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Comparative life cycle assessment study for erosion control application with conventional shotcrete and geomat solutions

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Abstract. Geosynthetic products are used more frequently in civil and environmental engineering applications due to their technological, commercial, and sustainable advantages. However, a quantitative analysis of the sustainability benefits of geosynthetics compared to traditional solutions is rarely conducted in real projects. Traditional engineering design primarily considers function, cost, and safety, while sustainable engineering design also takes into account the impact the design will have on society and the environment. To ensure sustainability in engineering, designers need quantitative tools to evaluate the metrics that can be applied in the design process. One such tool is life cycle assessment (LCA) for evaluating sustainability in engineering designs. The use of polymeric materials in construction projects may not immediately appear to have environmental benefits. However, geosynthetics can significantly reduce the use of other natural construction materials, which more than compensates for any negative impact. Additionally, geosynthetic solutions can reduce global warming potential due to their reduced carbon emissions. Although this topic is less widely discussed outside the geosynthetics industry, it is important for any construction project. Geosynthetic applications reduce carbon emissions and lower non-renewable energy consumption, ozone layer depletion, acidification, and eutrophication. This paper presents the results of a detailed comparative LCA study between a geomat and a traditional shotcrete-based erosion control solution.

1 Introduction

Traditional civil engineering design considers function, cost, and safety primarily, while sustainable engineering design considers the impact the design will have on society and the environment as well. The Brundtland report of the year 1987 by the United Nations World Commission on Environment and Development, coined the term "sustainable development" and defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Therefore, for engineering design to be sustainable, environmental, social, and economic factors must also be incorporated.

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Geosynthetics are increasingly replacing traditional solutions in civil and environmental engineering due to their cost-effectiveness, durability, and sustainability. There are several major geosynthetic applications, including soil reinforcement through the use of geogrid, erosion control through the use of geomat, drainage improvement through the use of geocomposite, lining with a geomembrane, and so on. In the past few years, geomat has gained wide popularity due to its effectiveness in controlling erosion as well as re-vegetating embankments and cut slopes. Geomat solutions are not only beneficial from a technological and commercial perspective but also contribute to sustainability goals.

Generally, geosynthetics offer significant sustainability benefits, however, quantitative comparisons between traditional solutions and geosynthetics are rarely conducted in practice.

As a comparison of sustainability benefits, this paper presents the results of a detailed comparative LCA study for the erosion control application using the traditional shotcrete (Case A) and MacMat R-type geomat (Case B).

2 Life cycle assessment

To ensure sustainability in engineering, quantitative design tools are needed to perform the metrics that can be applied in the design process. Life cycle assessment (LCA) is one such tool for the evaluation of sustainability in engineering designs. LCA involves a complicated methodology for identifying the energy and other resource requirements as well as the environmental impacts associated with every stage in the life cycle of a product, process, or system.

In their current form, sustainable design guidelines are majorly based on the following principles/Guidelines.

- Brundtland report (1987)
- Hannover principles (1992)
- 12 Principles of Green Engineering (2003)
- The Sandestine green engineering principles (2003)

Typically, the LCA study is done by adhering to the requirements of ISO 14040 and 14044 standards. In the present work, the environmental performance of Cases A and Case B is assessed with the following impact category indicators.

2.1 Abiotic Depletion - Minerals & Fossil Fuel

This impact category indicator is related to the extraction of minerals and fossil fuels for any activity, thereby leading to its depletion. It is expressed as 'kg Sb' equivalents of minerals or in MJ equivalents of fossil fuels, due to the extraction activity. The geographic scope of this indicator is on a global scale.

2.2 Global Warming Potential

Climate change is related to emissions of greenhouse gases into the air. All substances which contribute to climate change are included in the global warming potential (GWP) indicator. The potential impact of the emission of one kilogram of greenhouse gas is compared to the potential impact of the emission of one kilogram of CO_2. The geographic scope of this indicator is on a global scale. The period is typically 100 years.

