Holistic evaluation of formwork materials for low-carbon concrete

Alexandra Daley[1], Mohamed Ismail[1], Leopold Wehner[1]
[1]*University of Virginia School of Architecture*

Abstract

In the current climate crisis, designers must explore scalable and immediate methods of reducing the embodied carbon of concrete structures. Such work depends on a quantitative understanding of the costs of concrete construction. Although the carbon costs of concrete as a material are well understood, identifying the layered costs of concrete formwork and construction is not as thoroughly documented. These costs have mainly been explored through qualitative data, but meaningful reductions in concrete's environmental cost require an understanding of the embodied carbon of concrete forms as well as the labor cost and complexity associated with different materials and methods.

This paper presents a framework for quantifying and comparing the embodied carbon and labor involved in concrete formwork and casting through several lab-scale prototypes of shape-optimized concrete built using various form materials and digital fabrication methods. Formwork options include materials that fall under traditional practice, emerging practice, and organic formwork. Procedures combine casting experiments of an optimized beam design with an embodied carbon evaluation for both formwork and concrete, comparing the strengths and weaknesses of each material. By testing and documenting a range of formwork materials, this research attempts to develop a detailed understanding of the labor and carbon associated with formwork options. Formwork materials are qualitatively and quantitatively compared for their precision, accessibility, ease of construction, and embodied carbon. After analyzing formwork materials from this casting process, key materials will be selected to scale up for full-scale prototyping and stress testing. While the outcomes of this study are highly specific, a framework of quantifiable formwork material comparisons will guide future research into scalable and accessible methods for low-carbon construction.

Introduction

Global urbanization is occurring at an unprecedented rate; over 200,000 people move to cities each day (UN DESA 2018) requiring us to double our built floor area by 2050. This will involve mostly concrete construction, an extremely popular and widely trusted material. Around 30 billion tons of concrete are used globally each year, and that number is rising (Nature Editorial 2021). The embodied carbon of all construction—emissions due to material extraction, manufacturing, transportation, and demolition--accounts for approximately 11% of all global carbon emissions (United Nations Environment Programme 2024). However, due to concrete's widespread use, cement alone makes up 8% of global carbon emissions. Additionally, twice as much concrete and mortar is used in construction when compared to all other industrial building materials combined (Van Damme 2018). Designers across industries rely on concrete as a versatile and durable material, yet its widespread use has led to concerns over the associated carbon costs. A global approach to sustainable architecture must therefore involve alternative, accessible, and more efficient building practices.

Considering climate change's increasingly severe effects, it is imperative that designers explore scalable and immediate methods for reducing concrete's embodied carbon. A strong opportunity lies in the redesign of concrete floors; in high-rise buildings, between 60 and 80% of the mass and embodied energy can be found in the floors (Foraboschi, Mercanzin, and Trabucco 2014) and past research has shown that reducing the amount of concrete used through structural optimization presents a promising pathway towards low-carbon construction (Feickert and Mueller 2023; M. Ismail 2023). Research by the authors (M. A. Ismail and Mueller 2021) has shown that carbon reductions of over 60% are achievable when typical prismatic concrete structures are replaced with shape optimized designs, using standard materials and meeting local code requirements. However, shape-optimized structures could raise the environmental and economic costs of formwork fabrication by complicating labor and material requirements, limiting the scalability of novel shape optimization methods. Therefore, to scale and broaden the potential impact of shape-optimized concrete construction, we need to quantify and compare formwork costs through three lenses: economy, labor, and the environment. This article presents a framework informing shape-optimized concrete form material selection by comparing their acuity, environmental impact, and economic costs. The scope of these initial findings is limited to lab-scale prototypes built using locally available digital and manual fabrication methods.

State of the Art

Shape Optimization

Structural optimization techniques usually fit into one of three categories: topology, size, or shape optimization (Afzal et al. 2020). Topology optimization rearranges a structure's parts and their interrelationships, removing material where it is not needed and often resulting in extremely complex shapes. Size optimization adjusts the sizes of a structure's parts without changing their arrangement or shape. Shape optimization modifies the shape of a structure by adjusting its parametric definition while maintaining its topology. This research primarily investigates formwork strategies best suited to shape optimization.

