Ecological and economic impact of an innovative bioproduct used to consolidate the concrete elements of hydrotechnical constructions

C Sbirlea¹, D N Isopescu¹, D Ungureanu¹, S G Maxineasa¹
¹ “Gheorghe Asachi” Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Civil and Industrial Engineering, 1, Prof. Dr. docent Dimitrie Mangeron Blvd., Iasi, 700050, Romania

E-mail: catalin_sbirlea@yahoo.com

Abstract. The present paper takes into observation the evaluation of the environmental and economic impact of a innovative bioproduct that can be used in order to reduce the volume of rehabilitation works needed during the life cycle of different structural reinforced concrete elements utilized for hydrotechnical constructions. In order to determine the performances of the analysed material, seven scenarios that imply the use of different rehabilitation solutions have been considered. In order to achieve the goal of the study, the Cradle-to-Gate Life Cycle Assessment type of study was used. The amount of materials, the distances from the extraction point to the site of the materials and the implementation technology are detailed in all proposed scenarios. In recent years, researchers carried out various studies on the use of raw materials in different compositions, with different quantities, in order to improve the sustainability and mechanical characteristics of constructions, as well as to increase the users’ level of satisfaction. The research and development of new types of materials that can be used in the construction sector with a low ecological influence will have a tremendous positive impact over the present state of the natural environment. The authors conclude that by considering the resulted values, the analysed solution based on the use of calcium carbonate can be considered a suitable solution with respect to the environmental and economic dimensions of sustainability.

1. Introduction
In the last decades, the needs and demands of the ever-growing global population have significantly increased the need of developing new solutions in order to reduce the global environmental impact. Taking into account the fact that the construction sector is considered one of the most pollutant economic activities, it is required that civil engineering specialists develop new materials and structural solutions in order to significantly reduce the negative influence of the built environment over the natural one. Therefore, the development of innovative materials that increase the physical and mechanical performances of the constructive elements of hydrotechnical works should be analysed from an ecological point of view [1-4]. It is important to note that it is increasingly required for a new material to have both good results in laboratory tests, from a physical and mechanical point of view, as well as a low environmental impact.

Taking into consideration the importance of hydrotechnical constructions, the development and use of new materials which have self-healing properties and which can be used for increasing the lifespan of these structures should be considered as extremely important in the construction sector. Currently, specialized personnel closely check hydrotechnical constructions with a high degree of importance through various methods, with the goal of preventing but also providing prompt intervention in case it is necessary. Hydrotechnical works are a crucial part of our development, seeing as they directly influence water quality and protection against flood phenomena. At the same time, besides the fact that these structures consume tremendous amounts of traditional building materials that have an
important environmental impact, they are also responsible for negatively affecting the natural aquatic ecosystems. Thus, it is paramount to take under observation various solutions that can help reduce these negative impacts.

In the last years, the number of tools that can be considered in order to correctly assess and interpret the environmental impact of a product or of a service has significantly increased. For example, there are different software applications like GaBi Software (PE International, Germany), openLCA (GreenDelta GmbH, Germany), Sima Pro LCA (PreConsultants, The Netherlands), that can enable a correct environmental impact analysis for different stages of the life cycle of a product. In order to use the tools, the specialist must take into consideration the Life cycle assessment (LCA) methodology. In order to determine the impact on the environment, LCA studies help identify the flow of materials as well as the energy and waste of a product over its life cycle [5]. Depending on the stages from the life cycle of a product used in an analysis, there are different type of LCA, such as Cradle-to-Gate; Cradle-to-cradle; Gate-to-Gate [6, 7]. Taking into account the above, the goal of the present study is to analyse a solution, with respect to the environmental and economic dimensions of sustainability, based on the use of calcium carbonate in order to achieve self-healing properties for reinforced concrete (RC). The environmental and economic performances of the considered bio base product are compared with those of different other rehabilitation solutions. Both the assessment of the impact over the natural environment and the economic influence are determined and compared from a Cradle-to-Gate point of view. The ecological performances are determined by using the GaBi software.

