REDUCING EMBODIED GREENHOUSE GASES IN LIGHT RAIL INFRASTRUCTURE

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Abstract

Fast, reliable and affordable alternatives to driving, encourages sustainability: transit connects people and communities; transit gets people out of cars and improves the planet's air and water quality; transit provides access to jobs and reduces demand on fuel. The triple-bottom-line of people, planet, and prosperity is a natural fit for transit.

Transit agencies focus on operational efficiencies which, over the lifetime of the facility, dwarf the resources consumed during construction. However, in the process of building transit infrastructure and other mega-projects, significant energy is consumed and greenhouse gases are released. This creates an embodied impact rarely measured in detail during the project scoping and planning phases. Given the magnitude of construction material needed, there is a missed opportunity to minimize material use. As the stewards of public funds, transit agencies often invest their limited capital on the steadfast, stout designs and not on emerging technologies or leaner construction.

The authors recently embarked on the task of measuring the greenhouse gas impact of one regional transit agency's light rail expansions. Their goal was to use sound, current green design practices to help the owner of this mega-project take reasonable and measured steps to improve the environmental impact of their concrete infrastructure. By understanding the scale of embodied greenhouse gas impacts of the structural systems, fine-tuning their concrete specifications, and bringing owners, contractors, engineers and suppliers together, the team proposed that millions of pounds of greenhouse gas savings are possible. This is good news for the environment and the results advance the technical savvy of the region's design and concrete industries.

With 37 miles of funded light rail expansion, the authors estimate the amount of concrete procured would exceed half a million cubic yards. From massive concrete boxes to form underground stations, miles of box girders for aerial guideways, to giant drilled shafts for guideway support, the concrete needs to be strong and durable. Given the magnitude of the project's scale and with slight optimization, the opportunity to reduce cement content, even minimally, has a significant potential to reduce greenhouse gases.

After calculating volumes of concrete currently designed along the light rail alignment, The authors reviewed the performance and constructability requirements of elements with the largest impact. Working with the owner, they proposed adjustments to standard specifications and approached suppliers to find economical, workable, and available concrete mixes.

At the end of their task, with only minor modifications to specifications, no compromise to performance or constructability, and little, if any, cost premium, the team created a model standard for project consultants and contractors to follow. With this information, the owner can incorporate measurable benefits and leverage their buying power to reduce the impacts of their construction. The resulting adjustment in practice will strengthen local knowledge and capability, enabling wider regional adoption and allow agencies to deliver on their mission of realizing sustainable transit for the region.

Topics: Integrated design processes, multidisciplinary collaboration; Low-carbon structural materials; concrete; portland cement; greenhouse gas;

INTRODUCTION

In the next 10 years, Sound Transit will design, build and commence operation on 37.5 miles of light rail to fulfill its mission of providing mobility and transit choices to the central Puget Sound region in Washington state. As a regional transit authority for Pierce, King and Snohomish counties, Sound Transit's unprecedented investment in rail infrastructure also brings significant construction impacts and opportunities associated with the use of concrete.

The greenhouse gas, embodied energy, water and land use impacts of this material, which is unquestionably essential to infrastructure construction, is often viewed as unavoidable. The negative impacts of using concrete are viewed as short-term burdens that are far outweighed by the positive environmental and societal benefits that come from a well-functioning light rail system with a long-term service life.

While concrete may be a given in the palette of infrastructure design materials, the degree of impact of concrete – from embodied energy to the product's life-cycle greenhouse gas release – is far from a fixed value. This report addresses potential, industry-proven approaches that lessen the impacts of concrete, specifically greenhouse gas (GHG) emissions associated with portland cement content.

This report is based on a consultant team's report to Sound Transit. It offers a quantitative view of the impact of Sound Transit's concrete mix design, as well as what is currently possible and available from local suppliers. This report quantifies the potential greenhouse gas emission reductions that are under Sound Transit's control as they specify, design and build with concrete in portions of East Link, North Link and the planned extensions to Federal Way and Lynnwood.

The benefit of this analysis is two-fold: it provides Sound Transit magnitude of this opportunity, suggests realistic lower cement mix designs and offers suggested steps to assume a leadership position by proactively and dramatically reduce embodied GHG emissions and energy use from infrastructure concrete before they become another unquestioned "given" in construction.

Methodology

To obtain the findings of this report, the team completed the following. Each step is detailed in the followings sections.

1. Defined the scope (the physical extent) of the study

2. Estimated the quantity of concrete that will be placed (used) in the future light rail alignments
3. Identified an "average" concrete mix design that represents the business-as-usual mix (and cement content) for the most common concrete uses.
4. Met with concrete suppliers to understand the concrete market and what lower-cement mixes that are currently available to are cost and schedule competitive.
5. Calculated the greenhouse gas emissions for the business-as-usual mixes and the optimized lower-cement mixes.
6. Quantified the potential greenhouse gas emissions if Sound Transit consistently used these mixes.
7. Made recommendations for lower-cement mix implementation and risk mitigation.

ESTIMATING CONCRETE CONSUMPTION FOR LIGHT RAIL

Projects Analyzed

In collaboration with Sound Transit's structural engineering liaison the consultant team first defined this report's geographic scope, focusing solely on future light rail system and park-and-ride facilities. The team then quantified the amount of concrete for designs not yet finalized, where an opportunity exists to use optimized concrete mixes with lower cement content. The following infrastructure was studied.

