Reducing the Global Warming Potential of Structural Reinforced Concrete: A Case Study

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Abstract

Overall, roughly a quarter of global greenhouse gas emissions are associated with the production of structural materials. Among those, approximately 7% are linked to the production of cement, which is one of the key ingredients in concrete, although it only counts for 10% of the concrete mix. Over the last 50 years, the worldwide production of cement has increased almost tenfold. In light of that number - which does not account for the other components of reinforced concrete- and in order to meet the requirements of the Paris Agreement, there needs to be a significant reduction of the carbon impact of the construction industry.

Arup has led an initiative to provide recommendations on how to improve concrete mixes and reduce their Global Warming Potential (GWP). This paper presents the highlighted recommendations and presents as a case study the results obtained from a project that followed these recommendations. The case study involved the replacement of rail platforms using low-carbon precast curb units. A review of key factors and avenues to improve the carbon impact of concrete mixes is presented and recommendations are given. The application of those recommendations and their impact on the project are discussed. Setting environmental targets allowed a reduction of the GWP of the concrete mix used by 50% compared to the average in the precast concrete industry, without inducing costs or delays. The success of the initial project has led to these recommendations being used on a subsequent platform project at a different site.

Keywords: Sustainability; Global Warming Potential; Fly Ash; Precast concrete

Introduction

In their recent report [1] International Panel on Climate Change (IPCC) highlighted that regardless of the greenhouse gases emissions, the 1.5°C increase of the overall global temperature set in 2015 in Paris would be reached before 2030. It is notable that a quarter of global greenhouse gas emissions are associated with the production of structural materials. As concrete is the most widely used building material due to its low cost and high workability, it accounts for a substantial portion of the emissions associated with construction.

Concrete is a building material comprised of 5 major components: coarse aggregates, fine aggregates, water, cement and air. While cement accounts for only 11% of the concrete's components by volume, it contributes between 85 and 90% of the total greenhouse gas emissions associated with concrete. With cement production having increased tenfold over the last fifty years it is imperative that concrete be evaluated to reduce its global warming potential.

While the best way to reduce the impact of the construction industry on greenhouse gas emissions is to build nothing, this is not a realistic option given the need for housing and to replace aging infrastructure. Retrofitting existing structures for alternate uses is a developing concept, but it is not yet sufficiently utilized to compensate for the carbon emission of new construction. As such it is imperative that structural engineers consider the environmental impact of the materials they specify.

In this paper a framework developed with an industry partner to evaluate opportunities to reduce the impact of concrete is presented and this framework is applied to a project performed for a client in the infrastructure industry.

Framework to Reduce Impact of Concrete

Structural engineers have many opportunities to reduce the embodied carbon of concrete in their role during the design process. However, structural engineers can only design the structures that clients actually want designed, which requires clients who value a reduction of embodied carbon in their concrete structures projects.

Concrete is comprised of cement, fine aggregates, coarse aggregates and chemical admixtures and a typical mix proportion and embodied carbon are summarized in Figure 1 below for a flat slab construction.

The primary sources of greenhouse gas emissions in concrete are the reaction of limestone at high temperatures which releases carbon dioxide as a byproduct (approximately 50%) and from the energy to heat the kilns (approximately 40%).

Reduction of the total life carbon of concrete can be achieved through both modifying the constituents of the mix and through procurement practices. Specifying target embodied carbon values for the concrete mix and lower carbon cement options can significantly reduce the carbon of concrete as can a more efficient structural design and the use of existing structural components where available through the renovation and expansion of existing structures in lieu of constructing a new structure. Specifying higher strength reinforcement can also reduce the carbon contribution of the reinforcement through the reduction of the overall amount of reinforcement needed. A key component of developing designs with lower embodied carbon is to carry over successful elements from previous projects. The best practices outlined in the recommendations case study have not been applied to a building yet but have been applied to a precast curb project that is presented as a case study.

Case Study: McGill Study – Recommendations

Arup was engaged to undertake a sustainable concrete study for McGill University. This project consisted of reviewing different strategies that could be used to reduce the overall embodied carbon from concrete. The four different strategies were identified as the following: *Design*, *Material Specification*, *Setting Limits* and *Procurement*.

