21, rue d'Artois, F-75008 PARIS
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Effects of Decarbonization on Concrete Production and How Utilities can Embrace the Ensuing Innovation

A. PAGNOTTA
Burns & McDonnell
USA

SUMMARY

Concrete is essential to the current utility construction boom that is integrating renewable generation and enabling widespread electrification. However, concrete is also responsible for a share of greenhouse gas emissions, primarily related to the production of cement. Those emissions are often offset by using coal ash and byproduct iron slag to replace cement in the concrete mix. Due to the widespread retirement of coal plants and the decarbonization of the steel industry, coal ash and slag are facing supply shortages. Utilities must prepare to integrate alternative low-carbon cements into the concrete that forms the foundation of their power transmission networks. Natural, limestone-calcined clays, and recycled glass pozzolans are three supplementary materials, among others, with which utility engineers must familiarize themselves as they become integrated into the concrete supply chain. Many utilities are already showing that they are willing to lead the way on the path to a sustainable, decarbonized future, and all utilities can take advantage of how the positive aspects of low carbon cements can be integrated with the unique facets of power grid construction.

KEYWORDS

Concrete; Cement; Climate change; Sustainability; Decarbonization; Supplementary cementitious materials

apagnotta@burnsmcd.com

INTRODUCTION

The decarbonization of the global economy that is required to mitigate the effects of climate change is an immense undertaking involving a wide variety of industries and processes. Nevertheless, the climate science community has made its recommendations clear: reduce net greenhouse gas (GHG) emissions to zero as soon as possible, or humanity will continue to face ever-intensifying threats in our lived environment [1]. Utilities are already constructing the electrical infrastructure to support the widespread electrification that is required for our decarbonization efforts; however, that construction is also responsible for a share of GHG emissions. A substantial portion of construction emissions are linked to the creation of construction materials, and construction must begin using low and zero-emission alternatives to solve the current climate crisis.

Concrete is crucial to the current build-out of electric infrastructure due to its wide availability, versatility, durability, and fire resistance. However, the manufacturing of its principal component, cement, was responsible for roughly 6% of the total global warming potential (GWP[1]) in 2019[2]. That GWP is a result of the heating and ensuing chemical reactions that lead to the formation of the primary cement components, collectively called "clinker." Reducing the carbon footprint of concrete can be achieved by reducing the clinker content, and that reduction is already commonly achieved by the replacement of clinker with supplementary cementitious materials (SCMs). SCMs are industrial byproducts or minimally processed natural materials with the inherent ability to bind the inert components of concrete. Two of the most common SCMs are coal ash[3] from coal-combusting power plants and ground granulated blast furnace slag (GGBFS, sometimes called iron slag) from iron purification in steel production; however, the industrial processes that yield these byproducts are themselves targets for decarbonization. The ongoing retirement of coal-combusting power plants and the growth of the decarbonized steel industry will significantly impair current methods for reducing the carbon footprint of concrete. Utilities will need to prepare for the replacement of these traditional SCMs to ensure that the power grid that enables decarbonization is not contributing to the threat of climate change while it is being constructed.

This paper reviews the use of coal ash and GGBFS as SCMs in concrete. Next, we examine the current markets for these SCMs as well as current developments that limit the future supply of coal ash and GGBFS as SCMs. After establishing the need for replacing today's common SCMs, we review the ongoing developments in replacing traditional SCMs Finally, we discuss the role of utilities in integrating new SCMs into their construction specifications to support the future of electrification.

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[1] GWP adjusts an individual emissions contribution for its effect on planetary warming, as some emitted gasses trap heat at a greater rate.

[2] 2019 was the last year for which we were able to identify the complete dataset. This estimate uses the USGS 2019 global cement production estimate of 4.1 billion tons [2], the 2021 Portland Cement Association's cement carbon intensity estimate of 922 kg CO2 per metric ton [3], and the 2021 IPCC estimate of 59 Gt for 2019 total GWP of emissions [4]:

$$4.1 \cdot 10^9\ T\ cement \frac{0.907\ t\ cement}{1\ T\ cement} \frac{922\ kg\ CO_2e}{1\ t\ cement} \frac{1\ Gt}{1 \cdot 10^{12}\ kg} = 3.4\ Gt\ CO_2e$$

[3] Until recently, common parlance was "Fly Ash." However, the standard has recently been updated to "Coal Ash" to acknowledge the use of bottom ash as an SCM.