2.3 Ozone Layer Depletion

Depletion of the stratospheric ozone layer is caused by different gases. Due to this, a larger fraction of UV-B radiation reaches the earth's surface, which will have harmful effects on human health, animal health, ecosystems (terrestrial and aquatic), etc. The ozone depletion potential of different gases is expressed as kg CFC-11 equivalent emissions. The geographic scope of this indicator is on a global scale. The period is infinite.

2.4 Photochemical Oxidation

Photooxidant formation is the photochemical creation of reactive substances (mainly ozone), which affect human health and ecosystems. This ground-level ozone is formed in the atmosphere by nitrogen oxides and volatile organic compounds in the presence of sunlight. It is expressed as kg Ethane equivalents per kg emission.

2.5 Eutrophication Potential

Eutrophication includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water, and soil. EP is expressed as kg PO_4 equivalents per kg emission. The time span is eternity, and the geographical scale varies between local and continental scale.

2.6 Acidification Potential

Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, etc. AP is expressed as kg SO_2 equivalents per kg emission. The time span is eternity, and the geographical scale varies between local scale and continental scale.

3 Cases of LCA study

The use of shotcrete for erosion control of soil embankments and cut slopes has traditionally been popular and widespread. The process of shotcreting involves applying concrete at a high velocity to the surface that needs protection. Consolidation occurs as a result of the impact caused by the application. Its hardened properties are similar to those of conventional cast-in-place concrete, but the placement process results in a good bond to most surfaces and rapid or instant installation, especially on complex shapes or forms, such as embankments or cut slopes that have varying inclinations. The thickness and mix design of shotcrete are determined by various factors such as slope angle, slope height, soil type, etc. One of the most common methods of erosion control along a gently sloped road embankment is the application of 10 cm thick shotcrete onto a geotextile-separated surface. Figure 1 shows the typical details of the shotcrete option (Case A) in the LCA study for a 5m high road embankment.
In the past few years, reinforced geomat has gained wide popularity due to its effectiveness in controlling erosion as well as re-vegetating embankments and cut slopes. Reinforced geomats such as ‘MacMat R’ are composites with a three-dimensional mat structure that is embedded into a reinforcement that can be either a double twisted steel mesh or a synthetic geogrid. This composite is comparable to the erosion control properties of a geomat while preserving the reinforcement properties of a synthetic/metallic reinforcement. Vegetation can rapidly grow through the pores of a mat that is covered with a thin layer of vegetative soil.

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Figure 2 shows the typical details of the MacMat R geomat option (Case B) in the LCA study for a 5m high road embankment.

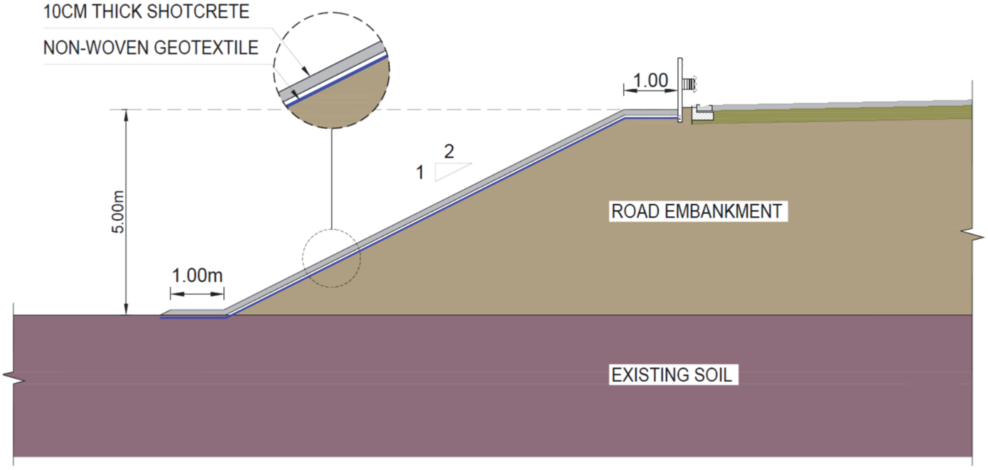

Fig. 1. Typical Details of Erosion Control with Shotcrete (Case A)

