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Development of a Prefabricated Arched Slab System for a Pedestrian Pathway: A Sustainable Strategy in the Huasco Landscape, Chile

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Abstract

This paper presents a case study on the development of a pedestrian pathway in Huasco, Chile, with the aim of reconciling construction practices with environmental conservation. The study is situated in a context that demands mitigation measures for a mine tailings deposit site. A novel, eco-conscious construction methodology is introduced. Prefabricated arched slabs are a sustainable alternative to traditional foundation blocks. They are specifically designed to minimize disturbance on the region's vulnerable rocky terrain. The methodology involves designing and fabricating an arched slab. This slab is designed to rest on the ground with minimal intrusion, thereby preserving the topsoil. A novel material innovation in this methodology is the partial replacement of cement with mine tailings, reducing the dependency on conventional cement and promoting the recycling of industrial waste. A two-module arched slab prototype has been successfully assembled under controlled laboratory conditions. This prototype serves as an evaluation of the practicality and effectiveness of newly proposed materials and techniques. The concrete mix, which incorporates mine tailings, was assessed, and found to be a structurally sound and environmentally friendly alternative. The article describes the process of designing and fabricating a prototype and highlights the potential of such sustainable practices in contemporary construction methods. It suggests that if these innovative techniques were more widely adopted, they could transform the fields of ecological architecture and landscaping.

Keywords: Sustainable Construction, Prefabricated Arched Slabs, Mine Tailings Reuse, Industrial Waste Recycling, Sustainable Structural Design

1. Introduction

Concrete is the most consumed material in the world after water, and its consumption is increasing; it has been shown that as a country invests in construction, its gross domestic product grows proportionally [1]. Its use is fundamental for the development of humanity, as it is a structurally efficient, durable, and low-cost construction material; however, it is under increasing scrutiny due to the emissions generated by the construction industry [2]. Concrete is made up of four main components: coarse aggregate, fine aggregate, water, and cement. The production of the latter is responsible for 8-9% of global CO2 emissions [3]. The cement production process is based on the calcination of limestone, which releases CO2, in addition to consuming fossil fuels, both in thermal and grinding processes [4]. There has been increasing research and investment in innovations that reduce the use of cement within concrete, using new materials and construction technologies. These alternative materials are commonly known as supplementary cementitious materials (SCMs), and can be waste or by-products from other industries, such as fly ash, from thermoelectric plants, blast furnace slag, from iron and steel refinement, and even mine tailings from valuable metal extraction.

SCMs not only serve to reduce the carbon footprint of concrete, but to modify and improve some of the concrete's properties in fresh and hardened state. They can be used to modify rheology, in applications like self-consolidating concrete, printable concrete, or shotcrete; to enhance mechanical properties, due to the filler effect; and to enhance durability properties.

Chile is a mining country by excellence, positioning it in the world as a leader in the extraction of highly demanded minerals such as copper, molybdenum, iodine and lithium [5]. However, it leaves the country with a growing problem: waste from mining activity. There are three main wastes from metal mining: overburden, which is the sterile material that must be removed to reach the mineral deposit; mine tailings, which are the residue from the separation of the mineral concentrate; and slag, left from the refining and extraction of the metal from the concentrate [6]. Mine tailings are made up of a mixture of ground rocks, water, and minerals, sometimes with the presence of heavy and toxic metals [7]. Globally, mining generates 14 billion tons of mine tailings annually [8]. 600 million cubic meters of the yearly mine tailings production correspond to Chile, where for every ton of fine copper in concentrate, 130 tons of mine tailings are produced [9]. This, together with the risks of catastrophic failure, land occupation and contamination of the air, surface water and groundwater [10], has caused the mining industry to focus on reducing and stabilizing its waste as much as possible, with a promising alternative being the conversion of these mine tailings into a valuable material, promoting circular economy. One application of these tailings with great potential is to replace a portion of the cementitious material in concrete with mine tailings.

