Cement Substitutes

Concrete is one of the most widely used construction materials in the world and, therefore, the associated economic, human, and environmental benefits and impacts are significant. An estimated 7% of global greenhouse gas (GHG) emissions are associated with cement production.[1] Concrete is a mix of aggregate, water, hydraulic cement (blend of Portland cement, ground limestone, and/or supplementary cementing materials - "SCMs") and chemical admixtures that modify the behavior of fresh and hardened concrete to make it easier to place and enhance strength and durability. The material cost and associated climate impact is largely dependent on the amount of Portland cement used in the concrete mix. Therefore, identifying ways to lower the impacts of Portland cement production or displace the need for production through use of alternative materials[2] rank high on the list of best practices to address the GHG emissions from the production of concrete.

Portland cement is manufactured by heating raw materials (mostly limestone) to about 2,500F (1,400C). Heating to this temperature requires significant amounts of fuel (sources include natural gas, coal, used tires, waste oils, solvents, etc.). Emissions from the combustion of these fuels represent about 40% of the GHG footprint of Portland cement. The remaining 60% of impacts are from production-related calcination process emissions, generated as raw materials are heated and decompose during production.[3]

SCMs can enhance concrete properties and reduce the need for production of Portland cement and the associated climate impacts. Examples of more-common alternative cements include fly ash (a byproduct of coal combustion), blast-furnace slag (a byproduct of iron production) and silica fume (a byproduct of silicon metal), others include ground limestone or other pozzolans (such as volcanic ash and glass). Fly ash can be substituted for Portland cement up to 30%. Oregon Department of Transportation (ODOT) specifications allow slag substitution up to a maximum of 50%. The Slag Cement Association suggests that up to 80% may be used in specific applications with proper precautions.[4]

Cement substitutes provide a GHG reduction relative to the production of Portland cement, although it is important to note this benefit can be diminished or negated depending on material transport distances and freight mode. The benefit may also decrease if contractors increase the amount of cementitious materials to comply with early-age strength tests needed for construction schedules. According to the National Ready Mix Concrete Association's U.S. average environmental product disclosures (EPDs), a 30-39% substitution of fly ash results in a 22% decrease in GHG emissions per unit of concrete compared to a Portland cement concrete mix, while a 50% substitution of slag results in a 39% reduction (for strength class 3001-4000 psi).[5] While alternative cements offer an opportunity to reduce climate impacts, there can be barriers to adoption including longer curing times to reach required compressive strengths, concerns about toxicity of the alternative materials, increased risk of salt scaling, and prohibitive transportation costs.

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[1] International Energy Agency (2018). Available online at https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

[2] Throughout this info sheet, alternative cements and SCMs are used interchangeably.

[3] Portland Cement Association (2020). Carbon Footprint of Cement. Online at https://www.cement.org/docs/default-source/th-paving-pdfs/sustainability/carbon-foot-print.pdf.

[4] Details online at https://www.slagcement.org/aboutslagcement/is-02.aspx

[5] NRMCA U.S. average EPDs found online at https://www.nrmca.org/wp-content/uploads/2020/02/NRMCA_EPD10294.pdf

Real World Examples

Examples are too numerous to mention – this best practice is used by many organizations for a wide variety of end uses including ODOT.

Current Conditions & GHG Inventory Results

Current Conditions

ODOT purchases large volumes of construction materials including ready-mix and precast concrete products, cement, aggregate, steel, etc.[6] While ODOT does control the life cycle of pavement in their system, the upstream climate impacts from production of these products is outside the agency's direct control. That said, ODOT does have the ability to request greater SCM content in their projects (toward the standard specification maximum in all applications) for better climate performance.

ODOT's specifications have included significant quantities of materials that lower GHG impacts, such as the substitution of alternative cements/SCMs for Portland cement and its use of reclaimed asphalt pavement (RAP) to substitute for virgin asphalt binder and aggregates. ODOT's baseline GHG emissions would be significantly larger without ODOT's use of these best practices. SCMs used on ODOT projects include fly ash, blast-furnace slag, and silica fume. ODOT's contractors have used 30% fly ash and 5% silica fume mixes, but are reportedly moving toward slag cement and away from fly ash in both ready mix and precast concrete products due to reduced fly ash supply in the region.

