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EARTH AS A BUILDING MATERIAL FOR CONTRIBUTING TO THE CIRCULAR ECONOMY IN THE CONTRUCTION SECTOR

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Abstract
The construction industry is responsible for one third of the total material extraction in the world and is one of the most polluting human activities. Building of new urban areas and public infrastructures requires large amounts of soil excavation, which in turn requires transportation, associated with high carbon emissions and waste management. In the EU, 75% of the waste generated by the building sector is composed of earth. The aim of a circular economy is to eliminate the concept of waste; so, these earths should be considered a valuable resource instead of debris stored in landfills. As a building material, earth is a local, low-energy, low-emission and recyclable construction material, although non-renovable. Moreover, earthen buildings commonly have a high environmental and health quality. In a context of growing scarcity of resources and uncontrolled production of waste, using earth for building is an interesting outlet for the reuse of these wastes. In this paper, the Terra-Cycle project is presented, which aims to quantify the earth from building sites and urban infrastructures excavation, and define the possibilities of reusing it in the manufacturing of products for the construction of buildings. The goals are to create a circular industrial process, and to present the basis for substituting the use of many current conventional building materials with high environmental footprint (such as concrete and ceramic products) by earthen building materials produced locally and on-site.

1. INTRODUCTION
Considering the high impact of the construction sector, being one of the most polluting human activities, it is mandatory to research and analyze new ways of building with alternative materials and systems [1]. After being neglected in part of the 20th century, in the recent decades, earthen architecture has been better valued again due to its efficient properties: as a construction material, earth is a local, low-energy, low-emissions and recyclable resource. Although it is not renewable and commonly non-toxic, almost every country presents abundance of appropriate soils for building, making it one of the most interesting building materials towards the future.

On the other hand, the development of earthen products and constructions systems in the last decades has been notable, with technological developments, regulations and guidelines, and further research analysis [2]–[4], that make it suitable to the modern requirements of the construction industry. However, the current economic system works as a linear process: materials are taken and exploited from the planet, products are manufactured, and finally thrown away when they are not useful. This established model can and should be changed, and this is the reason why circular economy is becoming more important in modern society.

The circular economy, according to the Ellen McArthur Foundation [5], is based on three principles driven by design: eliminate waste and pollution, circulate the products and materials, and regenerate nature. In this sense, it is important to understand the cradle to cradle concept [6], replacing the traditional way of thinking and changing the way of looking at these materials, not as wastes or residues but as resources. In the years to come, it should be possible to build millions of square meters by reusing the earth from excavations of buildings and urban infrastructures, rather than storing it in landfills and waste its potential, contributing to closing the loop of the end-of-life of building materials.

Nevertheless, the earthen construction still has to overcome may barriers, most of them associated to political and socioeconomical aspects rather than the technical ones [7]. In many countries it is associated with poverty and the lower classes, and people mistrust the traditional techniques as they perceive them as unsafe and brittle [8], [9]. But once these the difficulties and obstacles are overcomed, the benefits and potential of this material will be much more valuable. The contribution of earthen construction to circular economy can be spotted from the economic and technological, the environmental and the social perspective (Table 1).

Table 1. Contribution of earth building to meet the requirements of a circular construction model.

Requirements	**Contribution of earthen architecture**
Economic/technological	Abundant material from local extraction and affordable to build with [4], [10]. Developing guidelines and methodologies for quality control [3], [11], [12] Establishing new tools to build with earth [13], [14]. Development of local jobs and companies with traditional and new uses [15].
Environmental	Using the excavation earths as a building material while reducing the exploitation. Producing composite earthen products with other wastes [16]. Profiting from earth contribution to passive indoor comfort [17]. Reducing the ecological footprint of buildings, improving LCA [18].
Social	Cohesion of the members of the community [19], recognizing the important knowledge of old professionals and artisans. Recognition and conservation of traditional building techniques [8], [20], [21]. Increasing social interest on earth buildings and products. Gender equality is reached in activities of formation about earth building.