1.1. Landscape integration and rehabilitation

The integration of mining infrastructures, sites, and environmental liabilities into the landscape is currently a crucial aspect of sustainable mining practices. International experience, particularly in Europe and North America, demonstrates a range of methods and initiatives that aim to predefine landscape quality objectives. These objectives guide the criteria for the location and configuration of activities in the territory. Additionally, strategies for mitigating and remediating environmental impacts are developed [11, 12]. Landscape architecture offers a multidisciplinary perspective and essential tools to address various scales of planning and design, promoting social use of remediated sites [13, 14]. Various technologies are available to control the emission of dust from tailings deposits, including the use of chemical products, vegetation, or layers of earth or stone material [15, 16].

A conceptual model for landscape integration and rehabilitation was designed and developed by a research team from the Pontificia Universidad Católica de Chile (PUC) and the Pontificia Universidad Católica de Valparaíso (PUCV) in 2020 and 2021. The Universidad de Santiago de Chile (USACH) and Compañía Minera del Pacífico (CMP) collaborated on a Master plan for landscape integration and rehabilitation in the southern coastal border of Huasco (MPLIR). This plan includes the area where the Huasco Pellets Plant Filtered Tailings Facility (FTF) is located (Figure 1). The MPLIR considers the definition of ecological management areas for the mitigation and compensation measures proposed in the Environmental Impact Assessment (EIA), in compliance with the requirements of the environmental authority. The measures have been designed with a strategic vision at a territorial scale, which promotes sustainable and innovative development based on new uses and pioneering programs for landscape rehabilitation in Huasco. This project aims to transform an area impacted by mining activities into a social and environmental asset, benefiting both the ecosystem and the community. The initiative is multidisciplinary and innovative in nature.

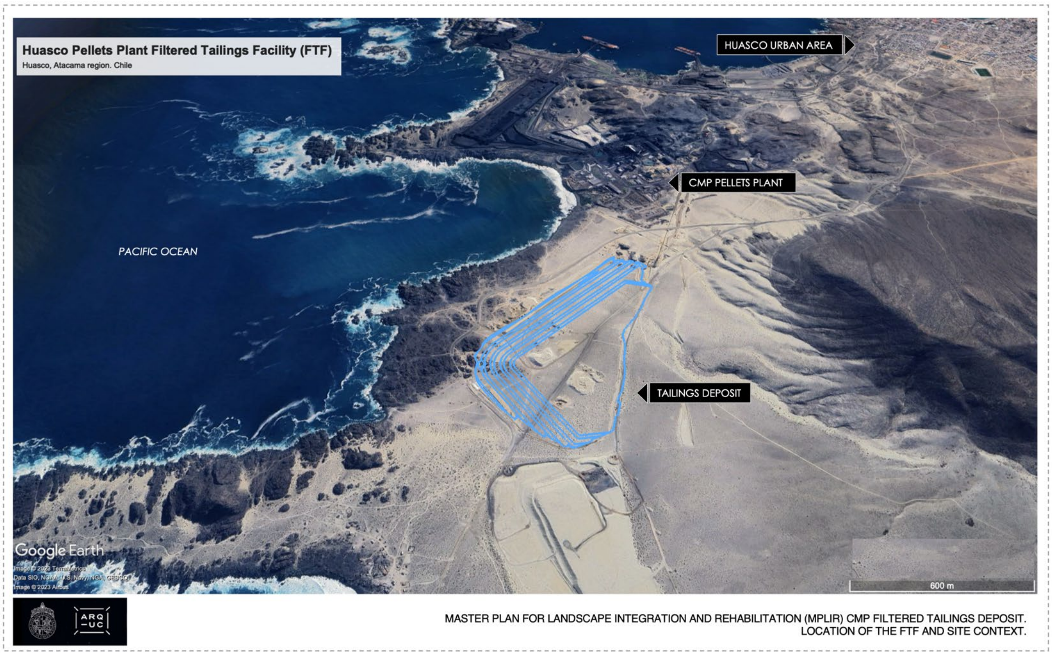

Figure 1: Area of the study site showing the location of the Pellets Plant and the location where the tailings facility will be located. Source: Moreno (2022).

