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Environmental Impact of a Reinforced Geosynthetic Retaining Wall Made of Modular Vegetated Concrete Blocks

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Abstract— **Thetechnique of geosynthetics-reinforced soil mass, which associates a modular concrete block facing, intends to create retaining walls while masking their concrete appearance. This is achieved through a process that allows for wall vegetation and irrigation, thus safeguarding the greening of the construction. Despite the many advantages of this technique, it remains underutilized by designers in North African countries. This paper aims to present this technique, focusing first on its objectives, advantages, and implementation processes. Secondly, it aims to showcase some results from an environmental study of a reinforced geosynthetic retaining wall (RGRW). The main goal of this environmental study, which is based on a life cycle assessment (LCA), is to compare two different types of retaining walls: the RGRW with modular block facing and a conventional reinforced concrete retaining wall (RCRW). The findings indicate that the RGRW type of wall exhibits a considerably reduced environmental impact in comparison to the typical wall. Specifically, the cumulative energy demand (CED) and carbon dioxide (CO2) emissions of the RGRW are significantly lower than those of the conventional wall.**

Keywords— Retaining wall, Life cycle assessment, Cumulative energy demand, Carbon dioxide emissions.

I. INTRODUCTION

Sustainable development has emerged as a pivotal concern in political decision-making and scientific research, with the primary objectives being energy conservation and a substantial reduction in greenhouse gas emissions [1].

The global challenge of reducing energy consumption and combating global warming, primarily caused by CO_2 emissions, is compelling engineers to design and construct structures that are increasingly environmentally friendly [2]-[5]. In this context, geosynthetic materials have gained widespread usage in various civil engineering projects, including foundation stabilization [6]-[7], road construction [8], railroad construction [9], bridge abutments [10], and earth retaining structures [11].

The implementation of RGRW aligns with this challenge by addressing soil stability issues [12] and providing a solution for camouflaging the concrete appearance of retaining walls through wall revegetating [13]. This technique boasts multiple technical, environmental, and economic advantages. It has gained global popularity, primarily driven by economic imperatives tied to growing ecological concerns [14]. However, despite its numerous applications and advantages, the utilization of this technique remains infrequent in Tunisia.

This paper presents the RGRW in detail, highlighting its advantages and implementation procedure. Subsequently, an environmental LCA was conducted, focusing on two environmental impact indicators: CED and CO_2 emissions. It aims to conduct a comparative analysis between RGRW and a conventional wall to identify and quantify the ecological benefits associated with the implementation of RGRW.

II. BACKGROUND

A. *Presentation of the RGRW, advantages, and implementation method*

The RGRW consists of horizontally laid reinforcement geotextiles, a modular concrete block facing, carefully selected backfill, and topsoil [15]. In its operation, the forces resulting from the weight of the backfill, surcharges, and the soil to be supported are transmitted through friction to the geotextiles. The sliding plane (highlighted in red in Fig. 1) induces tension on the geotextiles, which then transfer the forces from the active zone downstream to the resistant area at the back of the massif.

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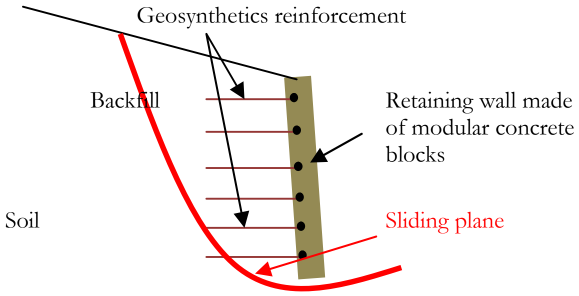


Fig.1Sliding plane

The RGRW presents numerous advantages. Firstly, the wall is dynamic and undergoes transformations with the changing seasons and over the years, as demonstrated in Fig. 2. In order to construct a block wall, a substantial amount of topsoil is required, along with an eventual integrated watering system within the block wings. This facilitates the rapid growth of vegetation, resulting in lush green walls resembling flowerbeds or hanging gardens. Consequently, the topsoil should possess favorable characteristics such as a rich organic content, high porosity, good aeration, excellent water retention capacity, and the presence of microorganisms.

Fig.2Development of vegetation on a RGRW on the A1 highway, Tunisia

Secondly, the wall possesses aesthetic appeal. Vegetated retaining walls are increasingly enhancing the beauty of cities and urban environments, as they offer a natural and visually pleasing aspect. These walls seamlessly blend into their surroundings, disappearing beneath a layer of vegetation. Additionally, they provide flexibility in design, allowing for curved or angular configurations, vertical connections, variable slopes, and the integration of stairs. Furthermore, these walls can be designed to have various appearances, ranging from gray concrete to stone tones.