Design

The initial design has the greatest impact on the embodied carbon of the structure, so considering design as a strategy for reducing embodied carbon in structures is an imperative first step. Methods for reducing embodied carbon through design are as follows:

1. Reuse and renovation of existing structures rather than building new, where possible.
2. Adopting realistic and appropriate design loading, rather than over or under-design of loading.
3. Design and adopt efficient slab systems design.
4. Maximize optimization of the overall structural design
5. Specification of the appropriate type of concrete system for the project.

Material Specification

Once a structural design has been optimized to minimize the embodied carbon of the overall design, further reduction of the embodied carbon of the concrete used in the structure is possible. This is through reviewing what the materials are that are being specified, and substituting materials who's production results in lower levels of embodied carbon. Figure 1 illustrates the embodied carbon for a typical Portland cement concrete.

Cement Type

The carbon footprint of concrete is mostly due to the Portland cement in its mixture. Excluding contribution of reinforcement, while cement makes up only 10-12% of concrete's total volume it represents 85-90% of the concrete's global warming potential.

Portland cement product can be substituted with Portland limestone cement. The limestone used in Portland limestone cement is used as a partial substitution to sand or cementitious material and increases the percentage of fines in the concrete. The limestone is finely ground, which contains high levels of calcium carbonate. General Use Portland-Limestone cement is widely standardized and is widely used, with limitations around reduced workability and reduced resistance to sulfate attack to be considered when specifying it.

	Portland cement	Aggregates	Supplimentary cementitious materials	Reinforcement
Standardized Initiatives	Portland limestone cement	– High-strength aggregates – Well graded aggregates – Avoid lightweight aggregates – Recycled aggregates – Secondary aggregates	– Ground granulated blast furnace slag – Fly ash – Silica fume – Ground glass pozzolans – Natural pozzolans – Calcinated natural pozzolans	Higher-grade steel reinforcement
Low carbon proprietary technologies	– CarbonCure – CarbiCrete – Synergia Ciment Québec – Solidia	Carbon negative aggregates	Carbon upcycling	

261 $kgCO_2e/m^3$
Total embodied carbon excluding reinforcement

	Portland Cement[A]	Water[B]	Coarse Aggregate[C]	Fine Aggregate[C]	Supplementary Cementitious Materials[D]
GWP factor[1] ($kgCO_2e$/ton)	940.50[3]	0.06	4.82	4.82	184.60
Mix proportion[2] (kg/m^3)	251.00	156.00	782.00	1046.00	84.00
Embodied carbon ($kgCO_2e/m^3$)	236.00	0.01	4.00	5.00	16.00
% Volume of concrete	11	7	34	45	4
% Embodied carbon of concrete	91	0	1	2	6

Sources:

A. EPD General Use and Portland-Limestone Cements, Cement Association of Canada

B. Based on Canadian water consumption studies

C. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential, Athena Sustainable Materials Institute

D. This is based on slag as a supplementary cementitious material. This is a conservative value taken from EC3.

Notes:

1: The global warming potential (GWP) refers to the amount of heat trapped in the atmosphere from greenhouse gases in terms of carbon dioxide equivalent (CO2e). It is used to report the embodied carbon of a material or product.

2: This is based on the CRMCA mix #31: 30 MPa with 25% Slag from A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by CRMCA Members, Athena Sustainable Materials Institute.

3: This is based on documentation that has been expired.

Figure 1 - Mix proportions and carbon footprint of a typical Portland Cement concrete[8] [9] [10] [11].

Supplementary Cementitious Material

Supplementary cementitious material can also be used to reduce the cement content and therefore the embodied carbon of the concrete mix; however, these materials can impact the strength, durability, volume stability, rate of strength gain, workability, and overall performance of the concrete. Examples of supplementary cementitious materials are the following:

- Ground granulated blast furnace slag
- Fly ash
- Silica fume
- Ground glass pozzolan
- Natural pozzolan

- Calcined natural pozzolan

Low Carbon Proprietary Technologies

Proprietary low-carbon technologies are available and vary globally, some examples of ones that are available in the North American market are as follows:

- CarbonCure
- CarbiCrete
- Synergy Process of Ciment Quebec
- Carbon Upcycline
- Solidia

The above-mentioned technologies vary, but all consist in re-using carbon dioxide as a product to “recycle it”: consequently, less cement is needed in the concrete mix.