1.2. Arched structures as sustainable design solution for construction

Arched structures are a clear example of effective use of material in construction. They operate on the principle of arching action, which allows for strategically position materials along a funicular path to create internal compression forces, rather than flexural stresses. [17]. This methodological approach allows for a reduction in material volume compared to traditional horizontal spanning structures [17, 18]. Arches have an inherent low-stress nature, which means that high-strength materials are not necessary. This allows for the use of alternative materials with modest compressive strength and minimal tensile capacity. These materials are often considered to have a lower environmental impact [19].

1.3. Article outlook

This paper presents a prototype pedestrian pathway in Huasco, Chile that uses prefabricated arched slabs. The pathway is part of an environmental mitigation strategy for a mine tailings deposit site and serves as a sustainable alternative to traditional foundation blocks. The application of arched structures in this project capitalises on their material efficiency and contributes to the sustainability of the construction industry.

The use of arched structures in building structures can significantly reduce their environmental impact, as suggested by studies on the environmental impact of arched floors [18, 20, 21]. Such structures have the potential to significantly reduce greenhouse gas (GHG) emissions, material depletion, waste, ecotoxicity, and human toxicity. The prototype pathway utilizes the arching action principle to reduce the amount of structural material needed, while also incorporating an eco-friendly concrete mix that utilizes mine tailings as a supplementary material to cement, thereby reducing environmental impact and promoting sustainability. This innovative approach demonstrates the potential for eco-effective construction techniques to be integrated with landscape design, promoting environmentally responsible development of mining infrastructures.

The paper is structured as follows: Following the introductory remarks that establish the environmental challenges and case study, the document proceeds to describe the materials and methodology, including the eco-friendly concrete mix and the design and fabrication process of the arched slabs. The results section analyses the fabricated prototype. The paper concludes by summarising the key contributions to sustainable construction practices and proposing directions for future research.

2. Methods

2.1. Concrete mix design for prototypes

The concrete mix design used in the protypes is detailed in table 1. At the time, only fine aggregate was used due to the initial dimensions of the formwork. The iron tailings used in the mix were previously homogenized and sieved to remove any agglomerated particles. A superplasticizer was used to improve the fluidity of the mix.

Table 1: Concrete mix design for prototypes

Materials	kg/m^3
Fine aggregate	1610
Ordinary Portland Cement	275
Iron tailings	166
Water	250
Superplasticizer	5

The mix used in the prototype has a compressive strength of 26 MPa at 90 days. This strength is comparable to non-structural concrete and can be used in low-solicitation applications, like pathways, urban furniture, and decorative structures. Durability testing has not been performed on this type of concrete and must be done to assure its long-term performance, particularly in the case of the Huasco region, considering its exposure to sea water and breeze. The case for Huasco is iron extraction, which generates a type of mine tailing which is very fine in particle size (under 50 microns) and with no presence of toxic elements or heavy metals.

2.2. Arched pathway design

The design of the arched pathway is based on modular cross-vaults. These are installed side by side as a series of parallel, unreinforced cross-vaults (Figure 2). These arches are strategically arranged on supports, which are in turn held in place by the weight of a compacted layer of rocky terrain.

