Comparative Analysis of Pedestrian Bridge Alternatives Using Steel, Ordinary Portland Concrete, and Geopolymer Concrete for Structural, Environmental, and Economic Performance

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Abstract

The accelerated population growth in Guayaquil has increased the demand for pedestrian infrastructure, emphasizing the need for sustainable, cost-effective materials. This study evaluates three alternatives for pedestrian bridges: A36 structural steel, conventional concrete (OPC), and geopolymer concrete (GPC). These solutions are compared using structural analysis in SAP2000, life cycle assessment (LCA), and cost evaluation through BIM modelling in Revit. Both A36 steel and Ordinary Portland Concrete (OPC) demonstrated superior structural performance, whereas GPC displayed increased deflections due to a lower modulus of elasticity. However, GPC offered significant environmental advantages, with CO_2 emissions up to 67% lower than OPC and potential cost savings of up to 11% at higher strengths. The findings underscore GPC's promise as a sustainable alternative, offering reduced carbon footprint and competitive costs.

Keywords: Geopolymer concrete; pedestrian bridge; structural analysis; life cycle assessment; BIM modelling.

1 Introduction

The city of Guayaquil has experienced exponential population growth over the last century, increasing from 12,000 inhabitants to 2,600,000 by 2020 [1]. This growth necessitates expanded road infrastructure, including crosswalks for user comfort and safety. According to El Telégrafo, pedestrian bridges in Guayaquil are insufficient for the population and existing road infrastructure [2]. Many pedestrians cross streets through unsafe areas instead of using bridges or crosswalks, either due to time constraints or lack of nearby options. The demand for these structures has grown, making it essential to reconsider the materials used to minimize environmental impact [3].

Steel and Ordinary Portland Concrete (OPC) are the most common materials for these structures. Both are reliable for their strength and versatility, but their production significantly impacts the environment, especially OPC, which emits around one ton of CO_2 per ton produced. OPC production contributes to 8,6% of global CO_2 emissions and 1,3% of greenhouse gases [4]. Steel, while also impactful, is recyclable and generates significantly less solid waste during recycling than primary production [5].

To address these environmental concerns, experts are focusing on sustainable alternatives to conventional concrete, such as Calcium Sulfoaluminate Cement Concrete (CSA), which reduces CO_2 emissions during production, and Geopolymer Concrete (also known as alkali-activated concrete), known for its durability, chemical resistance, and versatility in specialized applications. Among these materials, Geopolymer Concrete (GPC) has gained significant attention [6]. Made from industrial waste such as fly ash or slag, GPC consumes less energy and emits up to 80% less CO_2 than conventional concrete [7]. Historical examples include monuments in Tiwanaku and possibly the Giza pyramids [8]. A modern application is Brisbane West Wellcamp Airport, where 40.000 m^3 of GPC was used for runways due to its workability, low shrinkage, and tensile strength. Russia has also explored the use of Geopolymer Concrete (GPC) in 3D printing applications, leveraging its sustainability and adaptability for creating complex, durable structures with minimal waste [9].

This study aims to compare structural steel, conventional concrete, and GPC for crosswalk construction in Guayaquil. It evaluates these materials based on structural performance, durability, environmental impact, and cost.

The study highlights the importance of using fewer polluting materials for infrastructure. Considering environmental impact is crucial as climate change increasingly affects the planet. The findings aim to encourage specialists to adopt new, eco-friendly materials and techniques, positively contributing to global sustainability.