Digital Formwork Fabrication

The most common concrete formwork materials are metal, plywood, and, to a lesser extent, plastic.
(Li et al. 2022). However, the requirements of shape-optimized concrete beams differ significantly from those of general, prismatic construction techniques. Specifically, shape optimized structures often require a fine degree of precision in their formwork to capture complex curvatures and shapes. Newly developed systems for digital fabrication and prefabrication are natural answers to this need for precision.

Researchers at ETH Zurich (Veenendaal 2017), and Delft University of Technology (Schipper and Grünewald 2014), among others, have used tensile fabric-based formwork, fabricated shell structures, and other methods to achieve a high degree of precision. Such digital fabrication presents compounding opportunities that integrate with formwork, such as reductions in reinforcement material.
For example, researchers at the University of Cambridge have developed methods of achieving digitally precise formwork replacement through use of less boutique materials, using commercially available plywood while using steel ties instead of traditional reinforcement (Hawkins et al. 2017). Simultaneously, the Block Research Group has created a method of analysis and construction of complex compressive floor and roof systems made with ultra-high-performance concrete and digital fabrication (Echenagucia, Roozen, and Block 2016; López et al. 2014).

These are technically impressive and responsive formwork fabrication methods which enlist digital fabrication and complex structural analysis techniques to simultaneously reduce material use while allowing for new types of structurally expressive construction.

Research Gap

To identify the most impactful ways of reducing the embodied carbon of concrete structures, designers need a quantified understanding of the costs associated with concrete construction. Although the carbon costs of concrete as a material are well understood (Anderson and Moncaster 2020), identifying the layered costs of concrete formwork and construction is not as thoroughly documented. These costs have mainly been explored through qualitative data (Li et al. 2022), but meaningful reductions in concrete's environmental cost requires an understanding of the embodied carbon of concrete forms as well as the labor cost and complexity associated with different materials and methods.

Methodology

This research presents one possible method for evaluating and selecting formwork materials; quantifying and comparing the embodied carbon and labor involved in shape-optimized concrete fabrication through the lab-scale prototyping of shape-optimized concrete beams built using various form materials and locally available fabrication methods. This section summarizes the shape optimization method and evaluation framework before presenting the preliminary findings in Results.

Shape Optimization

This research uses a published method of concrete shape optimization, the modification of a structure's geometric shape without changing its topology. This method defines an element's geometry using control points and modifies the position of these points to iteratively minimize a quantifiable cost (embodied carbon, material costs, etc.) while ensuring the design meets structural (strength and serviceability) and non-structural (fabricability, clear cover, etc.) constraints. Control points are used to define the cross-section of a beam. Iterative transformation of these control points based on performance leads to a shape-optimized structure (Fig.1).

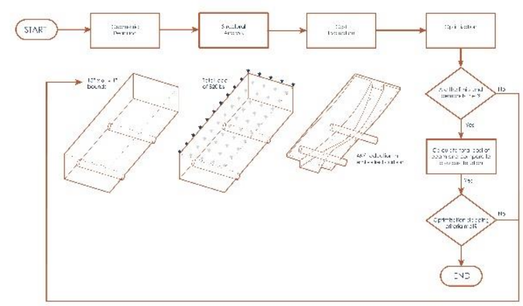


Fig. 1. Diagram of Shape Optimization workflow. After initial dimensions were set, the total load of 800 lbf was applied and optimized for the final flange and web shapes.

This shape optimization method was used to design a double-cantilever 18-in beam, simply supported at 3.5 and 11.5 inches along its length. (Fig. 2) The top flange is 6-in wide and the beam is designed to carry a total of 800-lbf distributed along its length. The beam is cast using 6-ksi mortar mix and reinforced with 1/8-in diameter 60-ksi steel wire along its bottom face with a mesh of 1/4x1/4-in chicken wire for flange reinforcing.

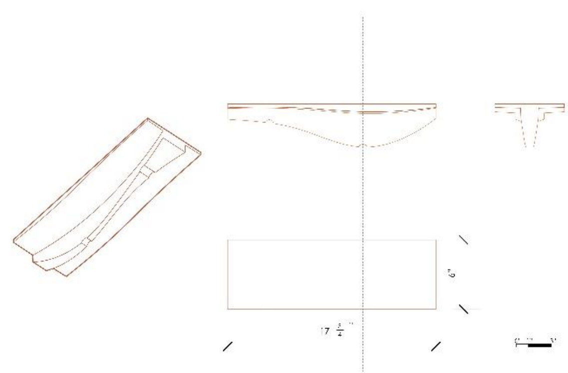


Fig. 2. Final beam design and dimensions; worm's eye view, elevations, and plan with support point locations.