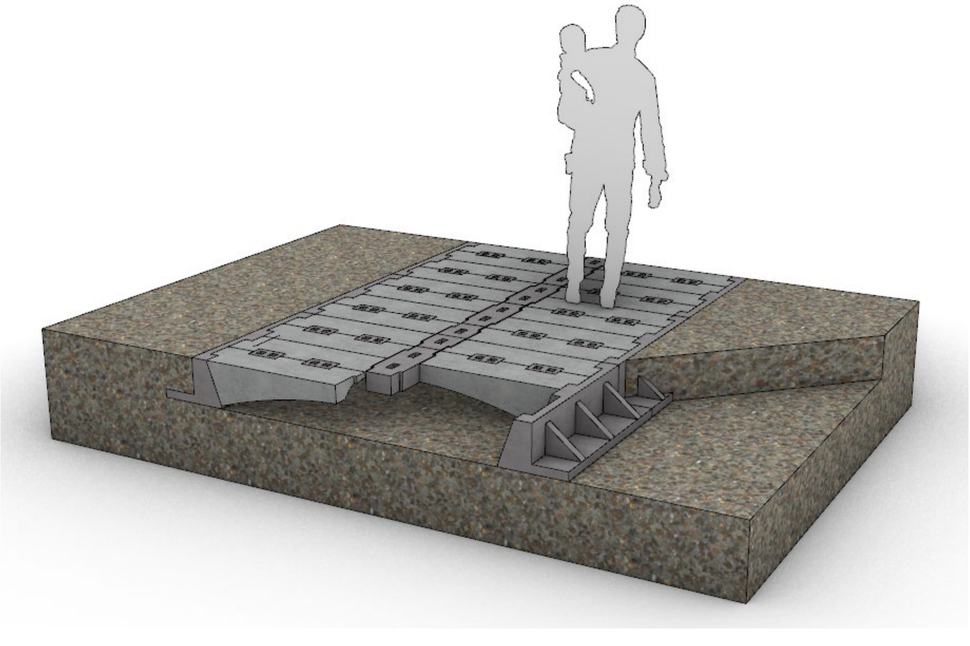

Figure 2: Perspective view of the arched system of pedestrian paths. It can be observed how the supports are anchored to the terrain.

By firmly anchoring the supports to the ground, the structure achieves horizontal equilibrium and eliminates the need for tension ties (Figure 3). The design eliminates the need for steel reinforcements in the arches, reducing the structure's environmental footprint and making it easier to recycle the materials at the end of their life. The cross-vault's depth is designed to provide ample structural capacity, offering robust resilience under a variety of load scenarios, including the effect of unevenly concentrated loads. This design consideration ensures that the structure can maintain its integrity and functionality under diverse and potentially challenging conditions.

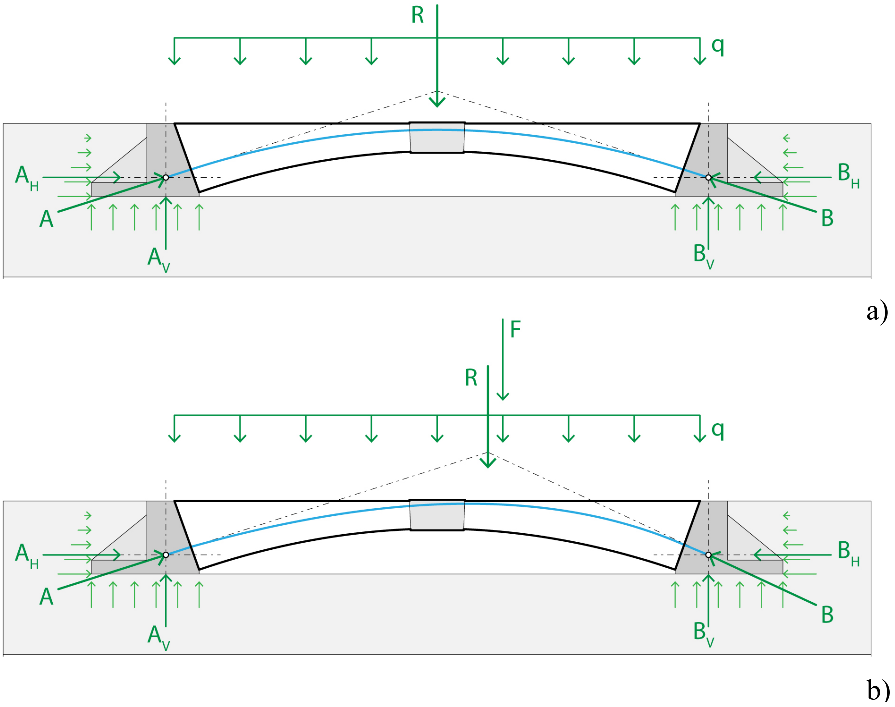

Figure 3: Horizontal thrust of the arched structure counteracted by the weight of soil on the supports. a) Arch under uniformly distributed load. b) Arch under uniformly distributed load and point load