North Extension (Northgate Link and Lynnwood Link Extension)

- An underground station at Roosevelt
- An underground station at U-District (formerly Brooklyn Station)
- Grade alignment from the tunnel portal just south of Northgate station to the Northgate Station.
- Preferred Alignments A1, B4, and C3M from Northgate station to Lynnwood based on the Draft Environmental Impact Statement (DEIS)

The tunnel from University of Washington station was excluded because a tunneling contract has already been awarded for that work, but underground stations north of University of Washington station contracts have not been awarded and contain significant concrete volumes. Aerial stations such as Northgate were excluded due to the effort needed to capture relatively small concrete volumes.

East Extension (East Link)

- Final Alignments B2M, C9T,and D2A, from the East Channel Bridge west of Mercer Island to the terminus at Overlake Station
- Includes a sequentially-mined tunnel segment in Downtown Bellevue
- A 1400-stall parking garage at South Bellevue station
- A 320-stall parking garage at Overlake station

A portion of East Link is in 60% final design. The team used preliminary design documents with some updates. The portion between Seattle and Mercer Island is built upon existing infrastructure, representing a relatively small amount of new concrete.

Figure 1: Alignment Map

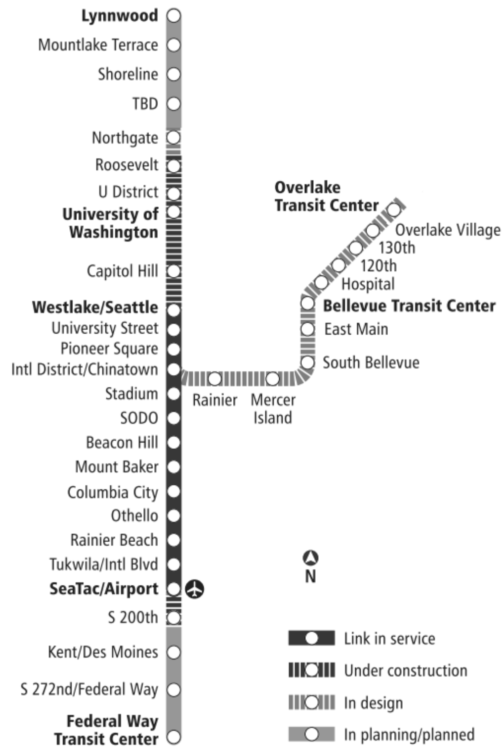


Figure 2: System Station Map

South Extension (Federal Way Link Extension)
Since this extension does not yet have an alignment selected for a DEIS, the team based all quantities on an assumed 70 percent of elevated alignments and 30 percent at-grade alignments. To estimate quantities, the team applied an estimated cubic yards of concrete per linear feet of alignment type based on East Link take-offs.

In all alignments, concrete pavements for roadways, parking lots, and sidewalks were not addressed. The concrete mixes for these pavements are usually specified by the city having jurisdiction, and therefore Sound Transit is not able to directly adjust the specifications for the work. For similar reasons, concrete for proprietary structures, such as panels for mechanically stabilized earth, was not included in the estimate.

Alignments and station maps are provided in Figures 1 and 2. Note that the projects analyzed are colored solid gray or a hatched gray in the figures.

Quantity Estimates

Estimates of concrete quantities for the alignments studied are listed in Table 1 by use type. While estimating an exact amount of concrete for these projects is not possible due to the constant variation in topographic conditions and variables during construction, the team used an approach that provided a high level of accuracy for the purpose of forecasting greenhouse gas emissions related to the projects' anticipated concrete usage. Depending on the detail of the engineering drawings available, the team used three methodologies:

For East Link, Roosevelt and U-District Stations

The team measured the volume of concrete from drawing cross-sections and typical details (See examples in Figures 3 through 6), and then multiplied the area of concrete by the applicable length to yield an estimated concrete volume.