Furthermore, the construction process for this type of wall is swift and does not require any foundation, as the concrete blocks are laid horizontally on a clean layer of concrete. In terms of material usage, the wall is economical with regards to concrete and steel, as no steel reinforcement is necessary. Additionally, many block designs are fully reusable and recyclable at the end of their lifespan. They can be easily disassembled for reuse or crushed and recycled to create new concrete [16].

Moreover, the geotextiles used for reinforcement exhibit flexible and deformable characteristics with low flexural and tensile stiffness. This flexibility enables the wall to withstand seismic events [16]. By overlapping the geotextile sheets (covering 10% of the sheet length), continuous reinforcement is achieved across the wall's width. The geotextile sheets are horizontally placed in the backfill, aligned with the direction of maximum strength, as illustrated in Fig.3.

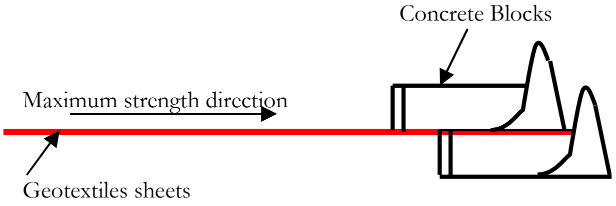


Fig.3Maximum strength direction of the geotextile sheets

The implementation of the RGRW involves several stages [15]:

- Laying a clean layer of concrete: this process starts at the lowest point of the wall. The clean concrete, with a thickness of 10 cm, is spread over an area slightly wider than the first row of blocks. It serves as a reference surface, and its top should be positioned at least 25 cm above the natural ground level (Fig. 4).

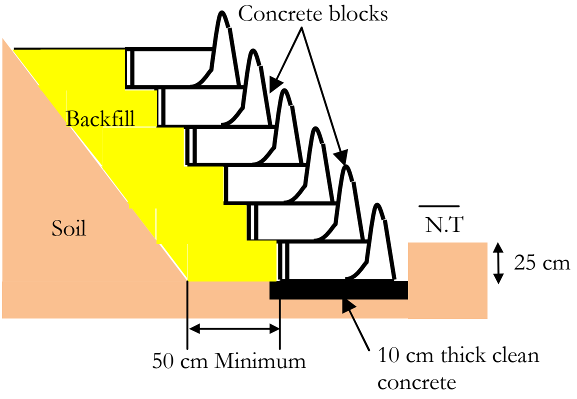


Fig.4Installation details of RGRW

- Laying the first row: The blocks are positioned in a way that maintains a spacing of 35 cm for straight walls.
- Placement and compaction of backfill: The draining backfill material is placed in each row and compacted to achieve 95% of the Optimum Proctor Normal (OPN) density per layer. The width of the draining backfill should be a minimum of 50 cm behind the blocks (Fig. 4).
- Placement of topsoil within the blocks.
- Placement of geotextile layers: It is recommended to have a first layer of geotextile reinforcement above the first row. The reinforcement layers are positioned between the soil layers based on the profile and density of the reinforcement specified in the design documentation. The geotextile sheets are laid horizontally in the direction of maximum resistance, perpendicular to the wall. The length of each sheet matches the width of the backfill.
- Laying the subsequent rows: The installation procedure remains the same for the successive rows. Integrated drip watering is typically incorporated in the notches every two or three rows.

B. Life cycle assessment (LCA)

LCA, a standardized method defined by EN ISO 14040:2006 [17]-[18], is an integral part of the sustainable development concept. It offers an effective and systematic approach to evaluating the environmental impacts associated with the entire life cycle of a product, service, or process.

The LCA is guided by several principles [17]-[18]:

- Comparison of comparable entities: Rather than comparing individual products, the focus is on comparing equivalent functions.
- Utilization of results within the context of assumptions: The findings of an LCA can only be effectively utilized when considering the underlying assumptions made during the assessment.

- Recognition of necessary simplifications: Due to the complexity of the calculations involved, it is essential to identify and acknowledge relevant simplifications made during the analysis.

III. METHODOLOGY

In response to the challenges of sustainable development and to provide reliable information to stakeholders in the construction industry, a study involving LCA was conducted to assess the environmental impacts of the RGRW. Consequently, a comparative analysis was performed between a RGRW and a conventional RCRW.