The study examines a modular approach with moulded arched beams joined by a key stone that acts as an interface to control the stiffness of the arched structure in each module. This control interface is necessary to compensate for variations in the position and distance between the supports.

2.2.1. Form finding.

Both directions of the cross-vault structure is analysed as a two-dimensional segmental arch subject to a uniformly distributed load and point load in different positions. The form-finding process to determine a funicular geometry is carried out using Graphic Statics. This analytical method is based on the reciprocal relationship between form and forces. Equilibrium is described using force vectors and closed force polygons [22]. Figure 4 shows the parametric model used for the form-finding process. The model includes a span, a rise ratio (the ratio between the span and the height of the parabola), and a load magnitude.

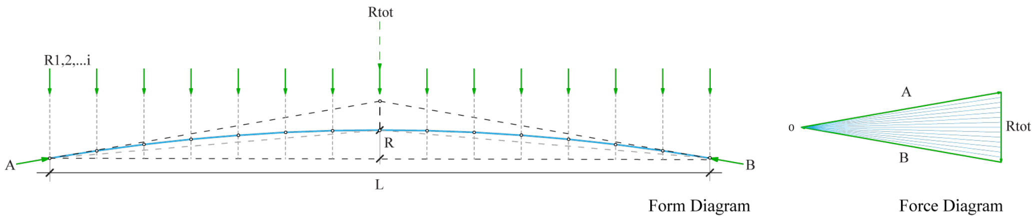

Figure 4: Parametric model used for the form-finding process.

2.2.2. Equilibrium analysis.

A parametric model based on Graphic Statics is used for the equilibrium analysis. Figure 5 shows the parametric model and the parameters analysed, including the material's mechanical properties, arch geometry, arch thickness, structural depth, distributed load magnitude and concentrated load magnitude and location. The safety of a proposed structure can be determined by examining whether the shape of the obtained thrust lines is contained within the longitudinal and transversal sections of the structure. The cross sections of the vault should allow for the maximum stress concentration found along the thrust line, considering safety factors and the mechanical properties of the material.

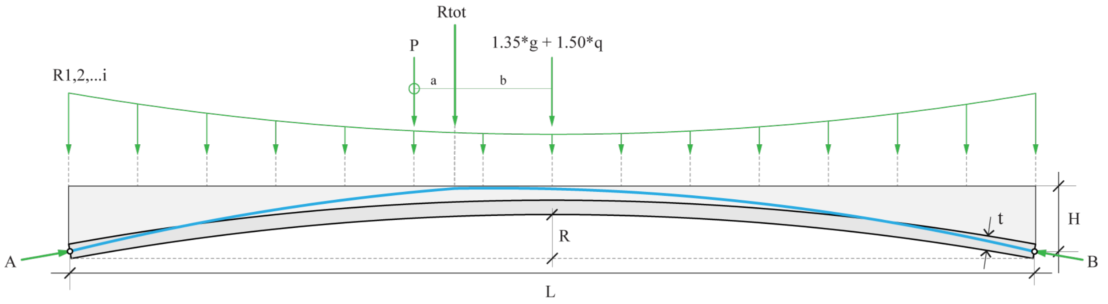

Figure 5: The parametric model used for the structural analysis of a given funicular geometry.

2.3. Arched pathway fabrication

The arched pathway is fabricated using moulds consisting of a minimum of five removable parts to facilitate the demoulding process. Each part of every mould is formed from layers of MDF that are 30 mm thick, which are shaped using a CNC router and joined with dowels. Once assembled, these parts are sanded to create a smooth surface and coated with epoxy to allow reuse. The design includes simple quality control measures and allowances for tolerances to enhance safety during construction. Figure 6 presents an exploded diagram of a module of the pathway.