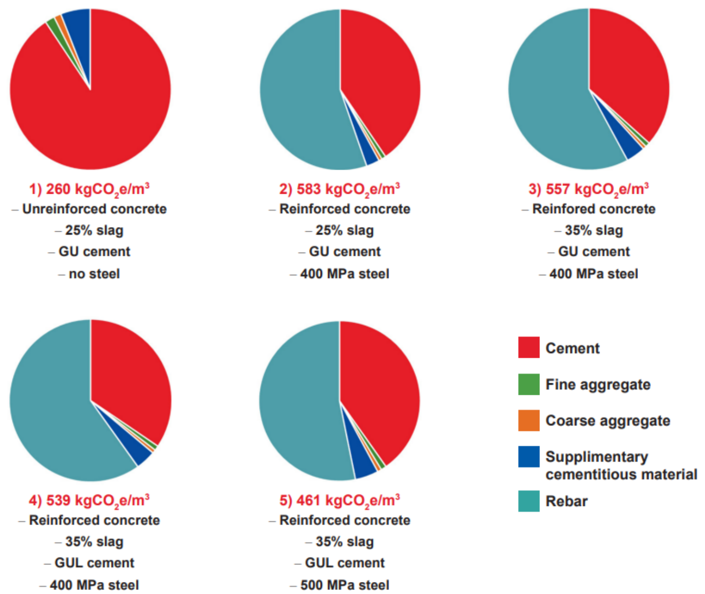
Aggregates

Aggregates make up the largest portion of a concrete mix, and therefore can contribute significantly to the embodied carbon of the material. Using high strength aggregates and optimizing the grading of the aggregate to utilize a well-graded mix reduces cement content in the concrete mix. It is for this reason that light-weight concrete (which is achieved by using low density aggregate and greater cement content) is more carbon intensive than normal weight concrete. Recycled aggregates can also be used (Recycled Concrete Aggregates) and their usage is codified in CSA A23.1:14/CSA A23.2:14 [5]. Recycled aggregates are categorized as Construction and Demolition Waste (CDW), Reclaimed Concrete Material (RCM) and Returned Hardened Concrete (RHC). The use of recycled aggregate will impact the performance of the concrete and needs to be carefully considered when specifying recycled aggregates.

Reinforcement

Another significant contributor to the embodied carbon of concrete is the reinforcement that is used. Using higher strength reinforcement reduces the overall amount of reinforcement required for a project, thus reducing the embodied carbon contribution of the steel. It should be noted that the design of concrete reinforcement is often governed by the minimum area of reinforcement steel required, and in such scenarios, there is no embodied carbon savings associated with the use of a higher strength steel.

The impact of implementing all the above material considerations on the embodied carbon of a concrete mix can be seen in Figure 2.



Notes:

1: The first pie chart represents an unreinforced concrete mixture. It is CRMCA mix#31: 30 MPa with 25% slag and Portland cement (GU). It contains no steel reinforcement.

2: The second pie chart represents a reinforced concrete mixture, CRMCA mix#31: 30 MPa with 25% slag and GU cement. It contains 400 MPa steel reinforcement.

3: The third pie chart represents a lower carbon reinforced concrete mixture, CRMCA mix#35: 30 MPa with 35% slag and GU cement. It contains 400 MPa steel reinforcement.

4: The fourth pie chart represents a lower carbon reinforced concrete mixture, CRMCA mix#36: 30 MPa with 35% slag and Portland-limestone cement (GUL). It contains 400 MPa steel reinforcement.

5: The fifth pie chart represents a lower carbon reinforced concrete mixture, CRMCA mix#36: 30 MPa with 35% slag and GUL cement. It contains 500 MPa steel reinforcement. Assumed recycled content of 500MPa is similar to 400MPa grade.

6: The design for pie charts 2, 3, 4 and 5 is for a 250 mm thick suspended slab

7: This figure first shows the significant impact of rebar on the embodied carbon of a reinforced concrete slab. The impact increases from 260 kgCO2e/m3 to 583 kgCO2e/m3. However, by introducing a higher slag percentage to replace cement, the embodied carbon decreases to 557 kgCO2e/m3 and by switching to GUL cement, it decreases to 539 kgCO2e/m3. Finally, by selecting higher strength rebar, the embodied carbon is further reduced to 461 kgCO2e/m3 for a 21% reduction from mix 2. This is achieved through a standardized approach.

8: The lower carbon reinforced concrete mixes (3, 4, 5) do not represent an aggressive low carbon concrete mix. The mixes were selected for their data availability and transparency from Concrete Canada. All mixes are from A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by CRMCA Members, Athena Sustainable Materials Institute. The GWP values for each constituent are from Table 1.

