2

CONCRETE SOLUTIONS GUIDE

Mix It Up

Supplementary Cementitious Materials (SCMs)

Substituting cement with supplementary cementitious materials (SCMs)—such as fly ash, ground glass, natural pozzolans, and blast furnace slag—creates an opportunity for cost-effective decarbonization. These waste and by-product components can be mixed into concrete, preserving performance while reducing the need for cement. Portland cement is responsible for 90% of the total embodied carbon of concrete;[1] reducing this input offers one of the most effective avenues for creating more sustainable concrete. Substitution often repurposes waste materials and is a cost-competitive intervention in many instances.

Key Takeaways

Up to 40% substitution of cement with SCM is possible based on individual mix limits and supply across the United States,[i] offering potential savings of 27 Mt CO_2e per year.[ii]

Substitution can deliver up to 80% emissions reductions for a given application.[iii]

Using SCMs can reduce the cost of the cement blend by up to $45/ton.[iv]

The availability of SCMs may diminish in the future, potentially requiring the development of new sources (e.g., reclaiming stored fly ash or mining natural pozzolans).

The primary barriers to increasing SCM use are prescriptive specifications, unfamiliarity from industry, and supply-side restrictions.

Opportunity

Both cement and concrete producers have opportunities to use alternative materials. Cement producers may produce blended cements (defined in ASTM C595), particularly portland limestone cement (PLC or Type 1L). Raw ground limestone acts as a seed crystal to enhance the cement hydration.

Concrete producers can also use a variety of SCMs to lower embodied carbon while meeting specifications. These include:

- Waste or by-product pozzolans such as fly ash and ground glass, which are mostly silica
- Natural pozzolans, such as volcanic ash, which perform similarly to waste pozzolans
- Ground granulated blast furnace slag (GGBFS), a by-product of steelmaking that contains calcium and silica, and that can almost entirely replace portland cement (up to 95% in ASTM C595)

These strategies can also be combined to further reduce embodied carbon. For example, a ready-mix operator could start with a portland limestone cement base and combine it with fly ash or GGBFS. The additional reductions in embodied carbon are complemented by improved strength and durability.[2]

Because SCMs have low embodied carbon relative to cement, substitution translates into steep emissions reductions, potentially in excess of 80% (see Exhibit 1).

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[i] Based on RMI analysis of USGS data for cement and slag production and ACAA data for fly ash production, as well as substitution limits set by ASTM C595. Estimates assume that all fly ash and slag can be processed to a suitable grade.

[ii] Based on RMI analysis of USGS cement kiln fuel consumption data using EPA emissions factors and EGrid data. Resource consumption for cement and SCMs based on R. Feiz et al., “Improving the CO_2 Performance of Cement, Part I: Utilizing Life-Cycle Assessment and Key Performance Indicators to Assess Development within the Cement Industry,” *Journal of Cleaner Production*, vol. 98 (2015): 272–281; and C. Heidrich, I. Hinczak, and B. Ryan, “SCM’s Potential to Lower Australia’s Greenhouse Gas Emissions Profile,” Australasian Slag Association Conference, Sydney, 2005.

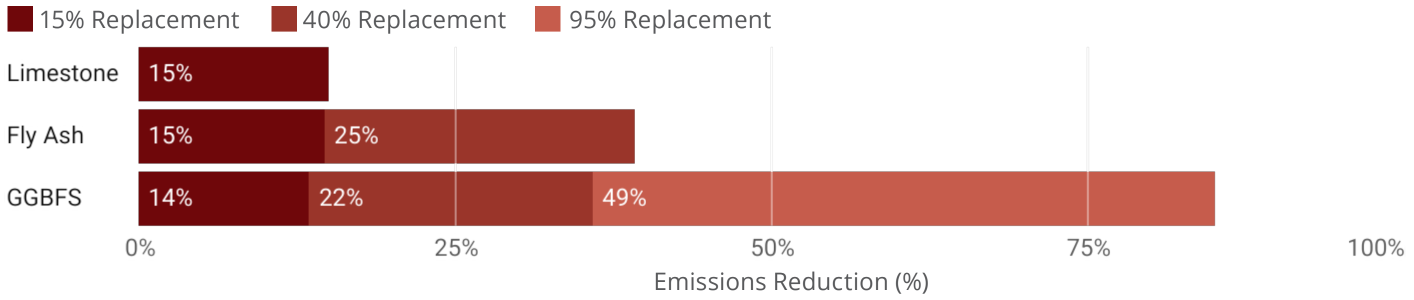
[iii] See footnote ii.