GHG Inventory Results

The production of concrete and cement products used in ODOT construction projects have an annual average climate impact of 20,000 MT CO_2e (for FY2016-19). These results account for use of alternative cements throughout the defined period. It is estimated concrete-related emissions would be 20 – 30% larger if not for ODOT's use of SCMs. ODOT keeps sound records of concrete and cement product purchases including detailed mix specifications,[7] quantities purchased and financial data. This record keeping has served ODOT's historic needs, but this system will require modification to cost-effectively and accurately monitor climate impacts to track progress toward goals.

Practice Alternative(s): Market Study

Availability and Access

The most referenced alternative cements (slag and fly ash), which are the most commonly used by ODOT, both arrive in Oregon at the Port of Portland. From there they are trucked elsewhere in the state. Blast furnace slag is produced in British Columbia, Canada and Asia. Fly ash is currently produced in Centralia, Washington (reportedly shutting down in or around 2025), and also from sources in Wyoming and Canada. Fly ash can be transported from other parts of the country, but freight costs and associated GHG impact can become prohibitive if it is shipped from too far away.

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[6] During the period, FY2016 – 19 ODOT used an estimated 250,000 cubic yards of concrete annually.

[7] In a ODOT Excel-based report titled CDM Survey. This report captures details of mix specifications cross referenced with project and bid items. There is also information on Contractor and Contractor Mix Design Number, but this information is less consistent and unfortunately the Contractor Mix numbers do not always align with information on Environmental Product Disclosures.

Type 1L limestone cements, where up to 15% of Portland cement is replaced with ground limestone, are available in the Pacific Northwest (per AASHTO M240 standard specification for blended hydraulic cement). This substitute provides about a 10-15% reduction of GHG emissions compared to conventional mixes and has more available supply versus other SCMs. It also can be blended with other SCMs to increase GHG reduction benefits. Interviews conducted for this project indicated additional market availability of Type 1L limestone in the Portland region in 2022. Reporting from Portland Cement Association and National Concrete Consortium indicates the cement industry is moving toward all Portland-limestone cement (AASHTO M240) in the near future to replace Type I/II (AASHTO M85).

Another SCM currently available but not brought to scale is volcanic pozzolan. Multiple industry and ODOT engineers spoke about the availability of this material in the state as an existing natural source of SCM. One of these products has already been approved (Lafarge TS100) which uses pumice from Kamloops, British Columbia. A report was completed in 2018 by the Oregon Institute of Technology evaluating this material for use and comparing its energy demands and associated GHGs.[8] The report found with additional processing, Mount Mazama volcanic ash can be effective as a supplement to Portland cement for binding compacted gravel layers and reducing dust. It also found energy use and GHG emissions were comparable to fly ash as a SCM.

Ground glass may be a used as a SCM as well, which was recently made easier by the release of a standard ASTM specification (*C1866, Recycled Ground-Glass Pozzolan for Use in Concrete*). The context for this new standard is summarized by subcommittee members in a report titled *Ground-Glass Pozzolan for Use in Concrete*.[9] The report lists three glass types suitable for use as pozzolan in in Portland cement concrete: container glass, plate glass, e-glass (by product of fiberglass manufacturing). Overall the report found glass pozzolan has greater purity (uniform material free of hazards), widespread supply that is geographically distributed, with similar reactivity and performance compared to fly ash and slag, lower water demand, and similar environmental benefits as fly ash and slag. The report suggests container glass and plate glass may provide a 10-40% substitute for Portland cement, while e-glass may substitute for between 10-30%. The report references field validation testing taken place over the past ten years in concrete masonry units, pavers, precast concrete products, and sidewalks. The City of Montreal began testing post-consumer glass in sidewalks beginning in 2010. New York City has completed testing in 2016 in sidewalks and is included in Department of Design and Construction specifications. New York has tested up to 50% Portland cement replacement in high-rise construction. Two bridges are being constructed in Montreal, Canada using 10% Portland cement replacement.

The *Ground-Glass Report* is more optimistic about the prospects for glass pozzolan than ODOT and Oregon-based suppliers. ODOT subject matter experts (SMEs) report these materials are not being produced on the West Coast - only soda-lime bottles may be used (per ASTM 1866 Type GE/GS) - and that fiberglass does not produce a quality pozzolan that can be used in ODOT projects. ODOT further reports no suppliers (as of this writing) have requested to get their products approved for use in Oregon. Early conversation with potential suppliers indicate the quantity of available soda-lime glass in Oregon is not enough to invest in viable, long-

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[8] Sleep, Matthew and Masley, Morgan. The use of Mt. Mazama volcanic ash as natural pozzolans for sustainable soil and unpaved road improvement. NITC-SS-1075. Portland, OR: Transportation Research and Education Center (TREC), 2018. Downloaded online at https://ppms.trec.pdx.edu/media/project_files/NITC_SS_1075_Use_of_Mt_Mazama_Volcanic_Ash_as_Natural_Pozzolans_for_Sustainable_Soil_and_Unpaved_Road_Improvement_Accessible.pdf.