THE FUTURE OF TRADITIONAL SCMs

In concrete, material strength derives from the reaction of water with the cement chemicals, which are primarily combinations of calcium oxide, silica, and alumina. High concentrations of any of these three primary chemicals are positive indicators of a material's efficacy as an SCM. Coal ash and GGBFS are two examples of materials that have traditionally been used as SCMs. Many naturally occurring materials of volcanic origin (known as natural *pozzolans*), as well as calcined clays and silica fume, can be processed and used as SCMs; however, none are as common as coal ash and GGBFS. Table 1 shows the 2021 production quantities and concrete use percentage for cement clinker and traditional SCMs. Coal ash and GGBFS are orders of magnitude more important to the replacement of cement in concrete production. Coal Ash and GGBFS make up roughly 95% of US SCM production.

Table 1: 2021 Production Quantities and Concrete Use Percentage for Cement Clinker and Traditional SCMs

Material	US Production (2021) (Million Short Tons)	% Concrete Use	Reference
Cement Clinker	79.0	N/A	[2]
Coal Ash (Fly Ash + Bottom Ash)	36.7	34.2%	[5]
GGBFS	17.0	100%[4]	[6]
Natural Pozzolan + Calcined Clay	1.0	100%[5]	[7]
Silica Fume	0.1[6]	100%[7]	[8]

The chemical composition of coal ash varies with the type of coal that is being combusted and the method of collection, where more modern pollution reduction systems make some coal ashes unusable. The low percentage in concrete use is not necessarily a result of competing uses but stems from the fact that not all compositions make for quality SCMs [10]. Acceptable coal ashes are defined by ASTM C618 as having either a high concentration of silica alone (Class F), or a high concentration of the combination of silica and calcium oxide (Class C) [11].

The decline of coal ash availability directly results from declines in power generation that relies on coal combustion. Due to increasing competition from fossil gas-combustion and renewable sources, US coal generation has declined from 313.7 GW in 2011 to 208.3 GW in 2021, corresponding with steady electricity demand [12]. Along with improved pollution standards, the decline in coal-generated energy corresponded with a decline in Coal Ash production from 76.4 million short tons [13] to the previously reported 36.7 million short tons [5]. By 2050, the US Energy Information Administration projects that coal-combustion generation will likely fall below 100 GW [14]. As general demand for concrete and the need for SCMs increase, coal ash availability will continue to decrease.

[4] "Almost all GGBFS is used as [SCM]" [6]
[5] Assumed, concrete use is the reason for production
[6] Derived from 2021 USGS estimate of ferrosilicon and silicon metal production [8] and Fidjestol and Dastol's lower bound estimate of Silica Fume production from silicon metal of 400 kg per 1000 kg [9].
[7] Assumed, concrete use is the primary use of Silica Fume

Harvesting unused coal ash from waste disposal sites is a newly implemented solution to declining coal ash availability added to the 2023 revision of ASTM C618. The conditions at most disposal sites do not affect the pozzolanic properties of coal ash, preserving the efficacy of disposed coal ash as SCM. ASTM C618 now enables the use of harvested coal ash in concrete if it has been sufficiently processed to meet the physical and chemical requirements laid out in the standard. Harvested ash will play an important role in offsetting concrete's GWP in the near term. Despite a large supply (on the order of 1 billion short tons of usable material), that amount is finite and will not be replenished [15].