A. *Functional unit*

In this study, it is crucial to take the height of the wall into account when defining the functional unit for retaining walls. Two specific heights are considered: 3 m and 5 m. For each height, the functional unit is defined as a linear meter of wall.

B. *Wallsdesign*

The design process for both retaining walls was subsequently conducted. In the case of the RGRW, blocks with similar dimensions were utilized for both wall heights. Geotextile reinforcement sheets made of polyethylene terephthalate (PET) were employed. For the RCRW, the quantities of concrete and steel were determined through design software in accordance with the French codes BAEL [19]. These codes enable precise calculations of the amount of concrete required, thus facilitating the assessment of its environmental impact. For the concrete material, a class with strength of 25 MPa was selected for the RCRW design. In the case of the RGRW, the concrete blocks are hollow and spaced at intervals of 35 cm, with an estimated unit mass of 120 kg per block.

The design of the structures was specifically intended for construction on a sandy slope. The soil properties were defined as follows: unit weight of 20 kN/m³, friction angle of 30°, and cohesion of 0. The soil was assumed to be flat on both sides, upstream and downstream. The same backfill soil material was utilized for both walls.

The design life of the walls was established at 100 years.

C. *Life cycle assessment*

LCA is based on environmental indicators, representing the impacts that must be quantified in the study. A good understanding and analysis of these indicators is essential. The main indicators are the cumulative energy demand CED and greenhouse gas emissions, especially CO_2 [20].

To calculate the two environmental indicators, the Ecoinvent 3.3 database was selected as the most suitable database for this study. The Ecoinvent 3.3 database, referenced in [21], is globally recognized for its scientific accuracy and regular updates.

The life cycle of a retaining wall is divided into four phases: material production and transportation, wall construction, wall maintenance, and end-of-life. These phases define the system boundaries for a thorough LCA. An early sensitivity assessment revealed that maintenance may be omitted from the analysis. To simplify the assessments, the environmental implications of end-of-life activities like destruction, transportation to landfills, and recycling were not evaluated. As a result, the boundaries of the life cycle system in this study are stated as "cradle-to-grave," including the time frame up to the completion of the building.

The production phase includes all actions involved in making the building materials required for each wall, from raw material extraction through transportation to the construction site. In the case of the RCRW, ready-mixed concrete, this is manufactured at a facility rather than on-site, is thought to be more cost-effective. The concrete transportation distance was specified at 40 kilometers, encompassing the distance from the production site to the building site. Steel, geotextiles, modular concrete blocks, and topsoil were all transported over the same distance.The data chosen for the two environmental indicators, CED and CO_2, corresponds to a 28-ton truck, which is the most common mode of transportation for this type of construction. It is also believed that local soil might be utilized as backfill, in which case the environmental costs associated with transportation can be ignored.

The construction phase includes all actions associated with constructing the wall at its intended site. These activities might differ based on the type of wall and the materials used to build it. The RCRW building process consists of multiple sequential steps, including earthwork, reinforcement placement, formwork installation for the footing and wall, concrete pouring, and stripping. However, only the environmental impact of mechanical earthwork is considered in this study. According to early calculations, the specific machinery utilized in the other stages has a negligible influence on the total impact of the building phase. All of the aforementioned procedures, with the exception of earthwork, are carried out manually by workers for the RGRW, and hence their environmental implications are ignored.

Table 1 presents the environmental impact factors for CED and CO_2 for each elemental material as well as the transportation and the earthwork [21].

TABLE 1

ENVIRONMENT IMPACT FACTORS FOR CED AND CO_2 FOR ELEMENTAL MATERIALS, TRANSPORT, AND EARTHWORK (FROM [21])

Item	**CED factor**	**CO_2 factor**
Concrete	0.721 MJ/kg	0.0775 kg/kg
Geotextile	95.3 MJ/m^2	5.88 kg/m^2
Steel	14 MJ/kg	0.705 kg/kg
Material transportation over 40 km	3.22 MJ/(km.kg)	0.195 kg/(km.kg)
Earthwork	8.07 MJ/m^3	0.534 kg/m^3

IV. RESULTS ANDDISCUSSIONS

After defining the life cycle stages to be considered in the calculation of the environmental impact, the CED and CO_2 emissions were determined for each wall height in order to compare the environmental impacts of the two walls.

Table 2 summarizes the calculation results. The results demonstrate that the RGRW significantly reduces CO_2 emissions and CED for each wall height. As anticipated, the environmental indicators increase with the increase in wall height for both walls.