2. Definition of the bioproduct

The bioproduct, shown in Figure 1, is made of micronized calcium carbonate (CaCO₃) powder which is subsequently granulated in small sizes (2-6 mm), being strongly reactive with water. On the outside, it is protected by a layer of paraffin (1/2 of the bioproduct) that prevents CaCO₃ from reacting with water in the mixing process. Paraffin is a solid, white substance used as a raw material in various industries, with a melting point between 52°C and 54°C.

The chemical composition of the bioproduct [8] expressed in percentages is presented in Table 1. The bioproduct is added to the concrete composition in various quantities compared to the amount of cement and has the role of providing stable bonds at the molecular level, thus sealing the micro-cracks that may occur during operation. Calcium carbonate is widely spread in nature in the form of minerals (calcite, aragonite, vaterite), in bones, teeth, shells, corals and shellfish crust [9]. In rocks, it comes in the form of limestone, where it is almost pure, an example being the dolomites, which are a mixture of calcium and magnesium [9].

![Figure 1. Bioproduct.](image)

| Chemical composition of granular bioproduct | Amounts (%) |
|--------------------------------------------|-------------|
| Calcium carbonate (CaCO₃)                  | 91%         |
| Magnesium carbonate (MgCO₃)                | 2%          |
| Paraffin ½ from bioproduct                 | ~ 47%       |
3. Cradle-to-Gate LCA analysis

As stated before, the Cradle-to-Gate LCA type of study has been used in order to determine the environmental impact of the considered construction solutions. This type of study takes under observation the life cycle of a product from the extraction and processing of raw materials (“cradle”) to the factory gate (“gate”), before the assessed product is utilised, as shown in Figure 2. In each stage of its life cycle, a product is responsible for a different impact over the natural environment. These ecological influences can be translated into a high level of negative emissions into the atmosphere, soil and water, or in a certain amount of consumed natural resources [10]. Thus, even if the LCA analysis cannot clearly show that the use of a product or service is safe, it provides a number of indicators, depending on the type of the environmental impact categories considered, in terms of impact assessment scores [5].

![Cradle-to-Gate LCA](image)

**Figure 2.** LCA (Life Cycle Assessment) [11].

Concrete is one of the most widely used materials in the world, being employed in the construction of civil and industrial buildings, hydrotechnical constructions, roads and other types of infrastructure. On average, about 1 tonne of concrete is produced each year for every human being in the world [12]. In recent years, concrete has been subjected to detailed analysis given that this material has a significant impact on the environment. Out of the composition of the aggregates used in its manufacture, cement is responsible for the most important part of the greenhouse gas emissions that are related to the use of concrete. It is considered that at the global scale, the cement industry is responsible for approximately 8% of total CO₂ generated [12]. The scope of the Bio concrete concept is to replace a volume of cement with other materials or to make changes to the composition parameters in its design to obtain a concrete that is sufficiently durable, resistant, and sustainable. It is necessary to make an environmental impact comparison between bio and traditional concrete to clearly identify the ecological efficiency of replacing traditional raw materials that have a high carbon footprint, a toxic impact on humans and an important negative influence over the stratospheric ozone layers, with new materials. Research and development of new raw materials has an important role in our society, seeing as there are many analyses worldwide that show us that nature goes through a continuous process of change, one that is directly influenced by human activities. All these negative influences on nature and climate change are caused by the alarming growth of the global population, which in turn caused the high demand and need for industrialization. Raw material consumption is continuously increasing, endangering the existing natural stocks. Therefore, by adding that the construction sector is one of the most important consumers of natural resources, it can be stated that it is necessary to develop new solutions that will significantly help tackle this environmental problem. In addition to the consumption of large amounts of natural resources and the emission of polluting gases...
into the atmosphere, this sector is responsible for 25% to 30% of the total waste produced in Europe [13].