[iv] Based on USGS and BLS data for raw material and transport pricing. Results are consistent with McKinsey global pricing estimates: **https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.**

Substitution Limits

Given the different chemistry of the materials and subsequent impacts on concrete properties (e.g., strength or workability), the ASTM C595 standard sets out different substitution limits for limestone, pozzolans, and GGBFS at 15%, 40%, and 95%, respectively.

Exhibit 1: Emissions reductions in cement blends using SCMs



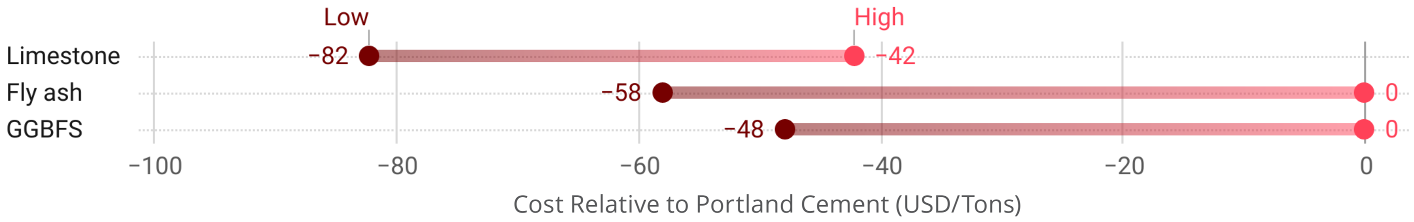
Emissions reductions for each type of SCM are dependent on the SCM's embodied carbon and the substitution limit. All of the SCMs have significantly lower embodied carbon than cement resulting in steep emissions reductions. Fly ash and limestone have almost no embodied carbon resulting in emissions reductions roughly equivalent to the substitution limit. There is a small amount of emissions associated with the processing and transport of GGBFS but the higher substitution limits for this material allows for large emissions reductions. Colors are the substitution limits. Values written on the bars are the emissions reductions.

Cost

The price of each material varies regionally, with most costs incurred through transportation. As a result, SCMs can be cheaper than portland cement in locations close to a source. In some cases, a concrete mix containing SCM can be produced at a ready-mix facility without additional capital costs beyond additional storage capacity.

As shown in Exhibit 2, for areas with a close source of SCM, this process innovation can offer significant cost savings compared with portland cement. For concrete producers farther from SCM sources, the cost difference is negligible.

Exhibit 2: Variation in SCM cost is mostly associated with required transport distance