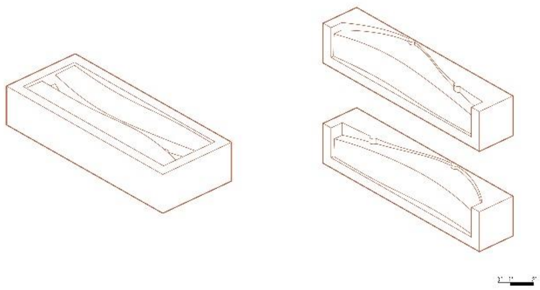


Fig. 3. *Formwork design developed from the final beam design. Formwork pieces were cut in half for easy removal.*

Evaluation Criteria

Research methodology combines casting experiments of an optimized beam design with an embodied carbon evaluation for formwork, comparing both the strengths and weaknesses of each formwork material. By testing and documenting a range of formwork materials, this research attempts to develop a detailed understanding of the labor and carbon associated with formwork options. The embodied carbon, accessibility, ease of construction, and precision were quantitatively and qualitatively compared. Based on previous work by the authors (Feickert and Mueller 2023; M. Ismail 2023), this framework blends environmental, economic, and socio-cultural concerns in construction material selection.

Material Selection

This research applies the above evaluation criteria to a selection of formwork materials chosen according to both traditional and emerging practices. As Figure 4 outlines, materials were selected after a literature review process was combined with fabrication constraints and material availability. The selected formwork materials are summarized in Figure 10, along with their supplier and fabrication method.

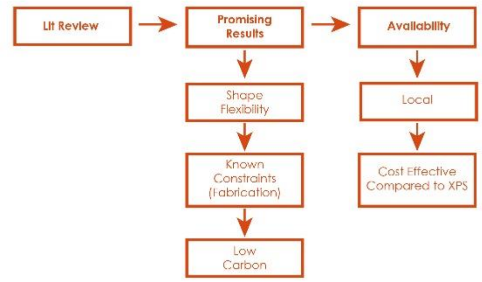


Fig. 4. Flowchart for Material Selection. After a literature review, material choices were impacted by fabrication constraints and material availability.

Many of the study materials including XPS Foam, Fabric, Bamboo, and Reeds, were chosen due to the literature review process, where research examples of these formwork materials spurred fabrication questions by the research team. Some, including cork and cardboard, were chosen due to fabrication experiences in the authors' architectural education. Lastly, 3D printed materials were of high interest, but due to fabrication constraints they were not explored in this specific study.

Results

This paper introduces a framework for an inclusive evaluation of formwork materials, one that considers quantitative and qualitative results in tandem. Through detailed documentation of material quantity, source, fabrication time, and realized beam outputs for each formwork option, we explore the advantages and disadvantages of each material option. Figure 10 combines all results into one comprehensive table, with formwork performance color-coded.

Cost

XPS foam is a cost-effective material in the United States. Each material selected in comparison to XPS foam had an economic cost of similar magnitude. Low Density Cork had the highest cost at $100, while Bamboo and Cardboard had the lowest at $0 (Fig. 10). These lower costs are related to local material availability, where