[9] Available for download online at https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=51729296

term production. While post-consumer glass is abundant in Oregon,[10] the majority of these materials are not soda mime glass. Another challenge for adoption is that a dedicated pozzolan production facility would need to be developed in Oregon to capture the material and process it to be ready for use as an SCM.

Cost

The City of Portland conducted a pilot study (in early 2020) to evaluate lower-impact concrete mixes and report costs for alternative cements equal to or less than Portland cement. These findings may not be applicable in the post-pandemic market-place due to a variety of factors.

Interviews with suppliers conducted for this project shared pricing has recently changed for blended SCM-cement in the marketplace due to multiple factors including supply chain issues, transportation, and a growing awareness from suppliers of the increasing demand for these materials. Prices as of this writing are reported as neutral or up to a 25% increase compared to conventional Portland cement. Suppliers also report blended SCMs can require a change in grinding processes at plants. Many plants would require an additional silo, which costs an estimated $100,000 with additional site-specific costs for permitting and other infrastructure.

Making the Transition (Lessons Learned)

- No single type of SCM fits all circumstances. Use of SCMs need to be well matched to environmental conditions, construction schedule, and availability.
- Alternative cements are not produced locally and therefore supply fluctuates. A long-term consistent supply needs to be identified in order to regularly utilize.
- Alternative cements requests are becoming more common and therefore costs may rise.
- Transportation distances and transportation mode must be considered when comparing GHG emission tradeoffs with Portland cement.
- Because additional capital equipment is needed, required use of alterative cements can hurt smaller suppliers unless they are supported in their transition to the new materials. ODOT reports most ready-mix facilities have silo space for at least one SCM. Some have more which would create a competitive advantage for those suppliers depending on ODOT material requirements.
- Typical cement content is used more than needed to ensure strength test are met, reducing risk for producers.
- Cure times can be longer for SCMs, which can have negative impacts on construction schedules. Thus, the use of SCMs should be focused on mixes that can have longer cure times without disruptions. Another option is to look at projects more holistically and define an appropriate amount of cure time and develop construction schedules them.
- Test maturity curves and compression at different days to see where the strengths are when piloting new mixes. Installing sensors within an installed mix can measure moisture and temperature and enables real-time data on curing status. This technique allows for other means to support curing (e.g., blankets).

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[10] Oregon Department of Environmental Quality's 2017 Waste Composition Study found that over 70,000 short tons of glass was landfill disposed (35,000 short tons of containers; 14,000 tons of plate glass).

Practice Alternative(s): Mitigation & Cost Scaling

Life Cycle Considerations

- All concrete mixes should be designed and specified for durability and smoothness first (e.g., reduced rolling resistance) before considering emissions from material production. An inefficient surface or significant additional maintenance over the life of the infrastructure could result in a net-emissions increase, even if emission reductions are made during material production.
- Concrete can sequester carbon over its life, which was recognized in research used for the most recent International Panel on Climate Change assessment report.[11], [12] However, EPDs do not currently account for this and an internationally agreed upon scale of emission reductions to adjust EPDs is not readily available.
- At the end-of-life, concrete may be used as a reclaimed substitute for virgin aggregate materials. The construction industry has not adopted this technology on a regular basis because the quantities used by ODOT (and potential GHG benefit) do not justify the risk to performance associated with the material substitution.

GHG Impacts

The GHG benefits from ODOT's current use of SCMs is included in the GHG baseline inventory calculated for FY2016-19. Figure 1, below, compares baseline emissions to various scenarios including: a no-SCM scenario (illustrates emissions without ODOT's current use of SCMs); a 30% SCM scenario (illustrates if all concrete used 30% SCMs); and a 50% SCM scenario.