TABLE 2

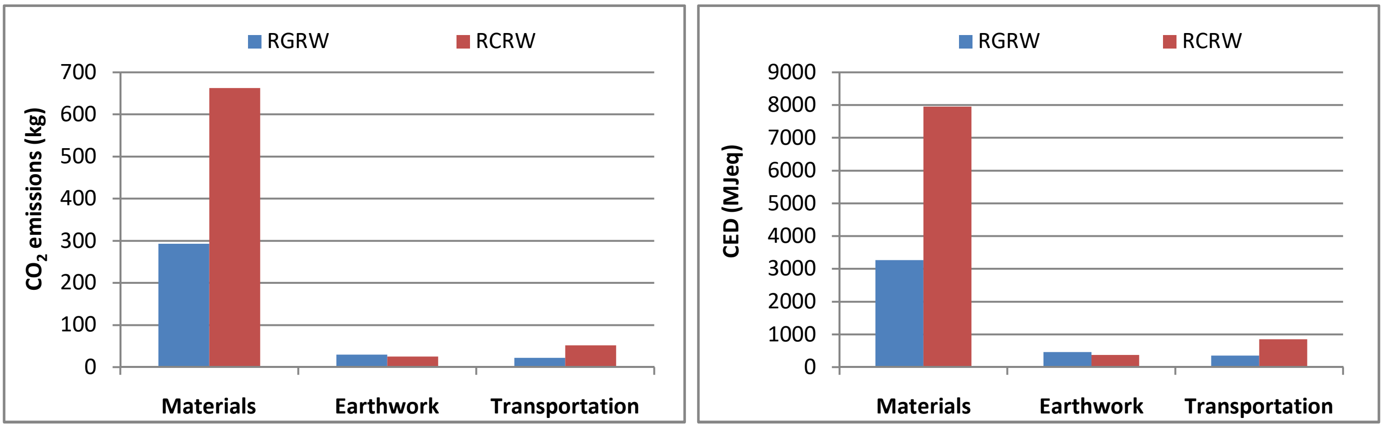
ENVIRONMENTAL IMPACTS OF THE TWO RETAINING WALLS ACCORDING TO THE WALL HEIGHT

Wall type	Wall height	Activity	Quantity	CO_2 emission (kg)	CED (MJ_{eq})
RGRW	3 m	Earthwork	21 m^3	11	169
		Concrete production	1625 kg	126	1172
		Geotextile production	5 kg	29	477
		Transport of concrete blocks and geotextile over 40 km		13	210
		Total		179	2027
	5 m	Earthwork	57 m^3	30	460
		Concrete production	2750 kg	213	1983
		Geotextile production	13.5 kg	79	1287
		Transport of concrete blocks and geotextile over 40 km		22	356
		Total		345	4085
RCRW	3 m	Earthwork	16 m^3	9	129
		Concrete production	3000 kg	233	2163
		Steel production	35 kg	25	490
		Transport of concrete and steel over 40 km		24	391
		Total		290	3173
	5 m	Earthwork	46 m^3	25	371
		Concrete production	6375 kg	494	4596
		Steel production	240 kg	169	3360
		Transport of concrete and steel over 40 km		52	852
		Total		740	9179

The comparison of the contributions of the different phases of the life cycle confirms that material production has the greatest environmental impact on both types of walls. Specifically, in the case of RGRW, for a 3 m wall height, materials account for 85% of the total environmental impact in terms of CO_2 emissions. Transportation and earthwork, on the other hand, contribute only 9% and 6%, respectively, to this impact. A similar trend is observed for RCRW, where material construction has an even greater impact at 90%. The impacts of transportation and earthwork remain relatively lower at 7% and 3%, respectively.

The significant difference in environmental impacts between the two retaining walls is primarily attributed to the higher use of concrete in conventional RCRW, which is known for its relatively high environmental impact. The substantial contribution of concrete to global warming can be explained by the clinker production process, where geogenic CO_2 is released. Furthermore, it is worth noting that the use of geotextiles to reinforce the soil in the RGRW has a lower environmental impact compared to the use of steel reinforcement in the RCRW.