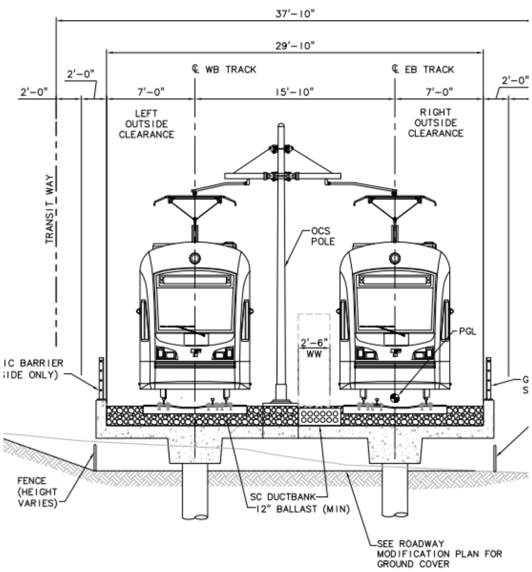


Figure 3: Trestle Alignment

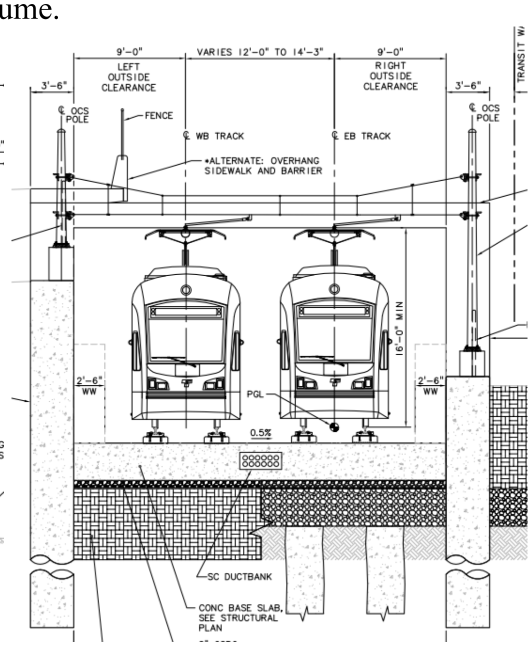
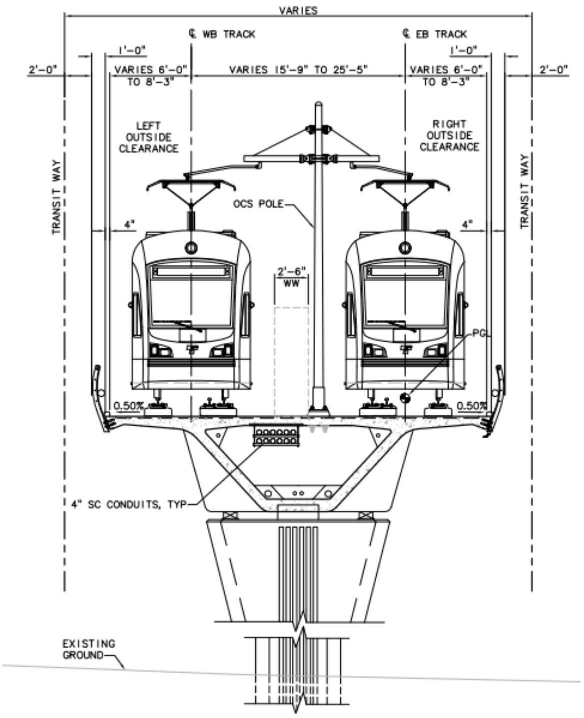


Figure 4: Secant Pile Retained Cut



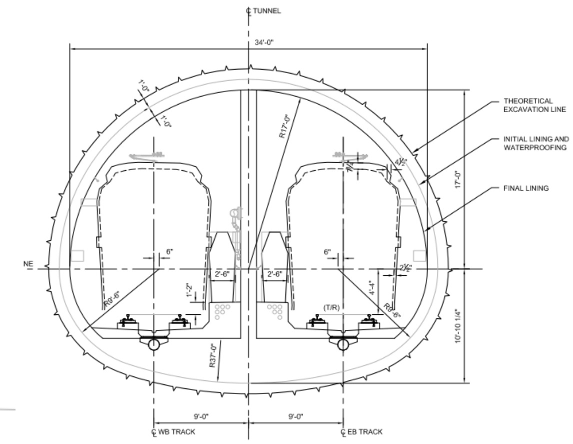


Figure 5: Aerial Guideway with Column

Figure 6: Sequentially-Excavated Tunnel

For All Other Segments

After reviewing the available preliminary drawings, the team divided the alignments into the following categories: at-grade, segments with retained grade, elevated and tunnel. The transitions between at-grade and elevated were treated as segments with retained grade. For each of these alignment categories, the team identified and proposed a representative condition to Sound Transit – a typical cross-section or other detail that most closely reflected the average. Once the team quantified the area of the representative conditions, that area – by its applicable length – yielded the estimated volume of concrete.

For Park-And-Ride Garages

To quantify the amount of concrete in structured parking facilities that do not yet have detailed design drawings, the team quantified the historic concrete volumes in previous Sound Transit parking garages. For the parking decks' concrete volumes, the team was able to calculate a per-stall concrete average and then apply that factor to the number of stalls at the planned park and-ride facilities. See Figure 7 for drawings of one of the proposed garages.