GGBFS should not be confused with other types of slag, a general term for the solid byproducts of metal smelting. GGBFS is specific to the refinement of iron ore in a blast furnace, from which molten slag must be drained and rapidly cooled to produce a reactive byproduct with a high silica, calcium oxide, and alumina concentration. After cooling, the granulated product can be ground to the same fineness as cement and used as an SCM [10]. Unlike coal ash and its decade of observable declines, US slag production has remained consistent over the last decade [6], which correlates with constant production of "pig iron," the purified iron product of blast furnace smelting [8]. To justify predicting a decline in GGBFS production with steel decarbonization, we must further examine current and near-future methods for steel production.

Steel is an iron alloy, and therefore a critical step in producing steel is the production of iron from its impure ore form. A blast furnace is the most common tool for purifying iron ore for steelmaking. Figure 1 shows the complete process for purifying iron from ore in a blast furnace. Three main compounds are added to the blast furnace: iron ore, metallurgical coal (also known as coking coal), and limestone. Hot air is forcibly injected into the bottom of the molten mix of the raw materials. The oxygen in the air rises through the molten stack, allowing the coal to combust and form carbon monoxide. Carbon monoxide then reacts with iron oxide in the iron ore, forming pure, molten iron and byproduct carbon dioxide. The most abundant impurity in the iron ore, silicon dioxide, is separated via a reaction with calcium oxide, which is introduced via the decomposition of limestone. The calcium oxide and silicon dioxide react to form wollastonite ($CaSiO_3$), which along with aluminum and magnesium oxides, settle into a molten layer above the molten iron. The molten iron is drained to a basic oxygen furnace to create steel. The slag is drained separately from the iron, properly cooled, and ground to GGBFS [16, 17].

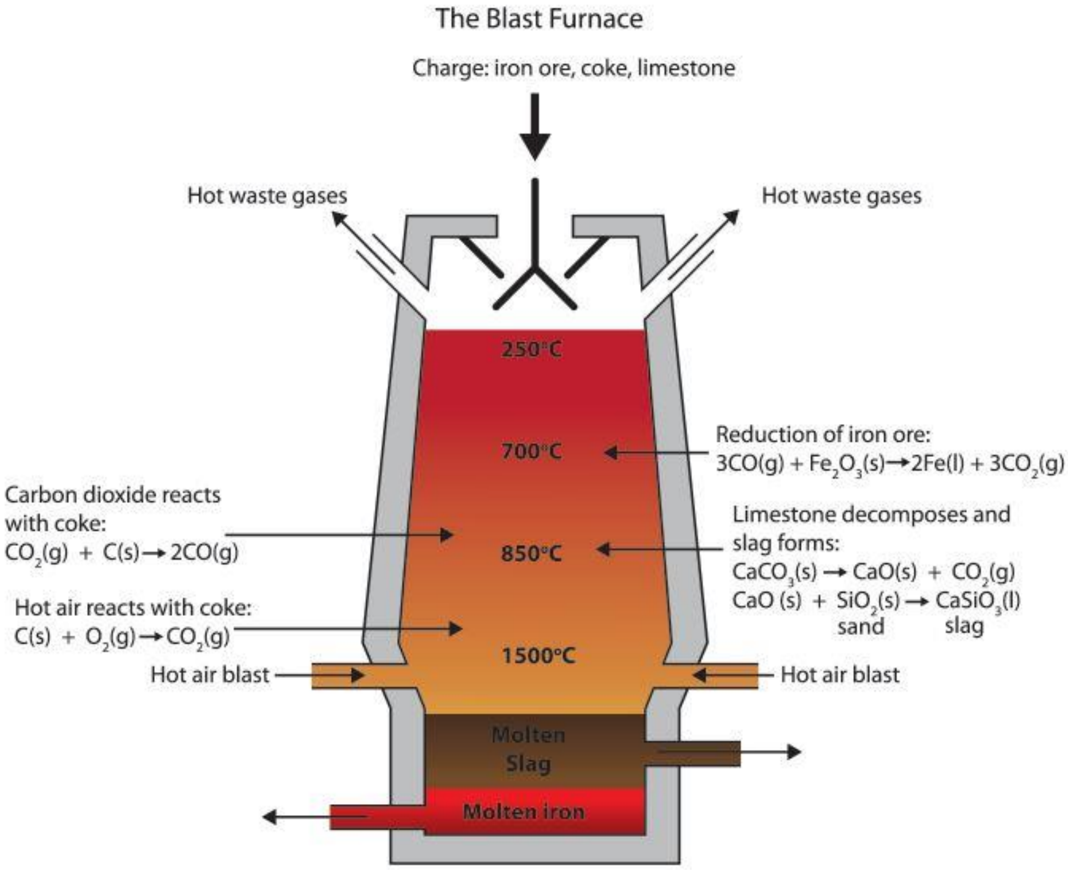

Figure 1: Blast Furnace Process Schematic [18]