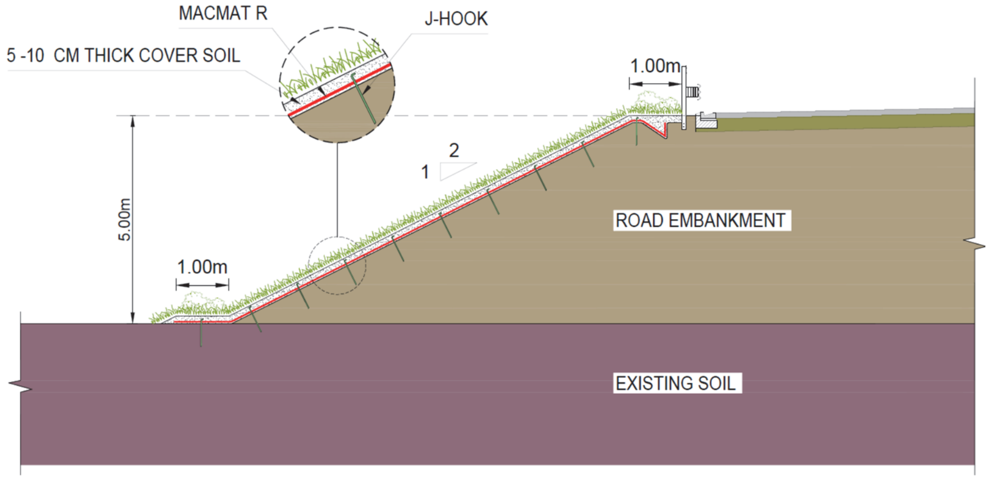

Fig. 2. Typical Details of Erosion Control with MacMat R geomat (Case B)

4 Inputs of LCA study

The following sections detail the inputs, methods, boundary conditions, software, etc. used for the comparative LCA study.

4.1 Process flow diagram

The Simplified process flow chart given in Figure 3 shows the important process steps in the present study. Maintenance, Operation, and disposal after the design life of the erosion control solution are not included in the system boundaries. Processes such as the operation of the storage of raw and geomat materials at the manufacturer's site, packaging of the geosynthetics, etc. are not included in the scope of the study.