One of the most adequate techniques to assess and prove the suitability of earthen architecture for the circular economy is the Life Cycle Assessment (LCA), as a methodology to value the environmental impact of a component, system or building. Regarding the LCA, the comparison between the traditional or vernacular buildings and materials against the conventional or modern systems is not a new concept, as several studies that perform analysis which show valuable results for the first ones can be found [18]. The specific LCA on earthen materials have also been reported in many studies, demonstrating the advantage of using the local soils as building materials [22]. Analysis of different techniques can be found, such as adobe masonry [23], rammed earth [24], [25], compressed earth blocks (CEB) masonry [25], cob [26], earthen mortars [27], or even the comparison between different techniques and mortars [28], [29].

The useful life of earthen buildings is long, as examples of constructions that have resisted for centuries can be found [30]–[34]. This vernacular architecture stands out for its durability and adaptation to the local environments and periods of history, finding logical solutions and typologies which imply a really low environmental impact [17]. Precisely, the variety and wealth of techniques makes earth an ideal candidate to substitute many modern industrialized systems; currently, both modern and traditional earthen buildings can be found, encountering this interesting contrast between modernity and tradition (Figure 1).

(a)

(b)

(c)

(d)

Figure 1. Earthen techniques in different contexts: (a) adobe in Oaxaca, Mexico; (b) wattle and daub in Michoacan, Mexico; (c) cob in La Pera, Spain; (d) rammed earth in Rupià, Spain. Source: authors.

2. METHODOLOGY

The project "Terra-Cycle. Excavated soil from urban areas becomes construction raw material" is presented, which offers an innovative and sustainable alternative for the construction sector, reusing and recycling the soil materials from excavations in urban areas to incorporate them to circular economy in the building industry. The project meets the two first basic principles of circular economy, by eliminating waste from soil excavation and by circulating this earth as a building material with a high value.

Terra-Cycle brings together different research fields like architecture, social sciences, geology, industrial ecology and environmental and civil engineering with the common objective of developing research on earth building. It is not possible to impact on the construction industry without including all the actors and experts involved, keeping in mind the environmental footprint of the materials extraction and manufacturing. Terra-Cycle is coordinated by Lleida University (UdL) and includes three sub-projects, where researchers of different European Universities are working together:

- Subproject 1: Circular economy in the earth building and database development of suitable soils (UdL and NOVA research team at the NOVA School of Science and Technology of University of Lisbon).
- Subproject 2: Local production of earth building materials and formative activities (Polytechnic University of Catalonia (UPC) and Gustave Eiffel University).
- Subproject 3: Quality test plan of earth building materials: University of Navarra (UNAV).

The main objective of Terra-Cycle is to incorporate the soil excavation materials of urban areas to the building industry. The high volume of material, the excavation debris in Spain, is estimated at 600 million tonnes for the next twenty years [35]; it is possible to capitalize all these commonly wasted resources for new applications contributing to the acknowledged circular economy. These soils extracted from excavation areas of urban areas, public infrastructures and other construction sites will be transformed into new building products, mainly of the following kinds: compressed earth blocks (CEB), earthen masonry mortars and plastering mortars. Through this process, it will be ensured that all these potential resources (excavated soils) are not wasted, as they can contribute to the production cycle (Figure 2).

Two previous European experiences have developed a process adapted to the existing material instead of seeking the resource adapted to the process. The first one is "Cycle-Terre" project in Paris (France), where the excavated soils from a new underground line construction have been used as earth material to produce locally earthen building products that can be used in the construction of public housing, with the involvement of the public administration. The second one is the Belgian company "BC Materials" [36], which uses excavation soils as earthen materials, thus actively reducing the amount of landfilling (and consequent transportation). The company works on the spot with its mobile production site and recovers the earth where it lies, to transform it into CEB and build where the earth was originally situated.