Two generally accepted paths to decarbonizing the steelmaking process are direct reduction of iron oxide either via hydrogen reduction or electrolysis. Both processes currently rely on pre-processing iron ore (pelletization) to increase the iron concentration. Pelletization consists of grinding iron ore to a fine powder that separates iron oxide via magnetic separation or froth floatation [19]. The purified product is processed into iron ore pellets, which commonly have iron concentrations above 65% and combined silicate dioxide concentrations much lower than those of iron ores used as raw material for blast furnace steelmaking.

The lower temperatures of these alternative methods for iron ore processing do not favor slag formation in the presence of limestone, which is why the pelletization process is applied before the iron reduction process. Impurities still exist and are removed by adding oxygen to the molten mix inside the electric arc furnace. The resulting slag is removed in a method similar to that of the blast furnace; however, EAF slag has a much higher percentage of iron oxides and a much lower percentage of silicates. Therefore, in its raw form, it is not as useful as an SCM due to the reduced concentration of silicates. Some work has been performed to explore the ability of further refinement to produce a more favorable SCM from EAF slag, but recycling of EAF slag is commonly performed to replace industrial aggregate [20].

Unlike the disappearance of coal ash with the phase-out of coal combustion power generation, there is no indication of a reduction in steel production. The silicates and alumina that are present in iron ore must still be removed to make steel, but there is not currently a process for collecting them from pelletization and producing a suitable SCM, nor is EAF slag suitable for use as an SCM. There may still be a route for utilizing steel-making byproducts in concrete;

however, we should expect a disruption at some point in the future as decarbonization proceeds.

NEXT GENERATION SCMs

A variety of SCMs already exist that could compensate for the simultaneous decrease in coal ash and GGBFS supply and the increase in demand for SCMs with sufficient acceptance and investment.

Natural Pozzolans – The use of natural pozzolans as SCMs is certainly not new, given the general knowledge of their high-quality use by the Romans thousands of years ago. Modern use is still challenged by variability among geologic regions, leading to challenges with acceptability among engineers. The latest report on the use of raw or processed natural pozzolans defines multiple categories with variable geography and chemical composition [21]. Pozzolans, while often associated with higher late-age strengths and "self-healing" properties, are also associated with low early-age strengths and accelerated carbonation, a common process in concrete that may lead to reinforcing steel corrosion [22]. The ability to blend natural pozzolans with cement during the cement production process to produce a Type IP blended cement [23] helps to reduce variability by removing the SCM replacement percentage and cement manufacturer from the control of the concrete mixing plant.

Calcined Clay and Limestone Calcined Clay Cement (LC3) – Clay's efficacy as an SCM derives from its essential composition of aluminosilicate minerals. Specifically, the commonly occurring clay variant Kaolinite can be calcined (i.e., heated) to remove the chemically combined water, then purified and ground to create Metakaolin, an SCM with a high degree of pozzolanic activity [21]. Limestone calcined clay cements are relatively new formulations of ternary blended cements (Portland cement combined with two other ingredients) that may allow up to 50% clinker replacement with lower purity calcined clay and limestone. The disadvantages are similar to those of natural pozzolans – increased carbonation rate and low early strength; however, the advantage as compared to pozzolans is the widespread availability of kaolinite and limestone and the consistency introduced by processing these raw materials directly into cement [24].