To enhance the interpretation of the results, the values of the two indicators for the different life cycle stages considered for a wall height of 5 meters have been illustrated in Fig. 5. The production of materials used in RGRW leads to 293 kg of CO_2 emissions, which is significantly lower compared to RCRW, with emissions reaching 663 kg, representing a 126% increase. Likewise, for material transportation, CO_2 emissions rise from 22 kg for RGRW to 52 kg for RCRW, indicating a 136% increase. For the earthwork, the values of CO_2 emissions for each wall type are very close. Consequently, RGRW exhibits a 44% and 42% reduction in CO_2 emissions for material production and transportation, respectively. A similar trend is observed for CED, as shown in Fig. 5b. RGRW demonstrates a reduction of approximately 42% in CED for both material production and transportation when compared to RCRW.

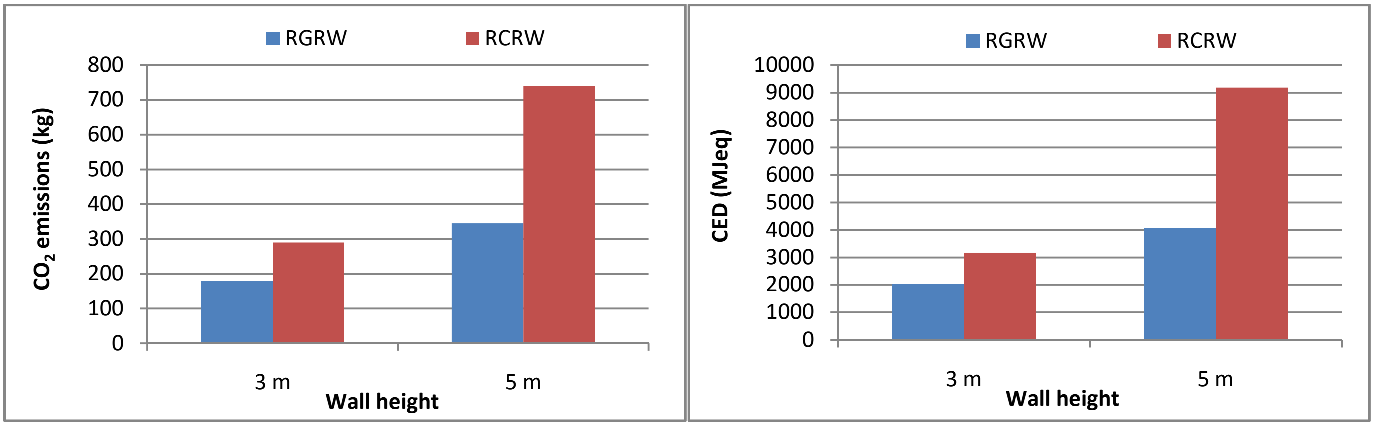


(a) (b)

Fig. 5Environmental impacts of the life cycle stages of the two walls for 5 m wall height: (a) in terms of CO_2 emissions (b) in terms of CED

Fig. 6 presents the total values of the two environmental indicators for the two walls being compared. Increasing the wall height from 3m to 5m led to an approximately 93% and 102% increase in CO_2 emissions and CED, respectively, for RGRW, whereas this increase reached 155% and 189% for RCRW. Once again, this can be attributed to the higher quantity of concrete used in RCRW. The increase is particularly significant for RCRW due to the thicker wall and larger footing dimensions.

Additionally, the results show that in comparison to RCRW, RGRW achieved a 57% and 125% gain in CED, as well as a reduction in CO_2 emissions of 62% and 114% for walls with heights of 3m and 5m, respectively.



(a) (b)

Fig. 6 Environmental impacts of the two walls for each wall height: (a) in terms of CO_2 emissions(b) in terms of CED

V. CONCLUSIONS

The reduction of energy demand and global warming caused by toxic gas emissions is a major challenge for infrastructure engineers.

To assess its environmental benefits, a comparative study was conducted between two retaining wall techniques: the RGRW and the RCRW. The results of the life cycle assessment based on two environmental indicators, namely cumulative energy demand and CO_2 emissions, revealed that material production has the highest environmental impact in both wall systems, accounting from 85% to 90% of the total impact depending on the wall type and wall height considered.

Furthermore, the RGRWexhibited superior sustainability compared to the RCRWmainly due to two key factors: the reduction in concrete demand and the absence of reinforcing steel in the modular block facing. The RGRW achieves 60% concrete savings by utilizing hollow and spaced concrete blocks for wall facing. Since concrete production is associated with high levels of CED, CO_2, and other polluting gases, the significant reduction in concrete usage in the RGRW consistently leads to lower environmental impacts, highlighting the advantage of this technique.

In conclusion, the study's results emphasize the ecological merits of the RGRW, which encourage engineers to adapt this techniqueto make cities more beautiful,to minimize environmental impacts and promote sustainable development.

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