Two production lines of earthen products will be developed: CEB and earthen mortars for masonry and plastering. The CEB is one of the most researched earthen materials [37], due to its similarity to the ceramic brick and the considerable mechanical behaviour it can achieve. Usually, the CEB incorporate low contents of cement or lime to the mixture as a stabilizer to increase their mechanical properties [38] and resistance to water, as multiple experimentation with different natural and non-natural fibers can be found [39]. Notwithstanding the common use of all type of stabilizers, an optimal design of the granulometric curve of the earth and their content of clays can contribute to achieve adequate mechanical performance [40]. The earth characteristics are also important, including the mineralogical composition of the clays, which act as binding agent of the mixture [41]. This premise matches precisely with one of the goals of Terra-Cycle, as it is expected to achieve the 0 km model and do not rely upon inorganic binder stabilizers or other external materials.

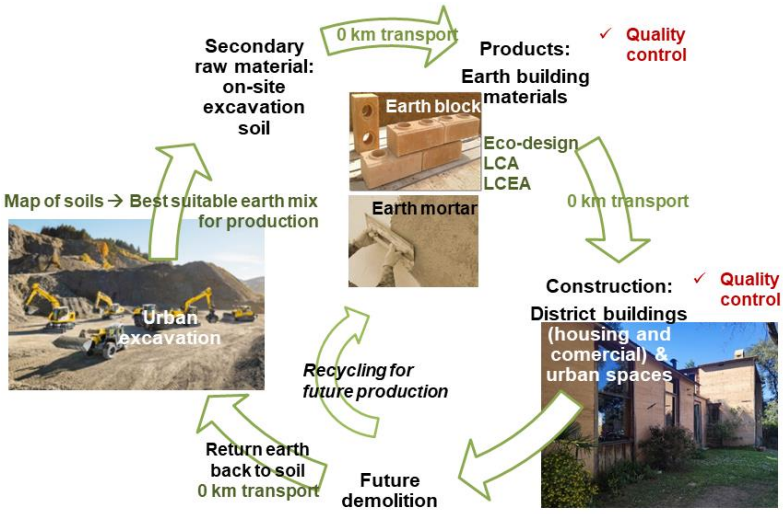

Figure 2. Circular process of earth building, conceptual frame of Terra-Cycle. Source: authors.

On the other hand, earthen coatings have demonstrated to be adequate for different types of wall systems and masonries [42], both on new construction or for the refurbishment of existent buildings. They also provide technical and environmental benefits due to their contribution for passive indoor comfort, low impact and sustainability. Furthermore, in previous cooperation experiences, researchers of the project could apply earthen coatings in adobe masonry buildings (Figure 3), including the participatory design with the communities and the knowledge transfer [43]. In specific contexts this is very important, as the users of the buildings have to deal with the maintenance activities and Terra-Cycle also expects to impact on training activities destined to the construction industry.

Figure 3. Conservation activities of traditional adobe buildings with earthen coatings in Santa Ana Chapitiro, Michoacan, Mexico. Source: authors.

Finally, the application of the project in a real study case is also considered and defined. This circular economy building process will be incorporated within the context of the "Parc de l'Alba" in Cerdanyola del Vallès, a municipality included in the Metropolitan Area of Barcelona, in Catalonia, Spain (Figure 4).

Figure 4. Real case scenario and location: "Parc de l'Alba" in Cerdanyola del Vallès, Catalonia, Spain. Source: https://www.parcdelalba.cat/

3. OUTCOMES AND CONTRIBUTION OF THE TERRA-CYCLE PROJECT

Terra-Cycle is expected to create a circular economy within the contemporary construction industry, with a well-designed inter and multidisciplinar methodology that includes the participation of experts from different disciplines. Besides the main goal of reusing the excavation debris, the project is expected to impact in many ways with the collaboration of the academic institutions, the construction industry, the municipal governments and the society. With the expected outcomes of the project, it will be possible to impact on some of the Sustainable Development Goals (SDG) of the 2030 Agenda, in specific: SDG7 - Affordable and clean energy; SDG9 - Industry, Innovation and Infrastructure; SDG11 - Sustainable cities and communities; SDG12 - Responsible consumption and production. The specific and secondary outcomes and goals of the project will be:

- Defining an innovative circular economic system based on earthen architecture related business.
- Starting a production line for building materials from excavated soil, making available construction materials with very low environmental impact.
- Facilitating the transfer of knowledge on this new sector to other regions of Spain and to other European regions, taking the base case of the Urban Metropolitan Area of Barcelona as an example of good practices.
- Involving local inhabitants in the process.
- Avoiding dumping massive volumes of extracted soil, thus reducing all the associated costs (use of a large number of trucks, fuel consumption, CO_2 emissions).
- Significantly reducing noise and truck traffic, thus improving the living environment for inhabitants.
- Promoting a low carbon urbanization and reversible building.
- Paving the way for new business companies and providing a large number of new jobs locally.
- Designing an industrial system to be easily duplicated and adapted in different sites in Spain and other European regions.
- Increasing public awareness of the benefits of living in earthen constructions: improvements in hygrothermal and acoustic comfort, using products with low ecological impact.
- Teaching earth-based construction techniques.

Regarding the building components produced with the soils obtained from excavations, the CEB and the earthen masonry and coating mortars will be two main products. The extraction material from the case study will be used for the production. The CEB will be applied as non-bearing walls for framing, load-bearing walls for certain buildings, with interior plasters or outdoor use; on the other hand, the mortars will have uses as coating for interior and exterior surfaces, and layering mortars for the earth blocks. The dissemination will take a big role, with the design and application of different training activities, including the architecture and engineering faculties and also the vocational institutes, where these initiatives are less common. The university and academic field present a lot of advantages and assets to research, design and experiment with earthen components and systems (Figure 5), like the CEB and the earthen mortars, and they will serve as valuable platforms and endorsements of Terra-Cycle.

Figure 5. Example of educational and training activities and application to modern building with Compressed Earth Blocks. Source: Bienal de Arquitectura de Chiapas.

4. CONCLUSIONS

Earthen construction is one of the most sustainable ways of building, with the proven experience of vernacular architecture and the adaptation of these typologies to local environments. The current linear economic model needs to change to a circular one because the planet resources are finishing. Precisely these natural materials with low environmental impact could help to reverse the situation. In this context, the Terra-Cycle project proposes a novel methodology involving several fields of expertise understanding that the construction industry feeds from multiple companies and professionals. Finally, the resulting industrial system needs to be duplicated, adapted and implemented to other sites and areas in Spain and other European countries, and eventually to other regions of the world according to the local necessities.

It is important to understand that earthen construction has been neglected for decades, and that the desired change of the industry is not an easy task. Notwithstanding the barriers to overcome, the rewards are huge, and after the fulfillment of the project it is expected to achieve several goals that will help to create a circular and sustainable building model which can be applied in severan European municipalities. By avoiding the dumping of massive volumes of soil, there will be a massive reduction of CO_2 emissions associated to transportation and manufacturing activities, while promoting clean energies and creating local jobs and initiatives that will help to raise awareness of the current challenges. This project will contribute substantially to the transition towards a circular economy of construction industry by:

1) Transforming a construction waste (construction site excavation soil) into building products, what reduces the use of primary raw materials and energy to produce common materials and products, such as raw clays to produce ceramics, stone to produce cement, or aggregates to produce mortars and concrete. It contributes to increase the use and quality of secondary materials (soil excavation), avoiding its dumping.

2) Earth building increases the recyclability rate of walls and coatings, as well as the recyclability of the different materials contained in said products, through the substitution of non-recyclable products and materials (such as cement-based walls and mortars and ceramic bricks).

3) Earth building substantially replaces the content of dangerous substances (such as blast furnace slag present in cement) in bricks and coatings throughout their entire life cycle, in accordance with the objectives set out in EU law, in particular by replacing these substances with compressed earth blocks and earthen mortars, which are safer alternatives, and guaranteeing their traceability thanks to the on-site production (of 0 km).

4) Reducing the generation of construction waste, in soil excavations, public infrastructures and buildings; increasing the development of waste management infrastructure necessary for recycling earth from soil excavation, while ensuring that the resulting recovered materials are recycled as high-quality secondary raw materials in production, avoiding the degradation cycle.

5) The training and transference of earth-based constructions techniques will be one of the most important contributions of Terra-Cycle, working together in capacity building activities intended to primary and secondary schools, professional schools, Universities, constructors and technicians.

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