Figure 2 - Concrete mix embodied carbon case studies [7][8].

Setting Limits

Limiting the overall cement content in a concrete mix is another effective way to reduce the overall embodied carbon in concrete material. These recommended limits undertaken as part of the McGill University study have not been tested within the local market due to the limitation of Arup's scope. Assigning limits needs to be done on a location specific basis and is dependent on available information from the cement industry. The figure below presents embodied carbon limits provided under EPD10092 for Portland Limestone Cement (GUL) with varying type and level of cement replacement and an industry average benchmark [7][8]. The McGill limits outlined in Figure 3 have been obtained using a higher level of cement replacement.

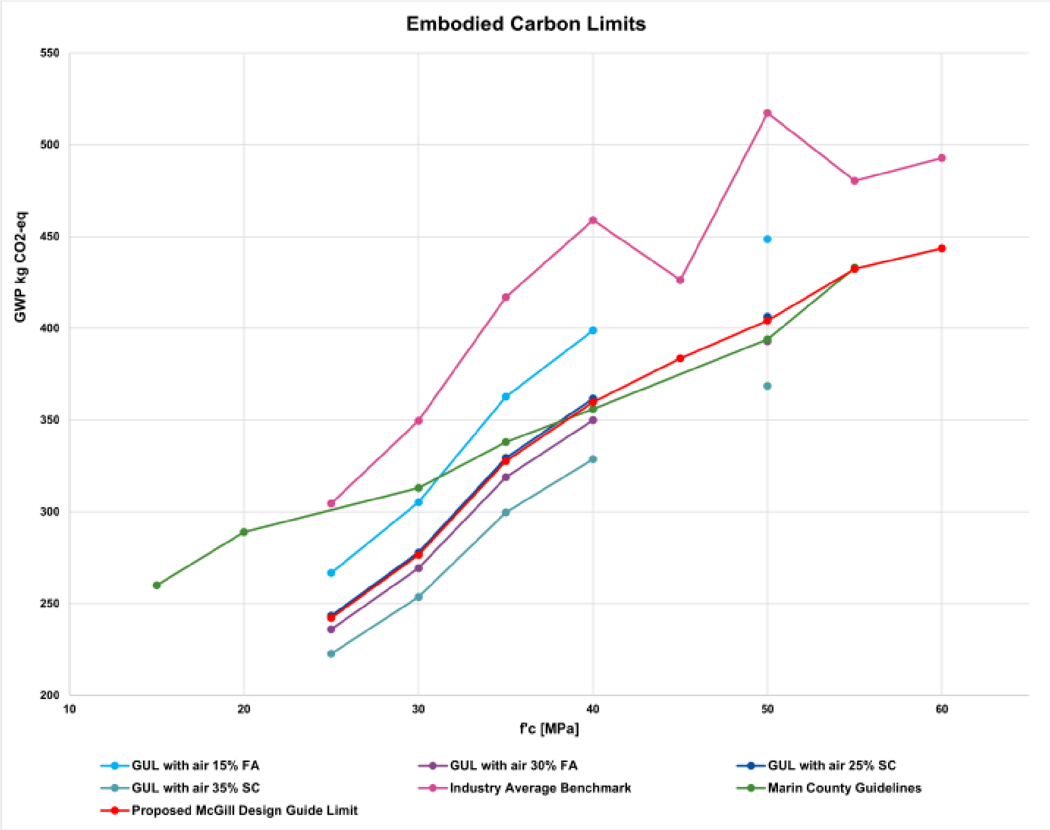


Figure 3 – Embodied Carbon Limits

Procurement

Procurement must be considered when specifying a sustainable concrete mix. This includes ensuring local availability and responsible sourcing of supplementary cementitious materials, as not all supplementary materials are available globally. Depending on a project's location, some material may not be available at all or may require substantial transportation, which has its own embodied carbon implications. Therefore, utilizing locally sourced materials may end up having a lower embodied carbon than internationally available supplementary cementitious material once transportation is included in the embodied carbon calculation. Furthermore, local standards, specifications and regulations may prevent the use of some lower carbon material substitutes, and therefore must be adhered to when specifying the concrete mix.

Overall, the specification and design of a custom concrete mix in general needs to be done with consideration for its specific application, as well as the environment and jurisdiction. It is important to gather as much information as possible about proposed products, mixes and solutions, where testing may be required to prove the proposed mix meets the required design performance. When considering the available information, it is extremely important to identify all the applicable structural and durability related properties needed for the design, as these may govern the mix design depending on the project problem.