The Cradle-to-Gate LCA type of study was used in the present paper in order to assess the environmental impact of traditional as well innovative materials used in construction by considering seven scenarios. Table 2 shows the impact categories used to quantify the effects on the environment [14].

| Impact Category         | Description                          | Unit   |
|-------------------------|---------------------------------------|--------|
| Global Warming Potential | GWP                                   | kg. CO2 eq. |
| Human Toxicity Potential | Human toxicity potential, cancer effects – HTPc | CTUh   |
| Ozone Depletion Potential | Ozone Depletion Potential – ODP | kg. CFC 11 eq. |

Table 3. Distances used in the LCA analysis.

| Material                | Distance (km) | Starting point   |
|-------------------------|---------------|------------------|
| Cement                  | 165           | - manufacturing unit |
| Steel                   | 25            | - place of installation |
| Sand                    | 30            | - ballast        |
| Gravel                  | 30            | - concrete station |
| Concrete                | 15            | - concrete station |
| Bioproduct              | 400           | - manufacturing unit |
| Construction lime       | 400           | - place of installation |
| Paraffin                | 400           | - manufacturing unit |
| Fiber fabric of glass /carbon | 1850   | - place of installation |
| Epoxy resin             |               | - place of installation |
Table 4. Recipe for 1 m$^3$ C16/20 concrete used in the LCA analysis.

| Raw material used       | Amounts (kg/m$^3$) |
|-------------------------|---------------------|
| cement I 42.5 R         | 270                 |
| sand 0-4 mm             | 716                 |
| fine gravel 4-8 mm      | 345                 |
| coarse gravel 8-16 mm   | 850                 |
| water                   | 170                 |

Table 5. Primary materials related to the size of the concrete beam 120 mm x 90 mm x 1500 mm.

| Raw material used       | Amounts (kg/m$^3$) |
|-------------------------|---------------------|
| cement I 42.5 R         | 4.4                 |
| sand 0-4 mm             | 11.6                |
| fine gravel 4-8 mm      | 5.6                 |
| coarse gravel 8-16 mm   | 13.8                |
| water                   | 2.8                 |
| steel reinforcement     | 1.8                 |

4. Evaluation of the environmental impact

4.1. Scenario 1

The present scenario entails the determination of the ecological impact resulted from the replacement of an existing reinforced concrete beam which no longer meets structural requirements with a new linear concrete element Gr.0 (Figure 3). Table 5 presents the type and amount of materials considered for the evaluation. By analyzing Figures 4 and 5, it can be observed that the mixing stage from the life cycle of the assessed product is responsible for the highest impact over the carbon footprint and human toxicity impact category. At the same time, the negative influence over the stratospheric ozone layer is mostly influenced by the steel rebars (Figure 6).

Figure 3. RC beam details Gr.0 in scenario 1.

Figure 4. Global warming potential in scenario 1.
4.2. Scenario 2

In this scenario, in order to fix the cracks on the surface of the Gr.1 concrete beam, an M100T mortar was used; the quantities of materials are mentioned in Table 6.

| Secondary materials   | Amounts (kg/m³) |
|-----------------------|-----------------|
| cement II AM 32.5 R   | 2.19            |
| sand 0-3 mm           | 0.052           |
| hydrated lime         | 0.599           |
| water                 | 0.502           |

The first step was to clean the crack with a spatula and wire brush. After removing the residue from the damaged surface and vacuuming the surface, the area was moistened to attach the filler. After the preparation of the mortar, with the help of the spatula, it is applied on the entire surface of the damaged element, as well as finishing layer (Figure 7). By analyzing Figures 8, 9 and 10, it can be observed that the amount of cement consumed is significantly influencing the environmental performances in all three considered impact categories.
Figure 9. Human toxicity potential in scenario 2.

Figure 10. Ozone Depletion Potential in scenario 2.