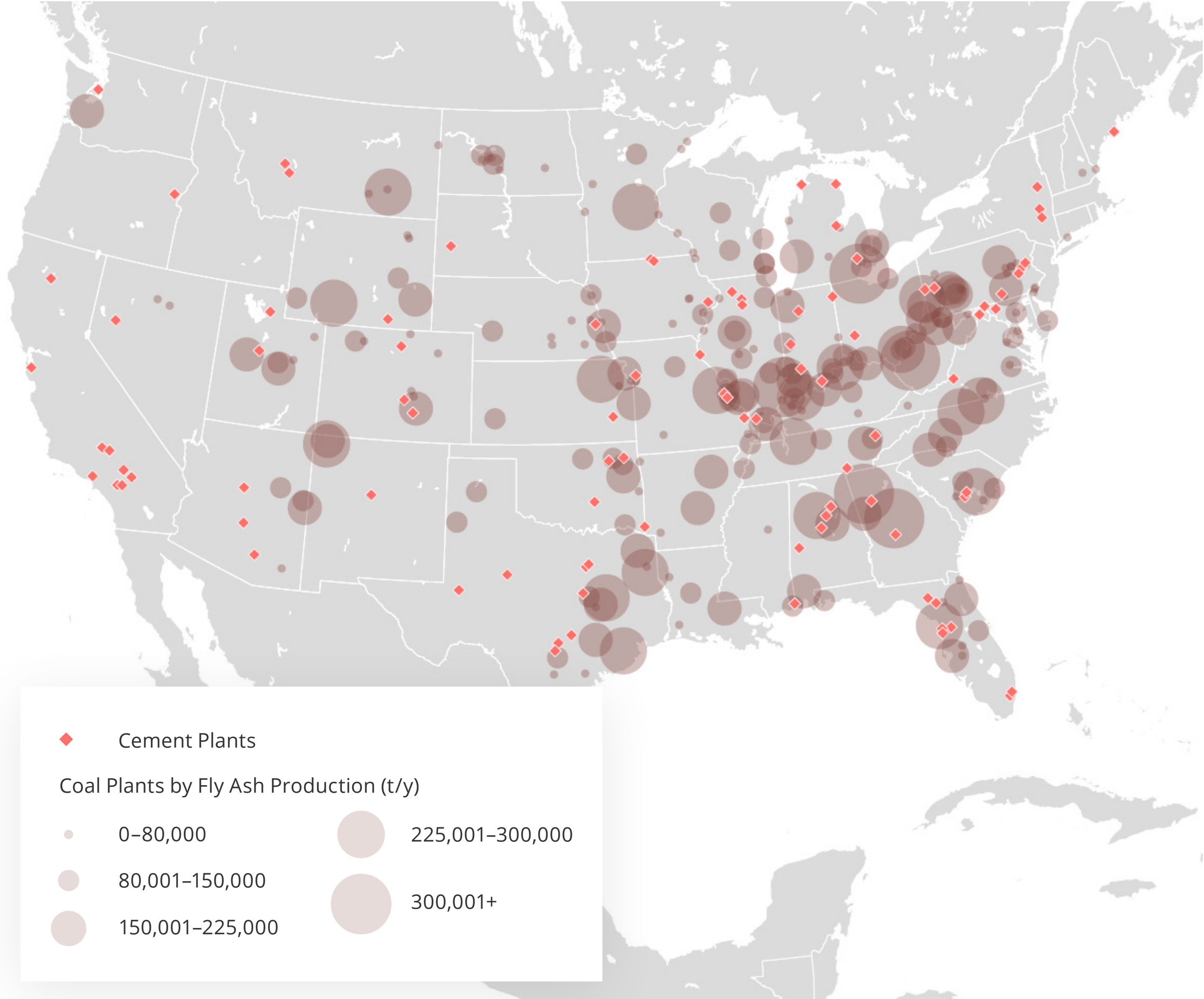


SCM costs are highly dependent on location. As result, there is a significant range of prices. In almost all places where an SCM can be sourced it will be less expensive than cement.

Considerations

Barriers to further adoption of SCMs include prescriptive specifications and a lack of familiarity with options (e.g., natural pozzolans and ground glass). But the greatest hurdle is the complicated supply-side dynamics of connecting concrete manufacturers with SCMs.