Case Study: Low-Carbon Precast Curbs

Arup services have been retained to act as lead technical consultant for the reconstruction of Via Rail Brockville and Brantford Stations. The project consisted in assisting Via Rail with the retrofit of platform of existing train stations, with a scope centered on increased durability, cost efficiency and duration of installation. Retrofit was deemed needed since the platform were over 20 years of age and deteriorated. Figure 4 shows an aerial view of the platform to be replaced.

Figure 4 - Brockville station. Platform circled in black.

Considering the volume of traffic on the track, having a technical solution for the platform retrofit that allows minimal installation time and that maximizes worker safety is of the utmost importance. Various strategies were considered, among them the use of precast curbs to be assembled on site. Figure 5 shows an overview of the platform suggested, with the overall layout of subbase, curb and platform with regards to the track. Figure 6 shows the precast curbs in detail. To cover the entire length of the platform, a series of 40 units were required.

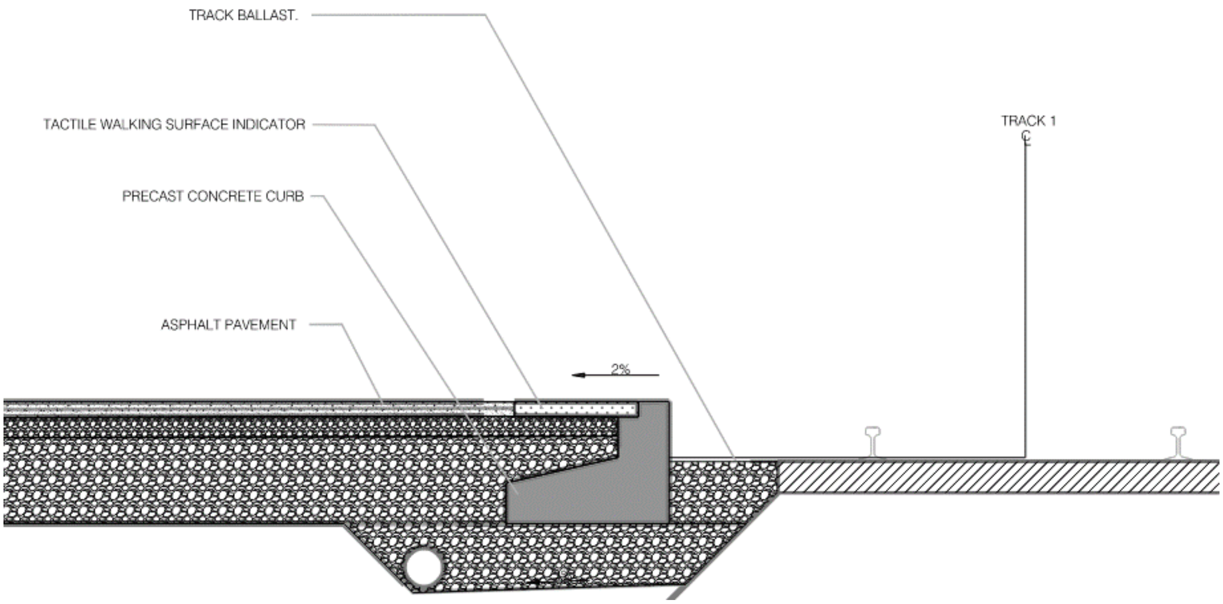


Figure 5 - Section cut of the new platform

a) b)