2 Methods

2.1 Description of design alternatives

Three different pedestrian bridge alternatives are presented in this article, to compare their performance as a function of the materials used. Alternative A is a pedestrian bridge whose main structural elements are made of A36 structural steel, which is one of the most used materials in the construction industry locally. Alternative B consists of Ordinary Portland Concrete (OPC), and alternative C uses Geo-Polymer Concrete (GPC). For the comparison to be equivalent among all the alternatives, it is assumed that the three pedestrian bridges were designed to resist the same live loads and have equal lengths (38.5 m). In addition, the access ramps or stairs are not taken into consideration, only the structure that makes up the main walkway. Alternatives B and C have the same geometric structure, thus allowing for a better comparison between the differences generated by the different materials. The structural geometry for A36 steel differs significantly from that of OPC and GPC due to the inherent material properties of steel, such as its higher strength-to-weight ratio and superior ductility. These characteristics allow for more slender and lightweight designs compared to concrete. The design of all alternatives follows the applicable standards in Ecuador, including the NEC-SE-DS and AASHTO LRFD, ensuring compliance with local and international regulations.

2.2 Materials

For alternative A, structural steel A36 is used, which has a unit weight of 76.98 kN/m^3, its yield strength is 248 MPa (36 KSI) and the elastic modulus is 200 GPa (29.000 KSI) [10].

Cold rolled tubular sections were used for the decking system that would form the bridge walkway. The beams in the main direction (longitudinal to the bridge travel direction) were considered with a diameter of 120 mm and a thickness of 3 mm, while the beams in the secondary direction (transverse to the bridge travel direction) were considered with a diameter of 100 mm and 3 mm thick. On top of the beams that make up the floor system, a steel plate with a thickness of 10 mm is mounted on which pedestrians will walk.

For alternative B, OPC was considered, whose unit weight is known to be 23.54 kN/m^3, the compressive strengths evaluated are 40 MPa and 50 MPa, and the elastic modulus is given by Eqn. (1), where f'_c is the 28-day compressive strength of the concrete and its units are in MPa [11].

$$E_{OPC} = 4700\sqrt{f'_c}\ [MPa] \quad (1)$$

Alternative C considers GPC which has a unit weight similar to conventional concrete of 2400 kg/m^3 [12], and it is analysed with compressive strengths of 40 MPa and 50 MPa for comparison, deriving the modulus of elasticity as determined by Eqn. (2) where f'_c is in MPa [13].

$$E_{GPC} = 4.26{f'_c}^2 - 111.74f'_c + 10365\ [MPa] \quad (2)$$

It is important to note that the modulus of elasticity for GPC decreases by up to 35% after 2 years of aging. This time-dependent behaviour should be considered in future studies, especially for the design of prestressed elements, as it can impact long-term structural performance [14].

Alternatives B and C are evaluated with two different compressive strengths to analyse the behaviour in the serviceability limit state, and to evaluate if these alternatives do not exceed the allowable deformations proposed by the standards. The result is a total of 5 case studies considering alternative A with structural steel A36.

The values of modulus of elasticity for each compressive strength and concrete material are shown in Table 1.

Table 1. Properties of concrete materials

Material	Compressive Strength [MPa]	Modulus of Elasticity [MPa]
OPC	40	29.42
OPC	50	32.89
GPC	40	12.71
GPC	50	15.43

For Alternatives B and C, the main walkway is composed of prestressed double T-beams that run along the length of the bridge supported on header beams, with a 5 cm thick topping.

The double T-girder is 100 cm high; the flange is 120 cm wide, and each web is 15 cm thick. The flange has two layers of reinforcing steel, both upper and lower, of 8 mm diameter spaced every 15 cm and, in the webs, there are a total of 36 strands; the properties of the steel used are as shown in Table 2.

Table 2. Properties of steel materials

Material	Yielding Strength [MPa]	Ultimate Strength [MPa]	Modulus of Elasticity [GPa]	Unit Weight [kN/m^3]	Use of Steel
A615Gr60	420	620	200	77	Rebar
A416Gr270	1690	1860	200	77	Prestressing

2.3 Structural Analysis

The structural analysis is carried out in SAP2000 to analyse demands and deformations, for comparison to strength and serviceability limits. The following input data were used for the analysis.

The dead load included the self-weight of the structure [15], calculated automatically by the program based on the modelled element sections.