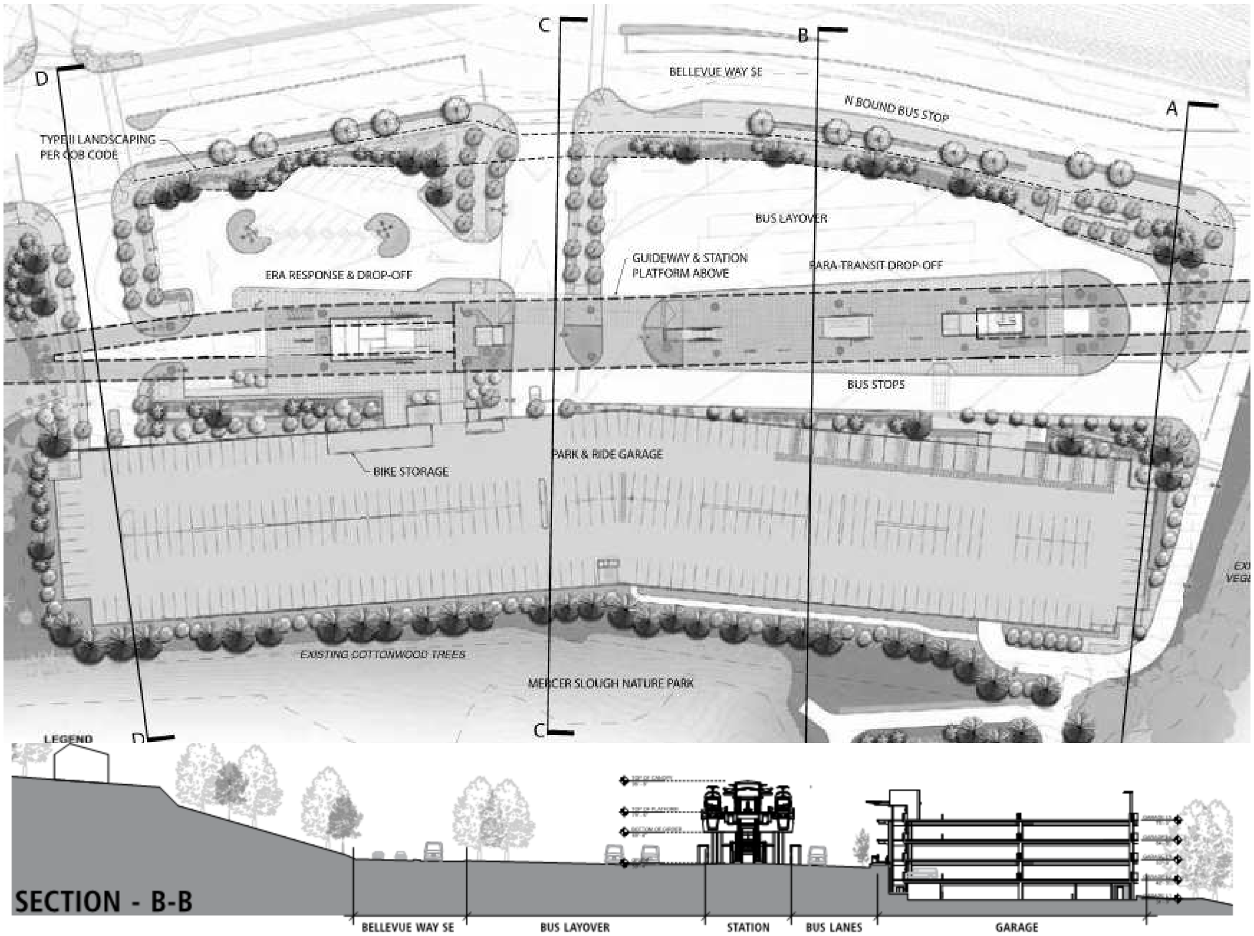


Figure 7: South Bellevue Parking Garage

Identification of Concrete Uses for Study

Once quantity estimates were presented, Sound Transit's engineering liaison suggested that the team focus on the following concrete applications which he identified as the most suitable or promising candidates for evaluating lower cement content mixes. For scope and budget reasons, the study was limit to four applications:

- Footings or slab-on-grade
- Shaft foundations
- Guideway columns
- Guideway superstructure/girders

These applications had the greatest potential to reduce the cement consumption of the entire light rail build-out, because of their required volumes and their potential to reduce cement contents without significantly increasing curing time (a common tradeoff of increasing supplementary cementitious materials while reducing cement).

IMPROVING EMBODIED GREENHOUSE GAS EMISSIONS OF CONCRETE MIXES

Identification of the Business-As-Usual Baseline Concrete Mix Designs

Concrete mixes are constantly being adjusted, and ingredients vary by each individual concrete supplier. There is not a prescriptive concrete mix specified constantly for commonly occurring concrete applications. The team overcame this challenge by using averages from mix design information submitted by contractors from previous Sound Transit projects as a simulation of future concrete work. This defines what concrete would be delivered if Sound Transit continues with Business-As-Usual (BAU).

The magnitude of greenhouse gas emissions created by placing concrete is primarily related to the amount of cement. By multiplying the mix proportions for one cubic yard of concrete by the concrete volumes, consumption of cement (and other ingredients such as water) was totaled for each use.

High-strength concrete and concrete that achieves strength quickly typically has more cement than average. Totaling cement quantities identifies these mixes, and their relative impact. For instance, shaft foundations for aerial alignments will require more concrete than any other use. Guideway girders will require the second largest amount of concrete by volume and more total cement overall. This is because guideway girders are precast, and such plants use large amounts of cement to accelerate curing in order to reuse forms most economically. High-cement uses, either by total volume or high proportion, were targeted with the intent that even modest reductions in cement content will significantly reduce overall GHG impacts.

Meetings with Concrete Suppliers

With BAU cement averages for common applications defined, the team met with the following concrete suppliers to understand how the cement content in the mixes could be reduced while still meeting the required structural and constructability requirements:

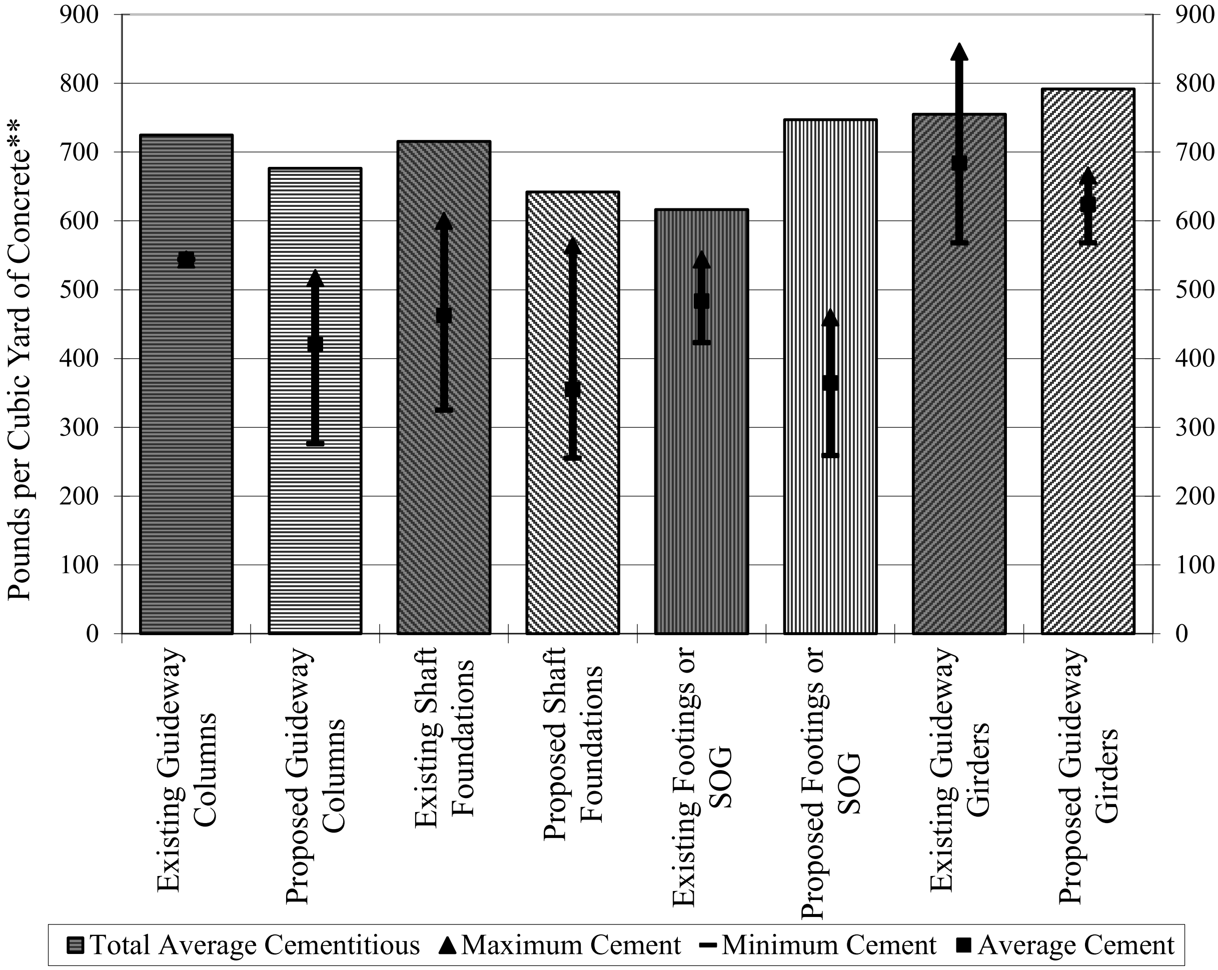
- Stoneway Concrete, Oct. 15, 2013
- Cadman Concrete, Oct. 17, 2013
- BASF Concrete Admixture Systems, Oct. 17, 2013
- CalPortland, Oct. 17, 2013
- Concrete Tech, Dec. 19, 2013

The team asked suppliers to review the business-as-usual cement contents for the four priority applications and requested that they suggest optimized mixes that reduce the cement content while meeting the same structural requirements.

Calculation of GHG Emissions and Potential Savings

After obtaining the lower-cement mix designs from the Stoneway Concrete and CalPortland, as well as the life-cycle assessments for lower-cement mixes from Cadman and BASF, the team calculated the difference between the average BAU cement content and the average cement content for the lower-cement mixes for each of the four applications. This difference yielded savings of cement per cubic yard of concrete placed per application. This amount was multiplied by the number of cubic yards estimated for each application in the alignments to get the total cement savings.

Comparisons of existing and proposed concrete mixes are shown in Figure 7. Note that the bars indicate average total cementitious content of mixes provided, which includes portland cement, fly ash and slag cement. Lines indicate the range of portland cement content with the square being the average of the mixes provided.



**multiply by to 0.593 convert to kg/m^3

Figure 7: Cementitious Content of Existing and Proposed Concrete Mixes by Type

Normalizing the Mixes Proposed by Suppliers

In reviewing the proposed mixes from various suppliers for each concrete application, it became clear that the degree that greenhouse gases reduction depends on both on the specific capabilities of a supplier and on the season, since the amount of cement will vary in response to summer and winter ambient temperatures.

For each use, the team averaged the quantities of ingredients (cement, water, etc.) needed for each mix proposed. The team also isolated the mix designs with the highest cement content and the lowest cement content. These two mixes provided a probable range of results. We did not include the business-as-usual mixes in the results if the same supplier could provide an improved mix. Table 1 summarizes the average optimizations and compares them to the business-as-usual totals.

Table 1: Average of Proposed Optimized Mix Quantities by Ingredient and Use

	Concrete For	**Volume (yd^3)***	**Water in Mix (lb/yd^3) ****	**Cement in Mix (lb/yd^3) ****	**Total Water (lbs)*****	**Total Cement (lbs)*****
Aerial Alignments	Guideway Girders	100,000	254	624	26,000,000	65,000,000
	Shaft Foundations	130,000	236	355	31,000,000	47,000,000
	Guideway Columns	28,000	235	421	6,500,000	12,000,000
Non-Aerial Alignments	Tunnel	28,000	235	421	6,500,000	12,000,000
	Trestle	50,000	224	375	11,000,000	20,000,000
	Footings, Slab on Grade	91,000	223	364	20,000,000	33,000,000
Other	Track Plinths	24,000	254	534	6,200,000	13,000,000
Below Grade Stations	Walls	15,000	242	480	3,700,000	7,300,000
	Lid Slab	9,800	242	480	2,400,000	4,700,000
	Floor Beams & Slabs	6,000	242	480	1,500,000	2,900,000
	Foundation Slabs	21,000	230	369	4,900,000	7,800,000
Parking Garages	Columns	540	250	658	140,000	360,000
	Foundations	4,000	250	423	1,000,000	1,700,000
	PT Beams	2,000	250	660	500,000	1,300,000
	PT Slabs	9,000	250	660	2,200,000	5,900,000
	Shear Walls	1,100	267	564	290,000	620,000
	Total	540,000			129,000,000	243,000,000
			Business as Usual		139,000,000	279,000,000
				Savings	10,000,000	35,000,000

*multiply by 0.764 to convert to m^3
**multiply by to 0.593 convert to kg/m^3
***multiply by 0.454 to convert to kg.