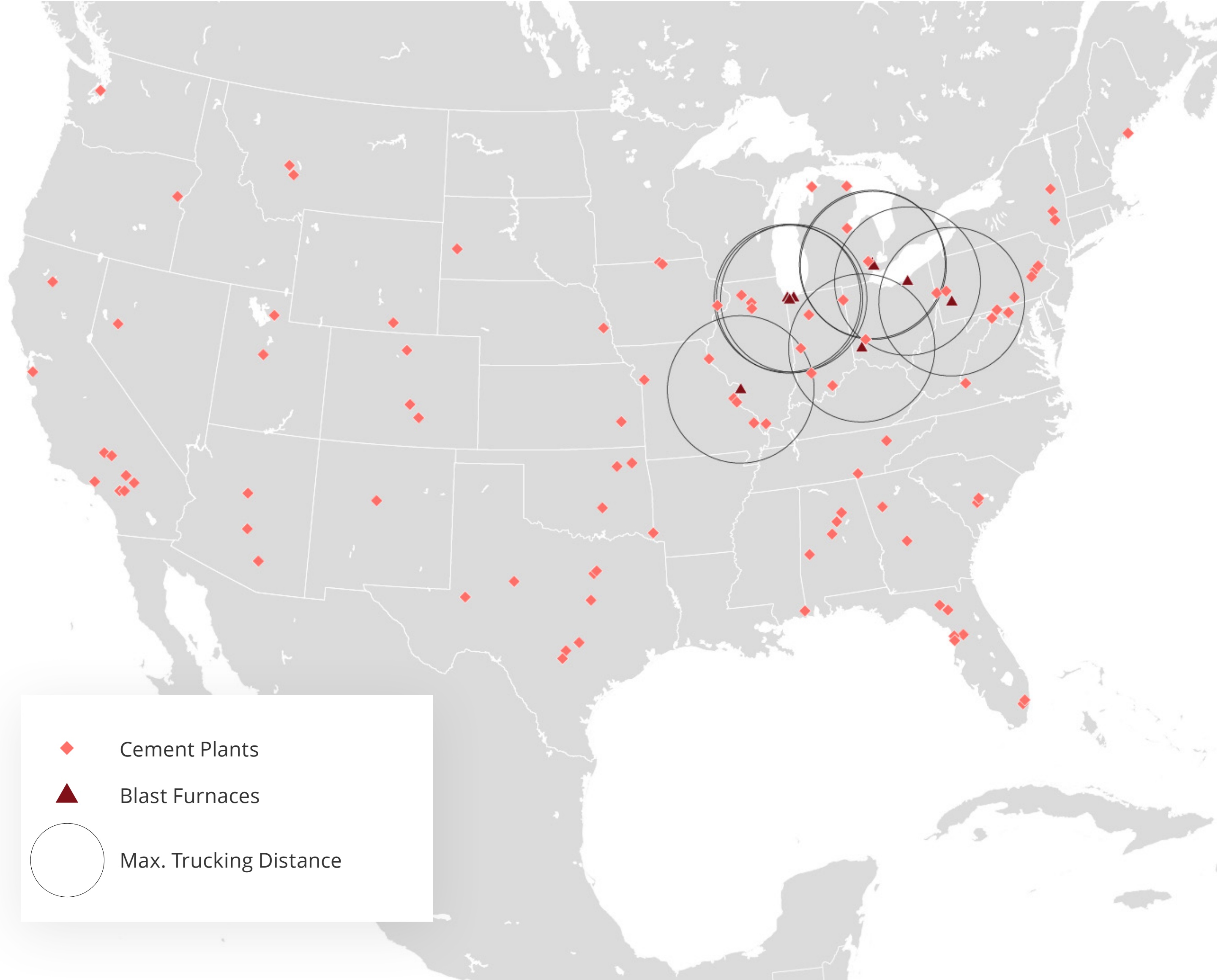
Exhibit 3: Fly ash supply is limited in the West



Fly ash is a byproduct of coal-fired power plants. As coal power is phased-out, fly ash availability will be constrained. This is already the case in the West where there are few coal-fired power stations producing fly ash in any significant quantity.

The overall ratio of SCMs in concrete mixes is limited to roughly 40% due to concrete quality considerations as well as material supply.[v] This estimate of potential overall substitution is based on the ASTM C595 limit for limestone (15%) and current US production of both fly ash (27 Mt/y based on ACAA data) and GGBFS (8 Mt/y based on USGS data).