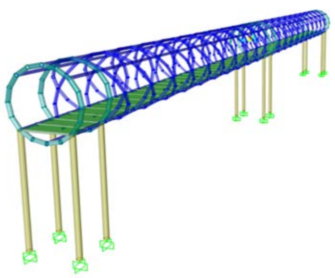
The live load followed the AASHTO LRFD standard, with a recommended value of 4.02 kN/m^2 for pedestrian bridges [16], representing five 80 kg persons per m^2 in the most critical scenario.

Seismic load calculations followed the Ecuadorian NEC-SE-DS standard [17], requiring geographic, geological, and soil type inputs. For Guayaquil, the Z factor (maximum acceleration in rock) is 0.4 times gravity, with soil type D adopted from local studies.

The η parameter, representing the ratio between spectral and peak ground acceleration, is 1.8 for coastal regions. Given the importance of pedestrian bridges, an importance factor I of 1.3 was applied, ensuring structural integrity during earthquakes. A response reduction factor R of 3 was considered, assuming non-ductile frames.

Load combinations were established in accordance with the AASHTO LRFD Bridge Design Specifications, considering the effects of gravity, dynamics and accidental loads. For the service limit state, deformations were evaluated under dead load and live load combinations without load factors. For the strength limit state, were used the following load combinations: (a) 1.25 D + 1.75 L, (b) 1.25 D ± 1.0 E, and (c) 0.9 D ± 1.0 E, where D is dead load, L is live load, and E is seismic load.

With materials, cross-sections, loads, and combinations established, the three alternatives were modelled in SAP2000 (Figure 1). Beams were modelled as simply supported by releasing moment transfers at their ends, closely simulating physical boundary conditions.



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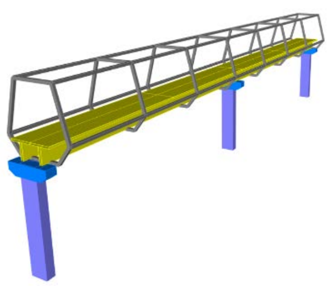


b)

Figure 1. Modelled structures in SAP2000 a) Alternative A: Structural Steel b) Alternative B: Ordinary Portland Concrete and Alternative C: Geopolymer Concrete

For the mass source, 100% dead load was considered. The seismic coefficient was assessed per the NEC-SE-DS standard, which depends on each structure's fundamental period. Parameters C_t and α, based on material and structural system, are shown in Table 3. No bracings were considered for steel and concrete structures.

Table 3. Parameters for determination of fundamental period

Material	C_t	α
Structural Steel	0.072	0.8
Reinforced Concrete	0.055	0.9

The fundamental period is computed by Eqn. 3 and this is entered in Eqn. 4 to compute the base shear. Φ_p and Φ_e depend on the irregularities in plan and elevation, respectively; a value equal to 1 was chosen for both cases.

$$T = C_t h_n^{\alpha} \quad (3)$$

$$V = \frac{I * S_a(T_a)}{R * \emptyset_P * \emptyset_E} \quad (4)$$

The base shear from Eqn. 4 was compared with SAP2000 results, which use Modal Spectrum Response Analysis. The shear from this method was scaled to at least 80% of the base shear calculated using Eqn. 4.

For Alternative A (A36 steel), compressive and flexural strength were calculated per AISC 360-16 sections E3, F8, and H1. SAP2000 automated the process, determining the demand-capacity ratio for bending and compression interaction.

For Alternatives B and C, flexural strength of T-beams was calculated using AASHTO LRFD equations and SAP2000. Initial calculations assumed rectangular beam behaviour to compute the neutral axis depth '*c*.' If the neutral axis was within the flange, bending strength was calculated based on flange width [18].

The SAP2000 Section Designer tool modelled T-beams, generating a moment-curvature diagram to determine maximum flexural capacity before failure. The results from AASHTO parameters were compared with SAP2000's diagram values. The lower resistance value was selected for conservatism, and percentage error was assessed at the estimator's discretion.