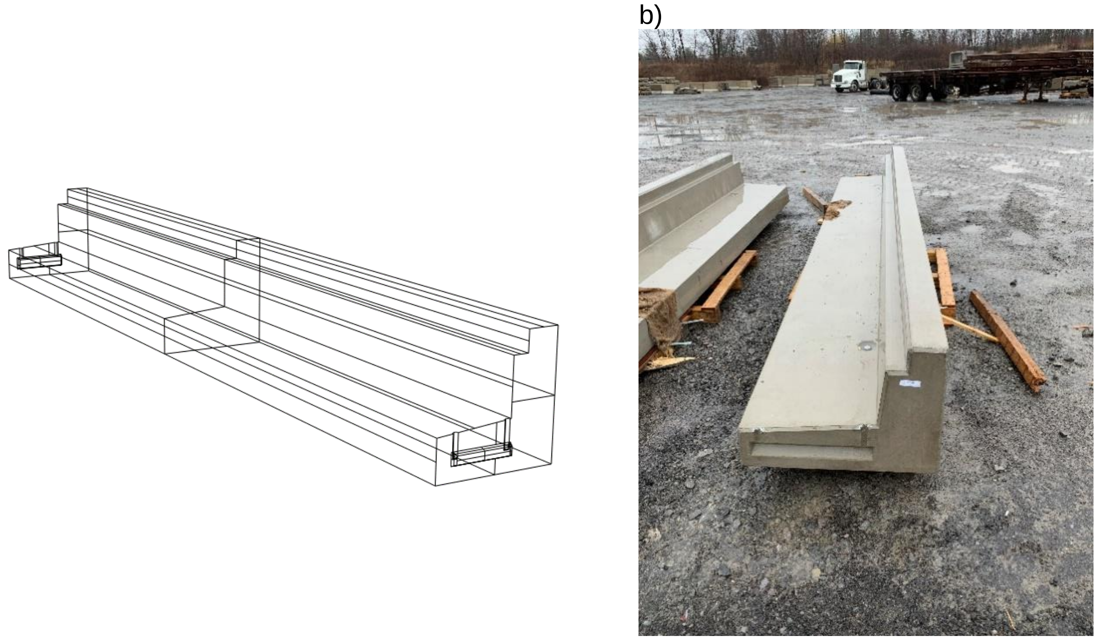


Figure 6 - Curbs designed for the corridor replacement program: a) 3D isometric view and; b) picture of a precast curb

Design Hypothesis

Curb was designed following the requirements of CSA A23.3-14 [2] and of the NBCC 2015 [3]. Considering that the curbs would be only loaded during transportation (that is under their self-weight), the load combination considered for design was 1.4D. The reduced loads were not significant, therefore the reinforcement suggested for the curb was selected as the minimal reinforcement that would allow for curb transportation without cracking.

The curbs were designed with shear keys (protruding and intruding) so that they could be slotted in with one another upon installation and locked into place by grouting the shear keys. Figure 7a shows a section cut of the shear keys. As the platform is accessible by any vehicle, the live load considered to be applied on top of the curb corresponds to the highest load pressure listed in the NBCC, that is 12 kPa. The shear key was designed in such a way that the shear resistance provided by the shear key would be sufficient to resist the live load imposed by the vehicle without any differential displacement happening in between curbs. Figure 7b shows the shear key in the curbs.

a) b)

Figure 7 - Shear key: a) front view and; b) picture of the recessing portion of the shear key on the precast curbs

Section Shape

Reducing the carbon cost of any given structural item starts with reducing the overall concrete quantity used. Instead of using rectangular section curbs, a stability analysis was performed to achieve a curb section with global stability against sliding and overturning. Overall, the optimization performed allowed a reduction of the section area by 46%, compared to a rectangular section.

Material Used

As the tracks themselves are not Via Rail property, and as all construction work operations have to be stopped when a freight train passes for safety reasons, it is imperative to reduce the time required to install the curbs. To minimize the installation time of the curbs, it was decided to produce them out of precast concrete. The use of precast removes the forming, casting, and curing time on site and improves quality as the concrete works are completed in a controlled indoor fabrication facility. The precast curbs are then transported to site and can be installed quickly by lifting them into place and grouting between the units. Figure 8a shows a picture taken during the installation of a curb. Using precast induces requirements: as the units have to be cast in a mould, which allows only two units to be poured at a given time, the time duration between the pour and the removal of the units from the mould is the critical factor on the project's critical path. To optimize production, the precast supplier recommended the use of a 35Mpa concrete. As the platforms are heavily exposed to chlorides, CSA A23.3 [2] recommends the use of C1-class concrete for chloride exposure [5], that needs to reach a compressive strength of 35 MPa. The use of a 35 MPa concrete was aligned both with the code requirements [2] and with the overall low-carbon target. Regarding the rebar used, it notable that given the reduced loads, the minimum steel area governed the design, allowing no embodied carbon reduction through use of higher strength steel. Regular 400 MPa steel was specified, to reduce the associated costs.

a) b)