Exhibit 4: GGBFS is only produced in the Great Lakes Region



GGBFS supply is even more constrained geographically than fly ash. The last remaining blast furnaces are located in the Great Lakes region and the maximum trucking distance (for a breakeven price with cement) further limits the area in which this SCM can be used.

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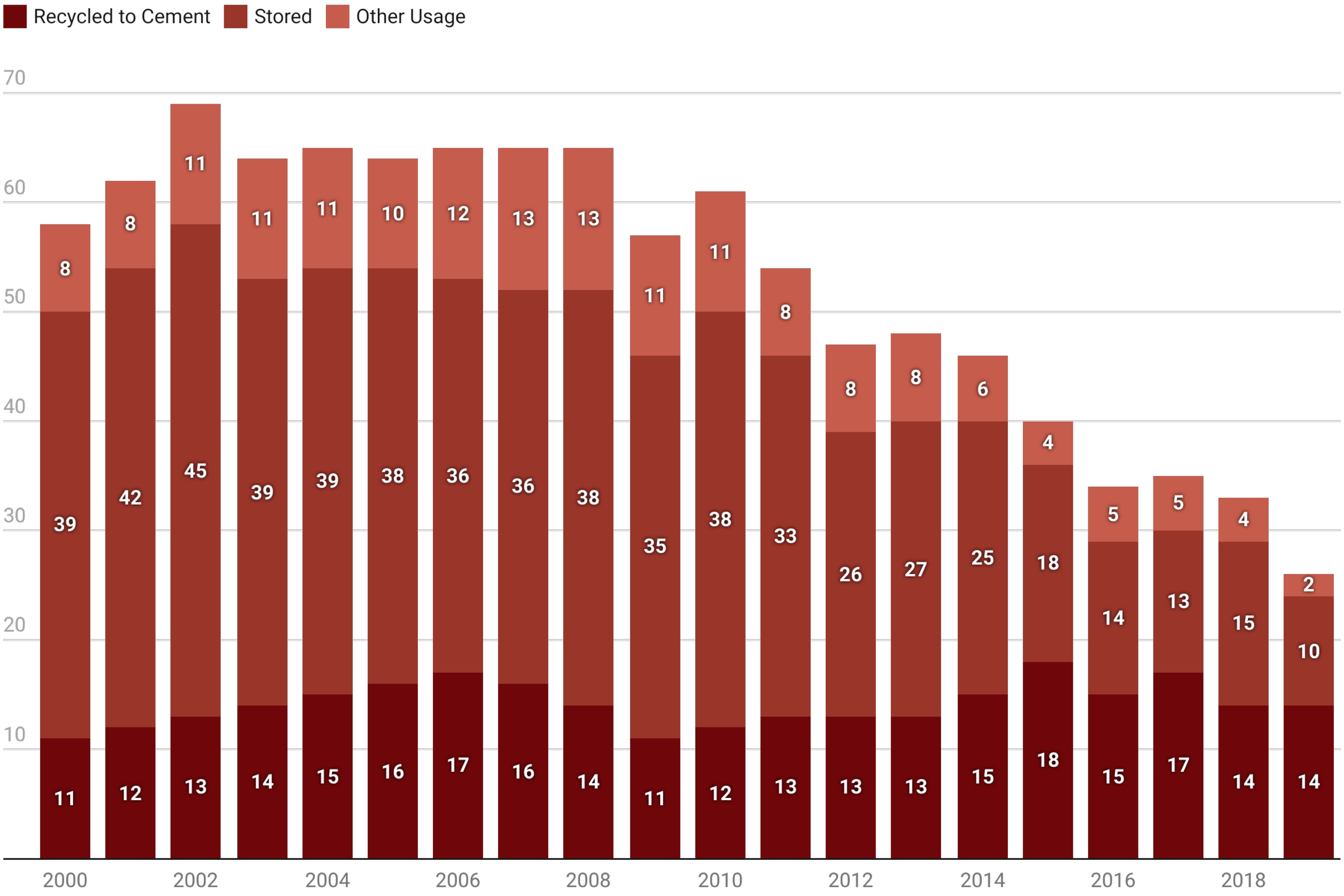
[v] Based on USGS data for cement production (https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf) and GGBFS (**https://www.usgs.gov/centers/nmic/iron-and-steel-slag-statistics-and-information**) and ACAA data for fly ash consumption (**https://acaa-usa.org/publications/production-use-reports/**).