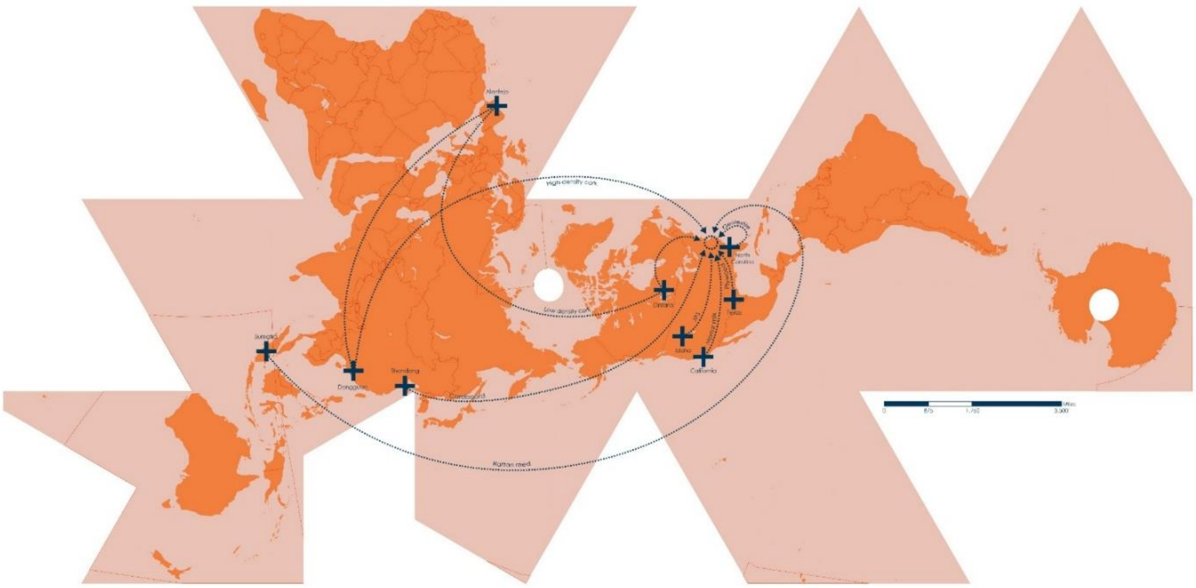


Fig. 5. Illustration of material pathways to testing site. Some materials had multi-leg, international journeys.

Cardboard and Bamboo were accessible as “recycled,” free materials to the researchers.

Labor

Labor is documented through the time spent working with each formwork material and the researchers’ own reflections on assembly and form removal (Fig. 10). The specifics of these reflections are important, as the type of labor as well as the fabrication time changed significantly between the materials. The lower carbon formwork options, including bamboo, reeds, landscape fabric, and cardboard tended to require more labor, as the fabrication of formwork became more time consuming. For example, the construction of bamboo and reed-based formwork involved creating planar transverse supports in which the bamboo or reeds were then set, followed by a layer of fabric or tape to hold the concrete (Fig. 6). Additionally, the removal of landscape fabric and cardboard took 5 to 10 minutes more than XPS foam and used hand tools such as chisels, while XPS released easily with no tools needed. The novelty of many of these materials necessitated extra time from the researchers to construct and dismantle the forms. Further time spent working with these new materials could reduce the time needed for fabrication. Some materials used CNC processes rather than manual construction: an Onsrud CNC Router was used to construct both the cork and XPS forms, drastically reducing the amount of labor required to achieve the desired shape in comparison to hand-manufacturing. This tool made the time necessary to construct forms easy to document. However, the machine is not widely accessible to many that work with concrete, so a range of successful fabrication strategies, like those utilized by the authors, are necessary.

Fig. 6. Formwork fabrication process, these images highlight the range of tools used to construct each form.

Environmental Impact

A primary consideration for evaluating formwork materials, environmental impact, is measured through the cost of embodied carbon for each material. Embodied carbon factors for each formwork material were researched and converted to the same unit to calculate the full embodied carbon (Fig. 7).

Cork, a bio-based material, has the lowest embodied carbon factors, but when considering the material's transportation (Fig. 5), these numbers outweighed those of the other formwork materials tested, including XPS foam. A material that could be a possible alternative to foam, and one that proves to be similar in its fabrication process, has high embodied energy due to its lack of availability in the United States.

However, the bamboo and landscape fabric formwork options have the lowest embodied carbon cost, which is promising for future formwork studies (Fig. 10). Both materials require better strategies for reducing fabrication time, which can also be attributed to the scale of the beam design and its impact on constructability.

Casting precision and aesthetic qualities

Both precision and aesthetic qualities of materials' casts are important secondary considerations in evaluating the success of a material's use in this study. At this scale, and with such novel techniques, casting precision naturally varies, but certain materials nevertheless fared far better than others. Considering the scale of these tests, most of the materials exhibited a high degree of precision as measured by the ratio of expected weight to measured weight. Unexpectedly, the formwork option with the best measured precision was the fabric form, which took an analog approach to fabricating the BSE generated beam shape. Notably, the bamboo form's shape did not achieve an accurate cast shape despite the accurate weight ratio recorded; the bamboo was not bound together tightly enough to prevent bulges in the fabric form between the reeds. Furthermore, each cast produced a unique aesthetic effect as shown in Figure 8. These aesthetic qualities may be primary reasons designers might choose one material over another.