2.4 Life Cycle Analysis

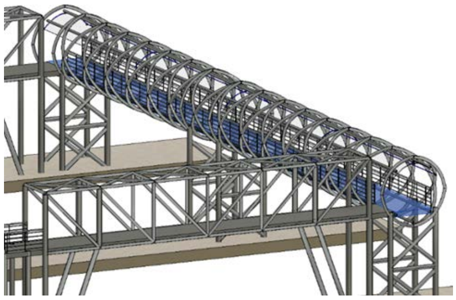
This analysis helps us to determine the environmental impacts (toxic waste, water discharges, greenhouse gases, high energy consumption) throughout the life cycle, generated by the production of a material or activity. Through this type of analysis, it is possible to determine which is the most critical stage generated by this type of activity and thus be able to provide solutions that help to mitigate or control the negative impacts on the environment [19]. This analysis is carried out in terms of sustainability for each stage involved in the manufacture of a product, i.e., from the extraction of raw materials from the environment, their production, transportation and distribution, the use of the product as such, and disposal or recycling and reuse [20].

To facilitate the analysis, it is necessary to approach it in different stages. First, the objectives and scope of the work must be defined. Then a life cycle inventory must be carried out, defining the inputs (main materials, raw materials) and outputs (emissions, waste) to quantify the impact on the environment [21]. Subsequently, a life cycle impact assessment is carried out to characterize and classify the potential impacts generated. Finally, the interpretation of results is carried out, in which the phase that generates the greatest impact is identified, so that improvements are proposed to reduce the environmental load [22]. In the case of the three materials presented in this article, the CO_2 emissions emitted to the atmosphere, their recycling potential, among others, will be analysed to highlight the advantages of each material with respect to each category analysed. Calculations were performed using the open-source tool The Structural Carbon Tool, Version 2.

2.5 Cost Analysis

To determine the estimated cost of each structure, the modelling was carried out in the program Revit considering only the main walkways. This program is designed to use BIM methodology, which helps quantifying the modelled materials, so that the error generated by the user if the quantities were to be estimated manually is considerably reduced [23]. Figure 2a shows the 3D Revit model of the bridge made of structural steel and in Figure 2b, the base material is the OPC and GPC. The prices of the materials necessary for the cost analysis were consulted directly from the suppliers, and precast concrete companies were consulted for the price of the double T prestressed beams.

In the Ecuadorian market, there is easy access to information on the costs of structural steel and concrete made with conventional Portland cement, but with respect to concrete made with geopolymers, there is no information available since this type of material is not yet marketed in the country. To make the comparison, scientific publications from other countries were used to highlight the production cost of 1 m^3 of GPC according to the expected compressive strength. These prices are compared with the production costs of 1 m^3 of OPC for the same strength [24], and scaled accordingly using the Ecuadorian prices for OPC.



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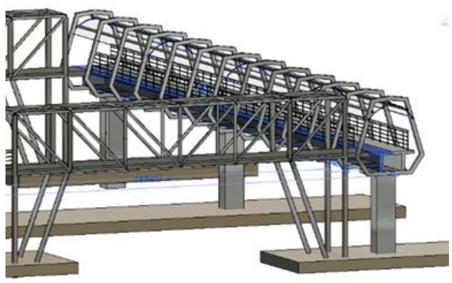

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Figure 2. Structures modelled in Revit a) Steel Pedestrian bridge b) OPC and GPC pedestrian bridge

3 Results and Discussion

3.1 Structural

After modelling the structures with all necessary parameters for structural analysis, demand-capacity ratios and deformations were verified and compared. For the structural steel bridge, demand-capacity ratios for flexural compression effects remained below 0.3. For OPC and GPC pedestrian bridges, flexural resistance of single T-girders was determined using AASHTO LRFD and SAP2000's Section Designer. The lower resistance from both methodologies was used to calculate the demand-capacity ratio.