For concrete producers, incorporating SCMs requires securing a reliable supply.

- Limestone: Although cheap and widely available, the use of limestone is limited to 15% in ASTM C595. The inclusion of limestone will primarily occur in blended cement, as it is already available to cement producers as a raw feed material for the kiln.
- Fly ash: New supply of fly ash will continue to decline with the retirement of coal-fired power stations, and as emissions regulations lead to ash with a high carbon content. New supply could be developed by reclaiming fly ash from legacy storage ponds. Current US fly ash production is below the maximum possible substitution rate in a concrete mix (40%). Finally, this maximum rate is not suitable for certain concrete applications (e.g., those requiring rapid early strength gain).[3]

Exhibit 5: Stored fly ash could represent a significant opportunity (million tons)



A large amount of fly ash has been stored across the United States over the past 20 years. As new fly ash production decreases (owing to the phase-out of coal-fired power), this stored material could be reclaimed and used in concrete production.

- GGBFS: The supply of furnace slag is limited to the Midwest, where blast furnaces are still in operation. Given its higher material cost, furnace slag can only be economically transported over relatively short distances (roughly 300 km). While the substitution limit, at 95%, is high in terms of the amount of GGBFS that can be incorporated into a concrete mix, the overall material supply is low at 3 Mt/y.[vi] This supply rate could potentially expand to 8 Mt/y through the installation of granulation facilities at all blast furnaces. However, this would still only amount to 8% of the total 102 Mt of annual cement demand in the United States. GGBFS imported from overseas is also available in coastal regions, but the emissions associated with shipping decrease net reductions in embodied carbon.

At present, fly ash presents the best opportunity for overall abatement, given the balance between substitution limits and material availability. Although the amount of fly ash used in cement has remained stable, overall production has reduced significantly as coal-fired power stations are retired. This trend will continue, with production expected to drop below current fly ash usage sometime between 2025 and 2035.

However, data from the American Coal Ash Association indicates that over the past 20 years, 600 Mt of fly ash were stored in various waste sites. Recovery of this fly ash could provide US concrete producers with 14 years of SCM at the highest substitution rate—40%—while providing a separate revenue stream to fund rehabilitation and closure costs once a coal-fired power station is shut down. Several promising studies have been completed on the feasibility of reclaiming stored fly ash as a new source of SCMs to mitigate cement emissions.[vii] Boral has published a case study from Washingtonville, Pennsylvania, where approximately 2 Mt of fly ash generated in the 1980s and 1990s are being reclaimed for use in concrete.[4]

The use of fly ash in concrete may also reduce some nonclimate environmental impacts of fly ash storage. An EPA analysis found that the environmental releases from concrete containing fly ash were comparable to or lower than those from ordinary concrete.[5] At the same time, the use of fly ash reduces the need to impound these materials in surface ponds, which are known to spill and contaminate local water supplies.[6]

In addition to fly ash, ASTM also allows for other pozzolans such as ground glass, silica fume (a by-product of silicon production), or naturally occurring pozzolans. Natural pozzolans, such as those found in volcanic ash, have the potential to significantly reduce the overall emissions associated with cement production. In geographies where natural pozzolans are cost-effective and sustainable to produce, they may serve as a valuable resource in the future if new production of other SCMs (including fly ash and GGBFS) dwindles with the decarbonization of the power and steel sectors.