Material	Weight (g)	Weight (kg)	ECC (kgCO2e/m3)	ECC (kgCO2e/m3) with transit	ECC (kgCO2e/m2)	ECC (kgCO2e/yd3)	ECC (kgCO2e/kg)	Density (kg/m3)	EC w/o transit (kgCO2e)	EC w/ transit (kgCO2e)
High Density Cork	4520	4.52	-116	5625.7				190	-2.76	134
Low Density Cork	2440	2.44	-116	2583.5				55	-5.15	115
XPS Foam	580.22	0.58022	500					45	6.45	6.45
Cardboard - Pancake	850	0.85			100		0.94	689	0.799	0.799
Cardboard - Section	100	0.1					0.94	689	0.094	0.0940
Bamboo	195.36	0.19536	-249.92	4.4				350	-0.139	0.00246
Reeds	76.4	0.0764	-249.92	???				400	-0.0477	???
Fabric	92	0.092					0.00235		.000216	0.000216
Plywood		3		96.52		127		600	0.483	0.483

Fig. 7. Table of embodied carbon calculations. Embodied carbon factors were converted to the same unit and compared before and after transportation was added.

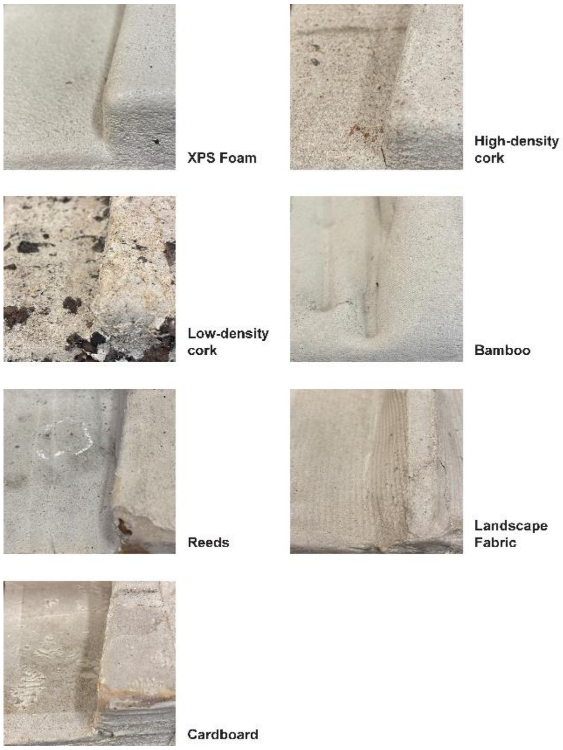


Fig. 8. Photographic comparison of cast beam texture, characterized by formwork material difference.

Conclusion

Concrete is a widely used material in the construction industry. Work to quantify and reduce this material's embodied carbon is well documented, but research gaps persist related to formwork materials. This research provides a framework for evaluating formwork materials related to concrete construction, one in dialogue with environment, economy, and labor.

Limitations and Future Work

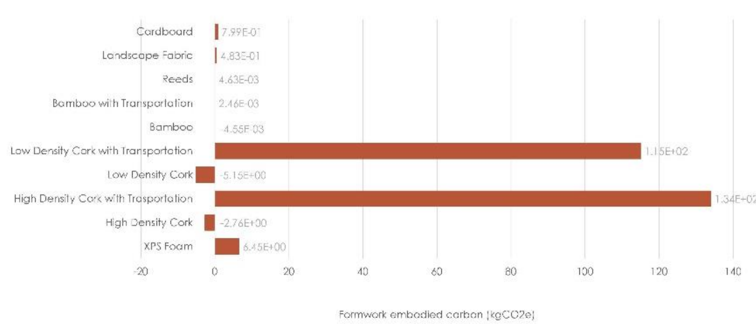
After analyzing formwork materials from this casting process, key materials will be selected to scale up for full-scale prototyping and stress testing. While the outcomes of this study are specific, a framework of quantifiable formwork material comparisons can guide future research into scalable and accessible methods for low-carbon construction.