4.3. Scenario 3

In this scenario, the percentage of bioproduct is 10% of the mass of cement (Figure 11). The materials were dosed and then mixed until the desired consistency was obtained. Before casting, the moulds were prepared by cleaning and lubricating with stripping oil. The casting was performed in several layers, after the first layer the reinforcement was introduced, and the continuation of the casting was performed in small quantities by vibrating the mould. The quantities of materials used in this scenario are presented in Table 7. By analysing the resulted values, it can be observed that in the case of the GWP and HTPc indicators, the amount of paraffin has the highest environmental impact, while in the case of ODP impact category, calcium carbonate is responsible for more than 99% of the total negative effect.

Table 7. Quantities of materials used in scenario 3.

| Secondary materials | Amounts (kg/m³) |
|---------------------|----------------|
| Bioproduct          | 0.437          |
| Paraffin            | 0.219          |

Figure 11. RC beam Gr.2 with 10% bioproduct in scenario 3.

Figure 12. Global warming potential in scenario 3.
4.4. Scenario 4

The LCA analysis was performed by taking into account the use of 20% bioproduct compared to the cement mass. The installation technology is the same as explained in scenario 3, the difference being the percentage of used bioproduct (Figure 15). The quantities of secondary materials used in this scenario are mentioned in Table 8. As in the previous scenario, in the case of the GWP and HTPc impact categories, the amount of paraffin used has the highest negative influence, while the CaCO3 has the most important impact in the case of the last considered environmental indicator (Figures 16, 17, 18).

Table 8. Quantities of materials used in scenario 4.

| Secondary materials | Amounts (kg/m³) |
|---------------------|----------------|
| Bioproduct          | 0.875          |
| Paraffin            | 0.437          |

Figure 13. Human toxicity potential in scenario 3.

Figure 14. Ozone Depletion Potential in scenario 3.

Figure 15. RC beam Gr.3 with 20% bioproduct in scenario 4.

Figure 16. Global warming potential in scenario 4.
4.5. Scenario 5

In this scenario, EPOMAX-L20 [15] was used, a two-component, injectable epoxy resin, used to repair cracks of 0.1-1.0 mm, with a consumption of about 1.1 kg/litre. The quantities of secondary materials used to repair cracks in the Gr.4 concrete beam are presented in Table 9.

| Secondary materials | Amounts (kg/m³) |
|---------------------|----------------|
| epoxy resin         | 0.111          |

After removing the degraded material with a spatula and a wire brush, the cracked surface was vacuumed. The epoxy resin was injected into the cracks using a special device. After hardening, this surface was cleaned of excess material as shown in Figure 19. In Figures 20 and 22, it can be noticed that epoxy resin has the most important carbon footprint and the highest negative effect over the stratospheric ozone layer. At the same time, the amount of diesel consumed accounts for almost 89% of the total negative impact over human health (Figure 21).

Figure 17. Human toxicity potential in scenario 4.  
Figure 18. Ozone Depletion Potential in scenario 4.

Figure 19. Injection of epoxy resin into cracks.  
Figure 20. Global warming potential in scenario 5.
4.6. Scenario 6
This scenario analyses the impact on the environment resulted from using fiberglass fabric to strengthen the concrete beam Gr.5 (Figure 23). Glass fabric type E-Glass [16] with a width of 100 cm was applied on the entire beam by using EPOMAX-LD [17], an epoxy resin that has a consumption of 0.7-1.2 kg/m² as specified in the data sheet. The quantities of secondary materials used in this scenario are mentioned in Table 10. Analysing the resulted values leads to the conclusion that epoxy resin has the most important negative effect over the natural environment in all considered environmental impact categories.

Table 10. Quantities of materials used in scenario 6

| Secondary materials | Amounts (kg/m³) |
|---------------------|----------------|
| fiberglass fabric   | 0.047          |
| epoxy resin         | 0.288          |

Figure 21. Human toxicity potential in scenario 5.
Figure 22. Ozone Depletion Potential in scenario 5.