Two compressive strengths were analysed for OPC and GPC (40 MPa and 50 MPa), resulting in four models. Flexural strength values were 2041.5 kN·m for OPC40 and GPC40, and 2079.8 kN·m for OPC50 and GPC50. Flexural demands were 711 kN·m for OPC40, 713.3 kN·m for OPC50, 683.5 kN·m for GPC40, and 690.4 kN·m for GPC50.

Table 4. Demand - Capacity Ratios for concrete materials

Material	Demand [kNm]	Capacity [kNm]	D/C
OPC40	711.0	2041.5	0.35
OPC50	713.3	2079.8	0.34
GPC40	683.5	2041.5	0.33
GPC50	690.4	2079.8	0.33

As shown in Table 4, demand-capacity ratios range between 0.33 and 0.35, indicating that all T-beams meet resistance limits. Flexural demands for GPC are lower due to its reduced modulus of elasticity, which decreases stiffness. Serviceability limits were evaluated using deflections generated in SAP2000 for the four models, as listed in Table 5. The limit was $L/240$, considering live and dead loads. GPC40 exceeded this limit with a deformation of 19.3 cm, compared to the 16.04 cm limit.

The differences in deflections are due to variations in the modulus of elasticity. The high deflection of GPC40 motivated the analysis of higher compressive strength (GPC50) and its impact on the total structural cost. Geopolymer concrete may

Table 5. Actual deflections and limit deflections for each material

Material	Deflection [cm]	Limit $L/240$ [cm]	Status
A36	10.2	16.04	OK
OPC40	10.5	16.04	OK
OPC50	2.41	16.04	OK
GPC40	19.3	16.04	Not OK
GPC50	4.9	16.04	OK

face limitations in prestressed structures due to its time-dependent material properties, such as higher creep and shrinkage and a reduction in elastic modulus over time, compared to conventional concrete. These factors could negatively affect load-carrying capacity, cracking resistance, deflections, and prestress losses. Despite GPC's environmental benefits and cost-effectiveness, these material characteristics may hinder its broader application in prestressed infrastructure [25].

3.2 Life Cycle

It is necessary to analyse the life cycle of each material to determine the impact they generate on the environment during their manufacturing process, useful life and as waste. On the one hand, it is known that structural steel A36 is a material widely used throughout the world, so data on the emissions generated by each kg of steel are available, which are presented in Table 6 [26].

The data in Table 6 are based on a primary process in which steel is manufactured using iron as raw material; when the process is carried out using recycled steel, CO_2 emissions decrease from 2.903 to 0.275 $kgCO_2e$: a 90% of reduction [27]. In the Ecuadorian industry and worldwide, steel recycling is common, so the emissions generated by this industry will be reduced thanks to this practice [28].

For the case of OPC, previous studies indicate that carbon emissions increase when aggregates are recycled by up to 3.4% more than when aggregates are not recycled, and it has been shown that up to 17% of CO_2 emissions can be reduced when 25% of

Table 6. Results characterization of environmental impacts for structural steel

Environmental impact category	Category indicator	Results characterization
Raw material consumption	kg Steel	1
Global warming potential	kg CO_2	2.903
Eutrophication Potential	kg PO_4^{3-}	0.0142
Acidification Potential	kg SO_2	0.0006
Photochemical Oxidant Creation Potential	kg C_2H_4	0.143
Energy consumption	MJ	41.13

cement is replaced with fly ash [29]. The data of the emissions generated by the extraction of raw materials, concrete production, demolition, and transportation for OPC produced with natural aggregates are presented in Table 7. These data are representative for 1 m^3 of concrete with a compressive strength of 31.2 MPa [30].