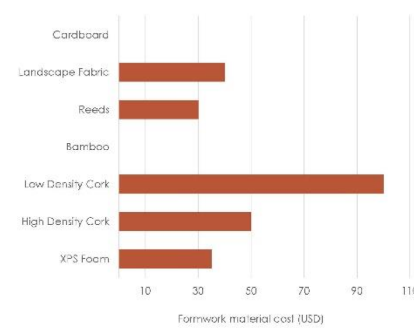
Concluding Thoughts

The results of this experiment were exhibited to the authors' University to inform and encourage ongoing discussions around the materials and fabrication methods used in architecture education. This dialogue mirrors the concerns of the architecture, construction, and engineering (AEC) industry, and suggests that the tools used in education can also improve through low-carbon design methodologies

Fig. 9. Cast beams and their formwork on display c. Tom Daly.

	Cost (Embodied Carbon)	Cost (Embodied Carbon + Transport)	Cost ($)	Fabrication time	Form removal time	Cast precision % difference real and designed weight	Cast quality	Fabrication notes	Path
1. XPS Foam	6.45	6.45	$35	**18 minutes** (CNC)	**approx 2 minutes** very easy to remove	**12% error** 6.8lb projected 6.0lb actual	**Very high,** with fine degree of precision and little residue.	Very straightforward to use and left in good condition after casting	Idaho
2. High Density Cork	-2.76	134	$50	**22 minutes** (CNC)	**approx 10 minutes** **approx 30 minutes** the cork did not release easily (2nd time)	**29% error** 6.8lb projected 5.4lb actual	**Very high,** with some cork particles still embedded	Need to be very careful with release agent, cork will soak it up	Alantejo Portugal, Dongguan China
3. Low Density Cork	-5.15	115	$100	**22 minutes** (CNC)	**approx 30 minutes** the cork did not release easily, form fell apart	**9% error** 6.8lb projected 7.4lb actual	**Medium,** precise but with a lot of cork particles embedded	Low Density Cork does not release well, only formwork to be lost to removal of cast	Alantejo Portugal, Ontario Canada
3. Bamboo	-0.00455	0.00246	$0	**30 minutes** (10 minutes cardboard cutting plus 20 minutes bamboo assembly)	**approx 5 minutes** jersey material made removal easier	**5% error** 6.8lb projected 7.1lb actual	**Low,** interesting texture but imprecise shape	Needs the be better constructed, promising formwork in terms of time needed and Embodied Carbon	Charlottesville
4. Reeds	0.00463	???	$30	**70+ minutes** (10 minutes cardboard cutting plus 60 minutes reed assembly)	**approx 5 minutes** thanks to masking tape, the formwork released	**4.5% error** 6.8lb projected 8.2lb actual	**High,** precise shape with visible reeds in the cast	Lightweight and low cost formwork, possibly some faster ways of constructing could be explored	Sumatra Indonesia
5. Landscape Fabric	0.483	0.483	$40	**180+ minutes** (60 minutes cutting base to size plus 120 minutes adjusting fabric)	**approx 10 minutes** some care had to be taken in the corners of the mold	**1% error** 6.8lb projected 6.9lb actual *analog recreation	**Very High,** with interesting texture	Takes a lot of pre-fabrication planning, but promising results	North Carolina
6. Cardboard	0.799	0.799	$0 - Recycled	**120+ minutes** (90 minutes cardboard cutting plus over 30 minutes assembly, including bandsaw)	**approx 15 minutes** parts of the masking tape got stuck	**2% error** 6.8lb projected 6.4lb actual	**High,** the pancake quality of the form transferred over to the cast	Very interesting end product, but time consuming	Shandong China





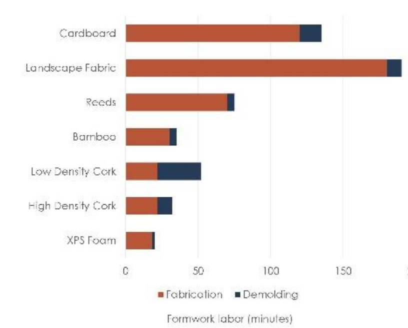


Fig. 10: Comprehensive table of results, summarizing embodied carbon, labor in time, accuracy, and cost of each formwork material along with reflections.

Notes:

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