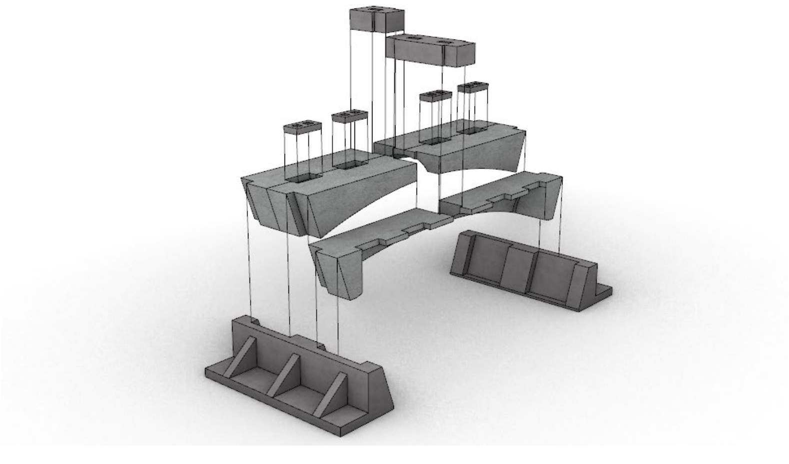

Figure 6: Exploded view of a module of the pathway

3. Results

A pathway module, equivalent to a cross-vault unit, was prototyped in a controlled laboratory setting (Figure 7). The prototype demonstrated that the arch system could be assembled and verified the usefulness of the keystone for adjusting the arch's stiffness was also verified. However, mould deformation problems during re-use resulted in a variability of up to 3mm between parts. This difference made the section difficult to assemble. The strength of the system was tested empirically by placing weights on different parts of the surface to simulate point loads. It was not possible to test the performance of the supports in situ. To simulate the action of the ground countering the lateral thrust of the structure, weights were placed next to both supports. More modules are being manufactured to test the system in situ. These tests are essential to evaluate the suitability and adaptability of the proposed construction system, the stability of the structure over time under variable load scenarios, and the material's resistance to the weather.

Figure 7: Prototype fabricated in laboratory.

4. Conclusion

This paper has detailed the development of a prototype pedestrian pathway that takes advantage of the structural and environmental benefits of the use of the arching action principle for structural efficiency and the use of mine tailings as a partial replacement for cement. The research demonstrates a viable approach to reducing the environmental footprint of construction projects by integrating these materials into a modular arched pathway design, while maintaining structural integrity and minimising the site disturbance typically caused by traditional foundation blocks.

A prototype was constructed in a controlled laboratory environment using a series of moulded vaulted beams connected by keystones. This setup enabled empirical validation of the assembly process and the effectiveness of the keystones in adjusting the stress within the arches. Although the initial tests showed promise, they also highlighted challenges related to mould deformation and variability between produced sections, which complicated assembly and highlighted the need for improved precision in the fabrication process.

Future research should extend beyond laboratory conditions to include in-situ testing. This will help to fully assess the prototype's performance under real-world environmental conditions and loading scenarios. Furthermore, to advance the prototype towards commercial application, it will be critical to address the observed pre-cracking issues and refine the mechanical properties of the materials used.

To scale up the solution, improvements to increase structural performance of the structure are needed to be investigated, including innovative design modifications such as optimised vaulted geometries that distribute the stresses more evenly. In addition, the durability of the materials, in particular their ability to withstand outdoor exposure, needs to be thoroughly investigated.

This paper aims to encourage practices to adopt sustainable construction techniques that utilize locally sourced, recycled materials and avoid significant alterations to the natural landscape. The practical and environmental benefits of this approach are discussed, contributing to a shift in construction paradigms.

It is important to rethink how building materials are sourced, used, and managed in an eco-friendly manner.

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