Recycled Glass Pozzolans – Post-consumer glass has been considered as an SCM due to its high-silicate chemical composition with moderate concentrations of calcium oxide. In addition, it is abundant, as 11.5 million tons of glass are produced yearly in the US and only a quarter of that quantity is recycled. When conformed to ASTM C1866 (Published in 2020, revised in 2022), ground glass demonstrates pozzolanic properties. Its substitution for up to 50% of cement can reduce the overall GWP of concrete by 40%. While studies have not observed deleterious effects, glass can contain high levels of alkalis which should be noted when the common concrete deterioration method of alkali-silica reaction is a concern [25, 26, 27].

In addition to the listed SCMs, there are procedures and products that can reduce the required amount of cement and cement paste by improving efficiency at variable scales. Overly conservative designs routinely require excess concrete to reduce the number of unique foundations and improve constructability. An emphasis on removing a degree of conservatism through optimized design would reduce the amount of concrete required for construction. Better quality control in precasting facilities typically results in smaller concrete components as compared to cast-in-place concrete, and therefore increased use of precast concrete also reduces the total amount of concrete required for construction. Optimized aggregate grading by including an intermediate aggregate between the size of gravel and sand can create an optimal packing of aggregate that reduces the required amount of cement paste in a concrete mix [28]. Portland Limestone Cements increase the unprocessed limestone percentage of a blended cement from 5% to 15% and are rapidly replacing traditional, plain Portland cement in the US and around the world [29]. Modern admixtures seed inert nano particles in cement paste, which allows for improved hydration efficiency and subsequent cement content reduction [30]. All of these emission reduction tactics should be considered in addition to the use of SCMs.

DISCUSSION

What can we say about the current state of concrete innovation in power grid construction?

While progress is still being made, many utilities are already leading the way towards a sustainable future by implementing lower carbon and renewable power generation into the grid, and preparing for widespread electrification. Some are even taking steps towards zero carbon construction. National Grid recently set a record for the world's largest cement-free placement of concrete by using nearly 1,000 cubic yards of concrete for their Hurst Substation Project in the UK. Not to diminish this incredibly important achievement, but in the context of this paper, it's important to note that the cement replacement was a combination of GGBFS and a fly ash geopolymer [31]. Coal ash and GGBFS should be used to their full potential while still readily available, despite their future availability challenges. While they continue to focus on the sustainability of the electricity generation, utilities can still lead the way in decarbonizing their construction, in the same way that automakers are introducing electric vehicles while incorporating zero-emission steel [32].

Is the power grid the right place to incorporate next-generation SCMs?

We explored a broader posing of this question in a previous paper, concluding that redundancy in power delivery networks favored the use of innovative materials but must be balanced with the importance of these networks to our [33]. However, two attributes of utilities make it imperative and favorable for them to incorporate next-generation SCMs. Utilities are, like natural pozzolans, regional. Utilities can shape their standards around local geography and local material availability, allowing their engineers to familiarize themselves with locally available natural pozzolans. In addition, concrete vendors like to regionally source coal ash and GGBFS, which means that future shortages in their availability will also be regional. Regional shortages may occur randomly and without warning, and utilities that are ready to adapt to these changes will be better prepared to continue construction without interruption. In addition, utilities primarily use concrete for foundation work and the encasement of underground conduits. Because they are mostly surrounded by soil, they will have less exposure to atmospheric carbon dioxide, offsetting accelerated carbonation resulting from the use of natural pozzolans and LC3.

How can utilities prepare for the changes that are coming to the concrete industry?

Engineers must first familiarize themselves with innovative materials. If an engineer encounters a new material for the first time when their deadline for construction is approaching, they are much more likely to reject it out of hand and request a cement or SCM with which they are more familiar. Additionally, many utilities and engineers have long used rigid standards for the concrete that is used to construct the power grid. To reduce emissions and allow for implementation of innovative materials, we must transition to performance-based specifications that allow concrete manufacturers to meet the strength, workability, and durability requirements of a project without the owners and engineers dictating the recipe. Concrete manufacturers are already incentivized to use materials that would otherwise be landfilled because their disposable nature often makes them less expensive than cement. Cement manufacturers are vertically integrating many SCMs into their standard offerings to improve consistency in the final product. Outside of performance specifications, utilities can specify limits on the emissions associated with a cubic yard of concrete, and verify conformance by requesting an environmental product declaration (EPD, essentially a carbon dioxide nutrition label). By specifying carbon intensity limits, utilities can drive innovation while they embrace it.