Figure 1

Strength Classification (psi) - % SCM - SCM Type	Concrete Volume	Baseline Emissions Factors	Baseline FY16-19 Ave. Emissions	Low-SCM Emissions Factors	Low-SME Scenario Emissions	30% SCM Emissions Factors	All 30% SCM Scenario Emissions	50% SCM Emissions Factors	All 50% SCM Scenario Emissions
description	cubic yards	kg CO2e / cuyd	MT CO2e	kg CO2e / cuyd	MT CO2e	kg CO2e / cuyd	MT CO2e	kg CO2e / cuyd	MT CO2e
2500-3000psi_0-19% FA/SL	50,324	264	13,294	264	13,294	204	10,283	164	8,253
2500-3000_30-39% FA	753	207	156	264	199	204	154	164	123
2501-3000_30-39% SL	879	204	180	264	232	204	180	164	144
3001-4000_0-19% FA/SL	73,077	326	23,826	326	23,826	251	18,307	200	14,615
3001-4000_20-29% FA	21,241	279	5,935	326	6,925	251	5,321	200	4,248
3001-4000_30-39% FA	14,850	254	3,773	326	4,842	251	3,720	200	2,970
3001-4000_30-39% SL	19,478	251	4,880	326	6,351	251	4,880	200	3,896
3001-4000_40-49% SL	1,958	225	441	326	638	225	441	200	392
4001-5000_0-19% FA/SL	257	400	103	400	103	305	79	242	62
4001-5000_30-39% FA	2,515	310	779	400	1,005	305	767	242	609
4001-5000_30-39% SL	2,673	305	815	400	1,068	305	815	242	647
4001-5000_40-49% SL	135	274	37	400	54	274	37	242	33
5001-6000_0-19% FA/SL	7,494	421	3,154	421	3,154	321	2,406	254	1,904
Vendor EPD (various psi & SCM)	58,562	321	18,813	321	18,813	321	18,813	321	18,813
FY2016-19 Totals	254,196		76,186		80,503		66,202		56,708
4-Year Annual Average	63,549		19,046		20,126		16,551		14,177
Difference from Baseline					1,079		-2,496		-4,869
% of Baseline					6%		-13%		-26%

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[11] Cao, Z., Myers, R. J., Lupton, R. C., Duan, H., Sacchi, R., Zhou, N., Reed Miller, T., Cullen, J. M., Ge, Q., & Liu, G. (2020). The sponge effect and carbon emission mitigation potentials of the global cement cycle. Nature Communications, 11(1), [3777]. https://doi.org/10.1038/s41467-020-17583-w

[12] Freidlingstein, P, et al.(2020). Global Carbon Budget 2020. Earth System Science Data, 12, 3269-2020. https://doi.org/10.5194/essd-12-3269-2020

Figure 1 Notes:

FA = Fly ash SCM

SL = Blast furnace slag SCM

Notes: The descriptions above classify concrete use by strength and percentage of SCMs. The GHG factors (other than from Vendor EPDs) used US average values base on these classifications. SCMs are presented in U.S. average values for a range of SCM content; 0-19% SCM substitution for Portland cement; 20 – 29% SCM; 30 – 39% SCM; and 40-49% SCM; and >50%. The Strength Classification "2500-3000psi_0-19% FA/SL" indicates mixes between 0 – 19% SMCs and does not indicate only mixes absent of SCMs (0%). This nomenclature is taken from the National Concrete Ready-Mix Association's National Average Environmental Product Disclosures. Likewise "30-39% FA [or] SL" indicates mixes between 30 – 39% SCM replacement for Portland cement.

Cost Impacts

Cost differentials for SCMs versus Portland cement were reported as cost neutral up to a 25% premium for slag and fly ash, depending on the alternative and market availability. Cost comparison data was not readily available for Portland/limestone cement versus Portland cement. Likewise, price information was not readily available for volcanic or glass pozzolans. However, reports reviewed for this section noted these options will become more economically viable as market demand and price for slag and fly ash SCMs increases.

Recommendations

- Determine if the allowable SCM levels in ACI301 are applicable for all ODOT applications. If not, research if there is room for increasing tolerances.
- Develop long term sources of SCMs for ODOT and other local agencies.
- Support vendors (as needed) to identify financial support from USEPA, USDOE, etc. and state resources (Oregon Department of Energy, Oregon Department of Environmental Quality and Biz Oregon) for new capital equipment or conversion costs to install infrastructure that enable maximizing SCM availability.
- Support research on SCMs and their viability on ODOT projects - specifically for materials with local or regional supply such as soda-lime glass.
- Update data tracking system to cost-effectively and accurately monitor climate impacts from materials like cement concrete.