Comparing the maximum cement reduction and the minimum cement reduction with the business-as-usual mix, guideway girders had the greatest potential for improvement with the lowest amount of range of improvement. The study found that precast suppliers will increase costs if cement content is capped. The team concluded that a modest 10% minimum cement replacement was possible.

Shaft foundations also had a very large potential for reduction, although there is a large range with the capabilities of the concrete suppliers. Some suppliers may not be able to meet, let alone improve upon, the embodied GHG efficiency of the BAU mix. Shaft foundations will require the largest amount of concrete by volume overall (130,000 cubic yards) – eight times as much concrete as both East Link parking garages combined.

Guideway columns had a large average percent improvement (23 percent) per unit volume, but overall they do not have as much impact as the aforementioned uses.

With the total of cement saved for all projects within this study, the team calculated the total pounds of GHG emitted for all of the Sound Transit work within this study using a conversion factor of pounds of GHG emitted per pound of cement produced.

In actual practice, the conversion factor will vary depending on the type of fuel used to produce the clinker, the relative locations of the concrete plant and the jobsite, as well as several other factors. To normalize for these variables, the team used the widely accepted average value of 0.93 pounds of carbon dioxide equivalent emitted for every 1.0 pounds of cement produced (Marceau 2010).

The maximum potential emissions savings for the planned Sound Transit light rail and park-and-ride projects using lower-cement mixes is equivalent to 47,000 tons of carbon dioxide equivalent emitted. Table 2 indicates the range of potential GHG emission reductions due to the range from suppliers and recommended reduction guidelines.

Table 2: Total Embodied Greenhouse Gas Emissions and Potential Emission Reductions

	Business as Usual	Proposed Reduction Scenario	Average Reduction Scenario	Minimum Reduction Scenario
Cement (tons*)	139,000	50,000	18,000	2,600
CO_2 equivalent (tons*)	129,000	47,000	17,000	2,400
Number of Cars Annual GHG Emissions**	24,000	8,900	3,200	500
Miles of Car Travel for Equivalent Emissions**	276,000,000	103,000,000	34,000,000	5,700,000
Percent Total	100%	36%	13%	2%

*multiply by 907 to convert to kg
**(EPA 2014) multiply by 1.60 to convert miles to km

PROPOSED LOWER-CEMENT DESIGN GUIDELINES

To make embodied greenhouse gas and energy reductions using lower cement concrete actionable, the team proposed specific design guidelines that could be incorporated in the concrete mix table of future concrete specifications. Table 3 is an example of such a table. The guidelines are performance based and define targets for minimum percentages of portland cement replacement and maximum average portland cement content.

Recommended Design Guidelines for Lower Cement Concrete

The current Sound Transit concrete specifications use performance requirements to meet the objectives of the project. The foremost performance requirement of concrete is compressive strength. Strength is not only needed in order for the structure to support the necessary loads, but strength also can be used and as a surrogate to measure other objectives such as stiffness and permeability.

Exposures to the elements such as water, earth, temperature, and oxidizers, can degrade the integrity of concrete over time. Accordingly, Sound Transit concrete specifications list the risk (or categories) of exposure for their concrete work, and the concrete supplier must make appropriate accommodations (American Concrete Institute 2011). These requirements, along with material characteristics that will benefit the placement and curing of the concrete, are specified in a table similar to Table 3.

The team proposed to add environmental performance to the list of specifications as shown in bold in the last two columns of Table 3. The team also suggested changing the table to increase the allowed time for concrete to achieve strength. This will aid suppliers in achieving the requirements by using SCMs. The benefit to proposing requirements in this manner is it reduces associated GHG emissions in a way that has been demonstrated in previous Sound Transit projects. It also gives the supplier leeway in determining the specific constituents of their mix.

Specifying maximum cement content for mixes may seem risky because cement has historically provided concrete its strength. It’s important to note that the cement allowed exceeds the average cement quantities the suppliers proposed by a margin and allows more time for the concrete to achieve strength. Furthermore mixes that can meet these requirements have already been used successfully on Sound Transit projects. The goal is to use them more by establishing them as the new business as usual. The limits proposed in bold in Table 3 are suggested guidelines to be vetted by a pilot program outlined in the section titled “Benefits, Challenges & Mitigation.”

Table 3: Recommended Guidelines for Lower Cement Concrete

Concrete Mix Designation	Use	Exposure Category	Required Compressive Strength f'c (psi)***	Acceptance Age of Required Compressive Strength (days)	Maximum Aggregate Size (in)*	Maximum Water/ Total Cementitious Materials Ratio (w/cm)	Cement Type	Air Content	28 days Shrinkage Control Limit (% of drying shrinkage)	**Minimum Portland Cement Replacement**	**Maximum Average Portland Cement Content (lbs/cy)****
5.A.1	Drilled shaft foundations	F0, S0, P0, C0	5,000	**90**	1”	0.45	Type II	N/A	N/A	**50%**	**370**
5.A.2	Shallow foundations	F1, S0, P0, C0	5,000	**56**	1”	0.45	Type II	4.5% ±1.5%	N/A	**35%**	**420**
5.A.3	Track slab-on-grade	F1, S0, P0, C0	5,000	**56**	1”	0.45	Type II	4.5% ±1.5%	0.04%	**35%**	**420**
4.A.1	Guideway columns	F1, S0, P0, C0	6,000	**56**	1”	0.45	Type II	5.0% ±1.5%	N/A	**30%**	**550**
7.B.1	Precast girders for aerial guideway	F1, S0, P0, C1	6,500	28	1”	0.40	Type II	3.5% ±1.5%	N/A	**10%**	**700**