[vi] See footnote vii on page 17.

[vii] Relevant studies include M. McCarthy, T. Robl, and L. Csetenyi, "Recovery, Processing, and Usage of Wet-Stored Fly Ash," in Coal Combustion Products (CCP's), Elsevier, 2017, 343–367; and I. Diaz-Loya et al., "Extending Supplementary Cementitious Material Resources: Reclaimed and Remediated Fly Ash and Natural Pozzolans," Cement and Concrete Composites, vol. 101 (2019): 44–51.

Related Solutions

1. Know Your Numbers: Performance-oriented specifications

3. Plug and Play: Sensors can save time, money, and materials

State of the Market

Portland limestone cement (PLC) is increasingly used due to the simplicity of implementation by cement producers and the reduction in the emissions intensity of the concrete by 10%. For example, the Colorado Department of Transportation (CDOT) recently used PLC as the basis for the Highway 287 replacement in an effort to meet the state's climate action plan.[7] CDOT's use of PLC also provided a basis for the synergistic inclusion of fly ash into the cement blend for parts of the project, further reducing the embodied carbon content of the concrete.

Although natural pozzolan production is currently small (0.5 Mt/y in 2017),[8] there have been some recent expansions, including Nevada Cement offering a natural pozzolan cement product and Charah Solutions offering a natural pozzolan product through its new grinding facility in California. The Natural Pozzolan Association now lists several producers as well as multiple prospective deposits that could increase the supply across the United States. Alternative waste material pozzolans have also been developed into commercial offerings. For example, Pozzotive's ground glass pozzolan has been used in a number of projects in New York, including pavement for United Nations Plaza and for stations on the 2nd Avenue Subway line.

Endnotes

1. M. A. Nisbet, M. L. Marceau, and M. G. VanGeem, *Environmental Life Cycle Inventory of Portland Cement Concrete*, Portland Cement Association, 2002, **https://www.quadlock.com/technical_library/third_party/Life-Cycle-Inventory-of-Concrete.pdf.**

2. K. Celik et al., "Mechanical Properties, Durability, and Life-Cycle Assessment of Self-Consolidating Concrete Mixtures Made with Blended Portland Cements Containing Fly Ash and Limestone Powder," *Cement and Concrete Composites*, vol. 56 (2015): 59–72.

3. "Fly Ash Facts for Highway Engineers," US Department of Transportation Federal Highway Administration, last modified June 27, 2017, **https://www.fhwa.dot.gov/pavement/recycling/fach03.cfm.**

4. "Fly Ash Reclaimed from Landfill," Boral Resources, accessed May 11, 2021, **https://flyash.com/wp-content/uploads/assets/Boral-TB48-Fly-Ash-Reclaimed-From-Landfill-6-6-18.pdf.**

5. *Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard*, US Environmental Protection Agency, February 2014, **https://www.epa.gov/sites/production/files/2014-12/documents/ccr_bu_eval.pdf.**

6. "EPA Response to Kingston TVA Coal Ash Spill," US Environmental Protection Agency, last modified December 23, 2016, **https://www.epa.gov/tn/epa-response-kingston-tva-coal-ash-spill.**

7. "A Colorado First: PLC & CDOT's Highway 287 Project," Portland Cement Association, accessed May 11, 2021, **https://www.greenercement.com/coloradodot.**

8. Tom Adams, *Aggregates and Pozzolanic Materials Overview, KMR Collaborative*, April 10, 2018, **https://arpa-e.energy.gov/sites/default/files/5.%20Adams_Aggregates%20and%20Pozzolans%20Presentation.pdf.**

Charles Cannon, Valentina Guido, and Lachlan Wright, *Concrete Solutions Guide: Six Actions to Lower the Embodied Carbon of Concrete*, RMI, 2021, http://www.rmi.org/concrete-solutions-guide/.

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