reached. The process of concrete production was studied including the stages of concrete production, emissions and the consumption of water and energy were estimated for the sample case of the K7 building demolished in Moscow, and innovative solutions available for use were provided.

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