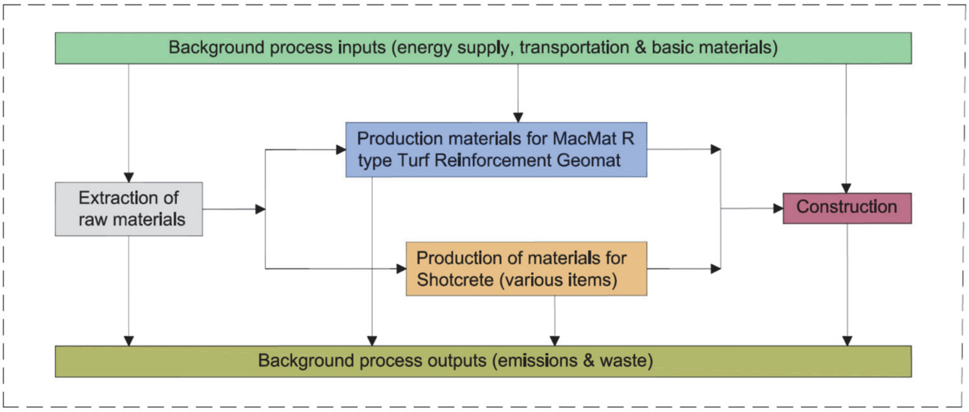

Fig. 3. Simplified process flow chart showing the most important process steps

4.2 Object of study and inventory analysis

The study adheres to the ISO 14040 and 14044 standards. The difference between Cases A and B lies in the solution considered for the erosion control of a typical road embankment as shown in Figures 1 and 2. The main difference lies in the amount of mining of sand and aggregates for shotcrete, manufacturing of cement, its associated energy consumption, and the use of geomat. The software used for the study is SimaPro and the method used for comparison is ReCiPe 2016 MidPoint (H). Table 1 below presents the full list of inputs used in the comparative LCA study. The percentage composition of the MacMat R geomat per 1 kg of the material is obtained from the corresponding EPD (Environmental Product Declaration) certificate, as reported in Table 2. The inputs for obtaining the environmental impacts of various processes in Figure 3 are considered by the SimaPro software from its in-built Ecoinvent database.

Table 1. Inputs for comparative Life Cycle Assessment of Cases A & B

Impact Category	Unit	Case A*	Case B**
Embankment Height	m	5.00	5.00
Embankment Slope Length	m	10.0	10.00
Embankment Length (functional unit)	m	1.00	1.00
Concrete for shotcrete	m3	1.00	-
Geotextile	m2	10.00	10.00
MacMat R Geomat	m2	-	10.00
Cover soil	m3	-	1.00
Steel J hooks	m	-	5.00

**Case A: Shotcrete lining, **Case B: MacMat R Geomat lining.*

Table 2. Percentage composition of MacMat R geomat per declared 1 kg weight

Material	Percentage
Polypropylene	30.47
Master Batch Polypropylene	0.55
Steel	68.98

5 Results and Discussions

The impact assessment was carried out using the ReCiPe 2016 method for unit length of a 5 m high embankment for cases A& B. The conventional solution of applying shotcrete (Case A) causes comparatively higher impacts in all categories (Table. 3) than the method of erosion control with a geomat (Case B). The higher impacts of Case A are caused by the emissions and resource consumption related to the production and transportation of cement, sand, and gravel.

As an example, the increased value of environmental impacts in Case A due to the use of cement can be explained by the production process of clinker. Previous studies have reported that, during the calcination process in clinker production, geogenic CO2 emissions rise significantly. The environmental impacts of sand and gravel are mainly caused by mining machines, the use of electricity during mining, and the energy requirements for transportation from stone quarries to job site. The use of geomat contributes reasonably to the renewable energy demands, due to the use of hydropower for electricity consumed in manufacturing.

Table 3. Summary of comparative LCA study results

Impact Category	Unit	Case A*	Case B**
Abiotic Depletion - Materials	Kg-Sb-eq	9.882	2.749
Abiotic Depletion - Fossil Fuel	MJ	675.110	426.129
Global Warming Potential	Kg-CO2-eq	1120.521	378.176
Ozone Layer Depletion	Kg-CFC11-eq	0.052	0.020
Photochemical Oxidation	Kg-C2H2-eq	273.690	86.650
Acidification Potential	Kg-SO2-eq	101.582	48.333
Eutrophication Potential	Kg-PO4-eq	12.123	0.925

**Case A: Shotcrete lining, **Case B: MacMat R Geomat lining*

6 Conclusions

In this paper, LCA studies are conducted on two types of erosion control solutions. Using shotcrete application and geomat to control erosion are considered Case A and Case B, respectively. According to the study, the following conclusions can be drawn.

- The environmental impacts of the geomat-based solution are lower than the conventional solution.
- Geomat-based erosion control technique eliminates cement, gravel, and sand, which greatly reduces environmental impact.
- Some environmental benefits of the geomat-based solution are offset due to the renewable energy demands arising from the use of hydropower for electricity consumed in manufacturing.

The LCA comparative study in this paper demonstrates how increased sustainability benefits can be achieved with a geomat-based solution for typical road embankment or cut-slope applications in comparison to the conventional shotcrete-based solution.

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