Figure 23. RC beam with fiberglass fabric in scenario 6.
Figure 24. Global warming potential in scenario 6.
4.7. Scenario 7

The last considered scenario assesses the impact resulted from using carbon fiber fabric for strengthening concrete beam Gr.6 (Figure 27). The MEGAWRAP-200 carbon fiber [18] with a thickness of 0.11 mm and a width of 60 cm has been applied on the entire beam by using the EPOMAX-LD [17] epoxy resin. Table 11 presents the amounts of materials considered. By analysing the resulted values, it can be observed that in the case of the HTPc environmental impact category, carbon fibers have the most significant influence (Figure 29). At the same time, the overall impact in the case of the other two environmental indicators is mainly produced by epoxy resin.

Table 11 Quantities of materials used in scenario 7.

| Secondary materials          | Amounts (kg/m³) |
|------------------------------|----------------|
| carbon fiber fabric         | 0.054          |
| epoxy resin                 | 0.288          |

Figure 27. RC beam reinforcement with carbon fiber fabric.

Figure 28. Global warming potential in scenario 7.
4.8. Comparing the environmental performances

By analysing the resulted values, presented in Figures 31, 32, and 33, it can be observed that:
- in the case of the Global Warming environmental impact category, the results reflected by the use of 10% calcium carbonate represent the most suitable application, followed by the
solutions studied in scenario 2 and 4;
- for the Human toxicity potential, cancer effects environmental indicator, the new reinforced concrete element and the use of the analysed bioproduct have the highest negative impact over human health, followed by the solution considered in the last scenario;
- the values resulted in the last environmental impact category show that the solution which entails repairing works from the first scenario has the lowest impact over the stratospheric ozone layer, closely followed by the use of 10% and 20% of bioproduct.

5. Evaluation of the economic impact

In this chapter, the authors have analysed, from a financial point of view, the sustainability of the materials used in the considered scenarios. The economic analysis was performed only in terms of material costs, the cost of labour not being included. Both the dimensions of the concrete beams of class C16/20 (120 mm x 90 mm x 1500 mm) and the quantities used are the same as in the case of LCA studies. By analysing Figure 34, it can be stated that:
- in scenario 1, the total replacement of the degraded beam was established. In order to compare the costs resulted in the other six scenarios, the authors decided the value achieved in this case to be considered as reference;
- in scenario 2, the costs of the repairing works of the considered cracks of the linear RC element only represent 17% of the value resulted in the first scenario;
- in scenarios 3 and 4, the bioproduct was used in a proportion of 10%, respectively 20%, and the resulted costs account for only 20%, and 39% respectively, of the cost resulted in the case of building a new RC element;
- the injection with two-component epoxy resin that was analysed in the fifth scenario implies costs that are higher by about 18% compared with the ones from the first scenario;
- the use of fiberglass and carbon fabrics on the entire surface of the concrete beam were considered in scenarios 6 and 7. By analysing Figure 31, it can be observed that in both considered scenarios, the strengthening schemes are more expensive then the solution from scenario 1 by approximately 114%.

6. Conclusions
The goal of the present study is to assess if the use of calcium carbonate can be considered a sustainable solution with respect to the environmental and economic dimensions of the sustainable development concept. This bioproduct is considered to achieve self-repairing capacity for the
reinforced concrete products, mostly for those elements that are used in hydrotechnical constructions. The assessment of the environmental performances of the considered construction products has been completed by using the Life Cycle Assessment methodology from a Cradle-to-Gate perspective, the studies having been performed by using the GaBi software. As shown in the present study, the use of bioproduct represent a solution that has a low impact over the natural environment.

The economic assessment has revealed that the solutions studied in scenarios 2, 3, and 4 are the only ones which imply costs lower that the ones resulted in the case of constructing a new RC element (scenario 1). By taking into account all the above, it is justified to conclude that the use of calcium carbonate in different reinforced concrete elements with the goal of achieving a self-repairing capacity represents a highly suitable solution that can be successfully used in order to accomplish the main objectives of sustainable development in the construction sector.

7. References

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