*multiply by 2.54 to convert to mm
**multiply by to 0.593 convert to kg/m^3
***multiply by 0.00689 to convert to MPa

BENEFITS OF CEMENT REPLACEMENT IN CONCRETE

By providing cement replacement limits in concrete specifications, the primary benefit is reduced greenhouse gas emissions from concrete. Portland cement ingredient accounts for the vast majority of greenhouse gas emissions in concrete. Supplementary cementitious materials (slag, fly ash and silca fume) with lower embodied emissions can be substitute a portion of the cement in order to achieve equivalent strength. Beyond the embodied GHG reductions, concrete with lower cement/more cement replacements has the following potential advantages:

- Reduced heat during the hydration process which can reduce potential cracking
- Potential cost savings when cement replacement is less costly than cement
- Potential reduction of water required

- Lighter color and higher solar reflectance index (SRI) value which can help reduce the heat island effect.
- Improved flowability during placement

Heat Reduction

The portland cement reaction with water is endothermic. (For every 100 pounds of cement, expect an approximate 10 to 15 degree Fahrenheit temperature rise from heat of cement hydration.) When concrete is placed in large volumes or with high proportions of cement (i.e. mass concrete), a large amount of heat will dissipate from the concrete into the air and adjacent surfaces. This can cause cracking due to temperature differentials.

If the heat is not dissipated enough, the elevated temperatures during curing can reduce strength and durability. One of the primary methods to mitigate heat gain is to provide supplemental cementitious materials, replacing a portion of the cement. This is especially important in mass concrete. The chemical reaction of supplementary cementitious materials will create 10 to 50 percent less heat than cement (Detwiler et. al. 1996). Mass concrete elements include drilled shaft foundations and station invert slabs. By requiring limits on cement replacement, excessive heat is less likely to occur.

Cost Reduction due to Cheaper Supplementary Cementitious Materials

Depending on the commodity price of cement, slag, fly ash and silica fume, reducing cement content in concrete can be a viable cost savings strategy.

- Of all the ingredients in concrete, Portland cement is the biggest cost component. Even though it is only 10 percent of a mix by weight, it takes a substantial amount of energy to manufacture.
- Generally, supplementary cementitious materials are less expensive to produce because they are by-products of other industrial processes.
- By using these materials to replace cement, costs will be the same if not lower.
- The suppliers that we contacted estimated that the proposed lower cement mixes range from a 8% cost savings to a 3.5% cost premium compared to the business as usual mix designs.

The cost of fly ash and blast furnace slag in the Seattle area is equal to or less than the cost of cement. The local source of fly ash comes from the Trans-Alta coal-fired power plant in Centralia, Washington. Another source of fly ash, used by Stoneway, comes from Edmonton, Alberta and costs roughly 10 percent more than cement (McKinnon 2012). Another advantage of using supplemental cementitious materials is the decreased viscosity, which means a savings reduction in the high-range water reducer admixtures needed for placement.

One exception of to this discussion is silica fume. Silica fume, a by-product of silicon and ferrosilicon manufacturing, is very beneficial to concrete but its price is significantly more because its demand is much greater than its supply. It is also more expensive to store and handle (Aïtcin 2011).

Local suppliers confirmed that they are securing future supplies of fly ash and slag to maintain their stock-piles. No supplier was concerned about future supply. Note that coal-fired power plants currently produce more than 75 million tons of fly ash each year. Forty percent is reused and the rest is sent to landfills (American Coal Ash Association Educational Foundation, 2014).

Water Reduction

Reducing cement can also lead to reducing water. The team's study indicates an approximate 8 percent reduction in water, with little variability between mixes. The amount of water eliminated is about 190,000 cubic feet for the entire alignment studied. The small range in water reduction indicates that BAU mixes are already well-optimized, likely using high-range water reducers instead of added water to increase slump to the amount needed for placement.

CHALLENGES OF CEMENT REPLACEMENT

While the team has confirmed that certain concrete suppliers can produce mix designs that suit the changes proposed, not all suppliers may be prepared to do so. Having many capable suppliers improves cost, quality and reduces risk.

Time Required For New Mix Designs

When a supplier does not have a mix that suits specifications, such as minimum amounts of supplementary cementitious materials or compressive strength at a certain age, the supplier must develop a new mix or modify an existing mix, while being able to produce and test a sufficient quantity of samples to adjust for strength deviations. This takes time. Most concrete strengths are measured after 28 days of curing, but strength can continue to gain over time. So if a 56- or 90-day strength is allowed or proposed, the time frame for testing can exceed the time between when a project is advertised and when a bid is due.

Schedule Impacts for Low Strength Mixes

If testing is insufficient or does not adequately reflect conditions in the field, quality is risked. The most common problem is slow strength gain, which impacts the schedule. This delays the initial set time, which subsequently delays the start of finishing and the length of time the formwork needs to stay on, slowing formwork reuse and eventually extending the time at which the concrete reaches full strength. Furthermore, concrete may need to be rejected and replaced if it cannot meet specifications. Reasons include inadequate strength, significant cracking from slow initial set, or defects due to poor consolidation or segregation of ingredients.