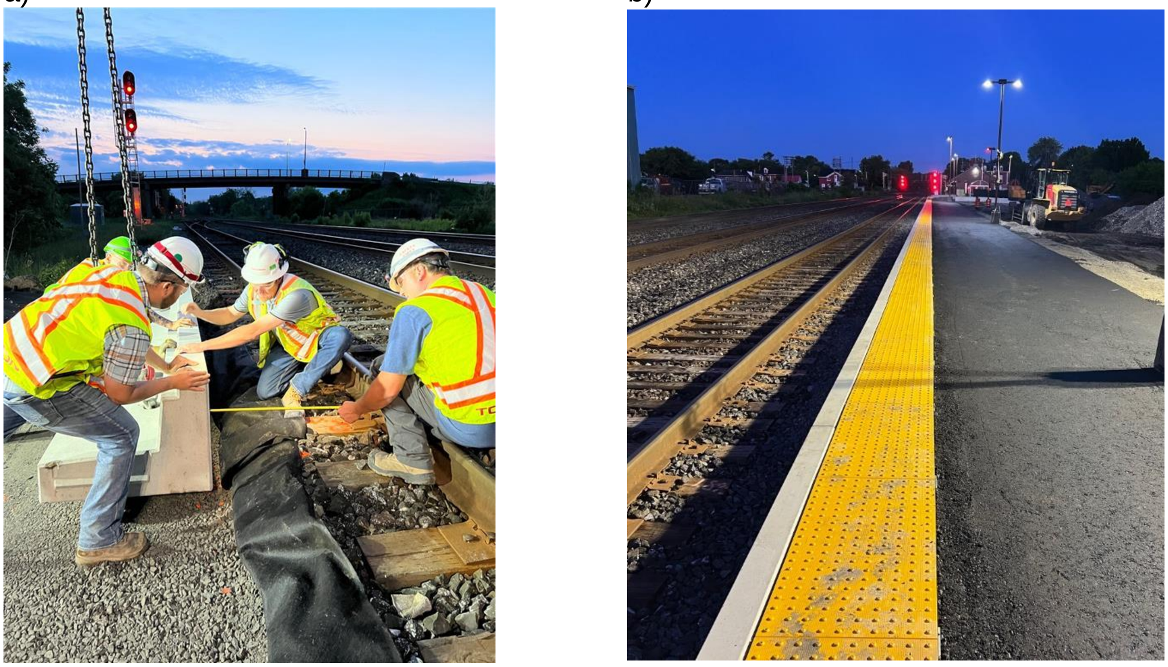


Figure 8 - Installation of a precast curb along the track.

Concrete mix optimization

Once the materials to be used are selected, the specifications of the concrete required are set and sent for tender. These have been written considering the recommendations from the study presented in the previous sections. Overall, GWP was set to 180 kg CO_2 eq. For comparison, the latest Environmental Product Declaration (EDP) for structural precast concrete gives an industry average GWP of 256 kg CO_2 eq. (42% increase) [6], while the last EPD for ready mix concrete indicates an industry average of 165 kg CO_2. (9% decrease), [7].

Discussions with the concrete supplier allowed an optimal solution to be reached, compatible both with the supplier production abilities and the low-carbon goal set by Arup. A significant proportion of cement replacement (50% cement, 50% slag) was initially suggested. However, maintaining the 50%-50% split increased the curing time substantially, thereby increasing the production time and the associated costs. It was consequently decided to limit the cement replacement to 35% (65% cement, 35% slag). Final concrete mix was rated at a 129 kg / T CO2 eq, half the GWP of industry average for precast [6].

Conclusions

Through the two case studies, the McGill Recommendations case study and the Low-Carbon Precast Curbs case study, Arup have had extremely positive results with the client's satisfaction with the project results. The industry partners have been highly receptive to the ideas presented in these case studies and to further pursue sustainability and sustainable development. Through the case study presented, a significant reduction of GWP for precast concrete mix has been achieved, without additional costs or delays, and with a great response from all stakeholders.

Further steps include continued modification of specifications to include the strategies outlined in the McGill Recommendations case study. Developing a carbon budget for the whole project would allow for some flexibility in where carbon reduction is focused on the unique challenges and opportunities of each project. While the environmental impact is paramount, reducing the overall volume of materials in projects will help reduce overall project costs as material costs continue to increase, providing an additional incentive to clients.

By implementing innovative solutions, structural engineers are able to reduce the carbon impact of the built environment. While the industry is not always quick to adapt to change, there are clear signs that owners and contractors are beginning to value the carbon mitigation strategies presented in this paper.

Acknowledgments

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