Table 7. Results characterization of environmental impacts for ordinary concrete

Environmental impact category	Category indicator	Results characterization
Raw material consumption	m^3 concrete	1
Global warming potential	kg CO_2	500
Eutrophication Potential	kg PO_4^{3-}	0.09
Acidification Potential	kg SO_2	0.62
Photochemical Oxidant Creation Potential	kg C_2H_4	0.025
Energy consumption	MJ	1100

Geopolymer concrete is a material that can be manufactured from industrial byproducts such as ashes generated from residues in metallurgy processes or thermoelectric plants [31]. Previous studies on GPC show that CO_2 emissions are lower compared to those emitted by conventional concrete. For GPC strengths of 40 MPa, 60 MPa and 70 MPa the emissions are reduced by 20.5%, 27% and 35% respectively compared to OPC with the same compressive strengths; cases have been evidenced in which this reduction is as high as 62.7%. [32].

3.3 Cost

The three alternatives were initially modelled in Revit for accurate material quantification, and the cost of the main walkway was estimated for comparison. For the A36 steel structure, the walkway comprises circular tubes (120x3 mm and 100x3 mm) and a 10 mm thick metal plate, with a total weight of 7687.96 kg. Based on municipal data, the cost of steel including erection is $3.44/kg, resulting in a total cost of $26,446.58.

The OPC walkway consists of two prefabricated 19.2 m double T-beams with a total volume of 24.36 m^3. Quoted by MAVISA precast company, the cost for two beams with 50 MPa strength is $19.800. For GPC, cost data in Ecuador is unavailable due to its limited production. Research indicates that GPC production costs decrease with higher compressive strengths, with GPC50 being 11% cheaper than OPC50 [35]. Using this data, the cost of GPC50 double T beams is estimated at $11,748, as shown in Table 8.

Table 8. Estimated costs of the walkway for the three alternatives

Alternatives	Estimated Cost [USD]
A36 Structural Steel Main Walkway	$26,446.58
OPC 50 MPa Main Walkway	$19,800.00
GPC 50 MPa Main Walkway	$11,748.00

4 Concluding Remarks

Although steel, OPC, and GPC structures differ significantly in material properties, their comparison is justified by analysing their performance under similar design conditions. These materials are evaluated based on their ability to meet structural requirements, such as strength, stiffness, and deflection limits, while considering environmental and economic impacts. By designing equivalent structures with comparable capacities, meaningful insights can be drawn regarding their suitability.

The demand-capacity ratios (DCR) for the five models analysed (A36 structural steel, OPC 40, OPC 50, GPC 40, and GPC 50) are relatively similar, ranging between 0.3 and 0.35, indicating potential oversizing. While structural design ensures compliance with strength requirements, it also aims to control deformations for user comfort. For GPC 40, excessive deflection (19.3 cm) exceeded the serviceability limit of 16.04 cm ($L/240$) due to its lower modulus of elasticity compared to OPC. Increasing the compressive strength to 50 MPa improved the modulus and reduced deflections, achieving compliance.

Environmental impact analyses highlight the significant advantages of GPC, which emits up to 62.7% less CO_2 than OPC, with total emissions of 4.2 tons compared to 12.18 tons for OPC and 22.3 tons for steel. Recycled steel further reduces emissions by up to 90%. Economically, GPC also demonstrates cost benefits, with the estimated cost of a pedestrian bridge at $11.748, compared to $19.800 for OPC and $26.447 for steel. Additionally, higher compressive strengths in GPC reduce production costs by up to 11% compared to OPC.

However, conventional concrete outperforms GPC structurally due to its higher stiffness, with a modulus of elasticity up to 54% greater. While DCR values remain consistent across materials, deflections vary significantly, underscoring the need for optimized cross-sectional designs to balance demands, deflections, and material usage. Such optimizations could improve structural performance while reducing material consumption and associated CO_2 emissions.

GPC emerges as a promising alternative for sustainable and cost-effective infrastructure, while OPC and steel retain advantages for specific structural applications. Future research should focus on refining GPC production costs and validating its practical adoption, especially in local markets where data is limited. Additionally, specimens with local materials can be analysed to optimize performance and reduce costs. This approach will enhance structural design efficiency, sustainability, and economic feasibility, addressing the challenges of modern infrastructure development.

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