Contractor-Initiated Requests to Increase Cement Content

Higher cement content, above what is specified or what is required to achieve minimum strength, results in faster curing times and quicker construction schedules. In projects with tight schedules or when there is a need to recover from schedule delays, the contractor may propose increasing the amount of cement as a schedule solution while exceeding the minimum strength required. This scenario can negate any GHG reduction goals that are intended by specifying lower-cement content mixes. The conflict between priorities is always present in construction and specifying environmental performance for concrete creates an opportunity for these conflicts to be addressed with a win-win option.

Promoting Cement Replacement without Incurring Responsibility for Means and Methods

A significant specification challenge is how to promote the reduction of cement usage through the use of supplemental cementitious materials (SCM) such as slag of fly ash without Sound

Transit incurring the responsibility of verifying that an mix design is suitable for a given application. This responsibility must remain with the contractor. By providing cement caps or minimum replacements that are based on recommendations of suppliers, a level playing field is maintained.

The team acknowledges that environmental product declarations (EPD) for concrete will provide a more direct means to measure and control embodied greenhouse gas emissions and associated global warming potential. Even though product category rules for concrete have recently been published by the Carbon Leadership Forum at the University of Washington (Carbon Leadership Forum 2013), no suppliers in the Seattle area have prepared third-party verified EPDs under these new rules, although BASF has offered to provide this service for its business partners (e.g. Cadman).

MITIGATION RISKS OF LOWER-CEMENT GUIDELINES

The following methods were proposed to Sound Transit as means to reduce the challenges identified above.

Provide a Pilot Project

The team recommended that Sound Transit create a pilot project where lower cement concrete is a subset of work bid. This way a contractor can solicit an alternative mix for the pilot, and compare its performance to business as usual – a mix they prefer to use for the main scope of work. By running the pilot as a subset of work, the risk of schedule can be mitigated through selecting concrete work that is not on the schedule's critical path. Working the pilot in tandem can provide concrete suppliers the necessary time to develop lower cement concrete mixes that may need to be tested after longer cure time, such as 90 days.

Use Alternative Test Methods

As mentioned before, compressive strength is used as a surrogate for stiffness of permeability. For drilled shafts, one primary design goal is stiffness of the foundation to resist lateral loading. If stiffness is the goal, engineers could specify the modulus of elasticity of the concrete needed, rather than compressive strength. Concrete could be bid and procured that may have the same elastic modulus at a lower compressive strength or while utilizing less cement.

Maturity testing is a non-destructive method to measuring compressive strength a certain age. It uses thermocouples connected to microprocessors to measure the heat produced by curing concrete over time. It is commonly used to determine early age strength for schedule-driven elements, such as post-tensioned concrete, slip-formed concrete, and concrete highway pavements. Maturity testing requires previously-tested compressive strengths to calibrate the maturity (time and temperature) data to that of the young concrete. Once a history of maturity data is calibrated for a low cement mix design, real-time data can track the quality of strength gain and determine whether concrete is underperforming well before its 56- or 90-day test age. This can be used to ensure quality of newly developed concrete mixes or reject poor performing work with less risk to schedule.

Set Targets for Improvement

The recommended caps on pounds of cement per cubic yard should be considered as average or targets through the course of the pilot project. This cap is set slightly above better-than-average mixes used in past Sound Transit projects. This gives the contractor the control to optimize or accelerate performance based on their schedule or means and methods.

Providing a minimum average cement replacement also provides a baseline, but does not set the upper bound for potential improvement. Cement replacement will be the easiest first step for lower cement concrete, but suppliers may utilize alternative inert or pozzolan fillers, reduced water content, or proprietary admixtures that provide adequate strength and durability while using less cement.

As a comparison, the targets proposed are significantly less than the more aggressive maximum cement caps currently used in signature public projects such as World Trade Center One and San Francisco's Public Utility Commission building. These projects used mixes with up to 70% cement replacement, and the San Francisco project reduced concrete CO2 footprint by 50% (U.S. Concrete 2013). The team feels the suggested targets set a realistic initial goal that moves the agency from the historic cement content to leaner cement mixes that are available locally and can meet the structural and constructability requirements. They deliver significant embodied GHG and energy use savings, but are not on the "bleeding edge."

RECOMMENDATIONS FOR ACTION

Sound Transit has a limited window of opportunity to meaningfully address embodied greenhouse gas emissions and energy related to concrete. The list below is a short summary of the specific and phased actions the team presented for Sound Transit to realize GHG reductions within their current phase of infrastructure build-out.

- Measure embodied GHG emissions, embodied energy, and water use related to concrete and other infrastructure
- Include embodied emissions and reductions below average in annual reports and environmental stewardship outreach materials
- Expand environmental performance beyond pilot program
- Verify and enforce GHG reduction goals through independent review of construction product submittals
- Incorporate and share lessons learned outside the agency

CONCLUSION

Greenhouse gas emissions relating to the construction of concrete infrastructure is significant for mega-projects such as Sound Transit's light rail expansion. Portland cement content can be used as a surrogate for greenhouse gas emissions until better environmental metrics like environmental product declarations become mainstream. By studying the historical concrete mixes procured, a business-as-usual baseline can be used to improve upon.

If the proper performance criteria is agreed upon, concrete suppliers can yield incremental GHG improvements by using more supplementary cementitious materials to replace cement. Incorporating cement replacement targets in specifications should be vetted through a pilot program in order to mitigate risks, track performance, and learn the lessons from multiple stakeholders. Transit agencies such as Sound Transit can have a significant influence on improving regional environmental standards and technical capabilities.

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