CONCLUSION

As could be expected with any widespread societal change, the cresting wave of decarbonization will bring a variety of cascading effects throughout every sector of our economy. The primary effects on concrete production are clear: coal ash and GGBFS SCMs will become technologies of the past, and their near-future replacements will be comprised of a variety of natural, lightly processed, and alternative byproduct SCMs. The construction industry needs concrete for many specific applications, and construction of the power grid that serves many of the decarbonization efforts is not isolated from the need for concrete. Many utilities are already walking the path of climate leadership, but all will be affected by the coming changes. In many cases, utilities are uniquely suited to integrate natural pozzolans, LC3, and glass pozzolans into their construction practices. Engineers and other construction professionals must also prepare themselves and their often-rigid specifications to incorporate new materials into concrete mix designs. Utilities can even take the step of specifying limits on the GHG emissions associated with construction to drive innovation in the concrete industry while they continue to enable decarbonization through widespread electrification.

BIBLIOGRAPHY

[1] IPCC (International Panel on Climate Change), Various Authors (2023) Synthesis Report of the IPCC Sixth Assessment Report.

[2] USGS (United States Geological Survey) Prepared by C. C. Tuck (2022a) "Cement" Mineral Commodity Summaries.

[3] PCA (Portland Cement Association) (2021) Environmental Product Declaration for Portland Cement.

[4] International Energy Association (2021) *Global Energy Review: CO2 Emissions in 2021*.

[5] ACAA (American Coal Association) Various Authors (2022) Production and Use Survey. https://acaa-usa.org/publications/production-use-reports/ Accessed 19 June 2023.

[6] USGS (United States Geological Survey) Prepared by C. C. Tuck (2022b) "Iron and Steel Slags" Mineral Commodity Summaries.

[7] NPA (Natural Pozzolan Association) https://pozzolan.org/about-npa.html Accessed 19 June, 2023.

[8] USGS (United States Geological Survey) Prepared by C. C. Tuck (2022c) "Silicon" Mineral Commodity Summaries.

[9] Fijestol, P. and Dastol, M. (2008) The history of silica fume in concrete – From novelty to key ingredient in high performance concrete" Proc. Of Congresso Brasileiro do Concreto.

[10] Mindess, S., Young, J. F., and Darwin, D. (2003) *Concrete*, Prentice Hall, Upper Saddle River, NJ.

[11] ASTM International (2023) ASTM C618/C618M-23 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.
[12] EPA (Environmental Protection Agency) Author Unknown (2023) "Power Sector Evolution" https://www.epa.gov/power-sector/power-sector-evolution Accessed 20 June 2023.
[13] ACAA (American Coal Association) Various Authors (2012) Production and Use Survey. https://acaa-usa.org/publications/production-use-reports/ Accessed 19 June 2023.
[14] EIA (Energy Information Administration) Tsao, S. (2023) *2023 Annual Energy Outlook.*
[15] ACI (American Concrete Institute) Committee 232, Diaz-Loya, I, Chair (2021) "Harvested Fly Ash as a Supplementary Cementitious Material" ACI PRC-232.5-21
[16] Fruehan, R. J. (1998) *The Making, Shaping and Treating of Steel.*
[17] FHWA (Federal Highway Administration) Author Unknown (2016) "Blast Furnace Slag" User Guideline for Waste and Byproduct Materials in Pavement Construction, Publication Number: FHWA-RD-97-148/
[18] IIMA (International Iron Metallics Association) Author Unknown (2021) "Pig Iron Production – Blast Furnace Route" https://www.metallics.org/pig-iron-bf.html Accessed 21 June 2023.
[19] Kozicki, C. and Carlson, C. (2022) "Iron Ore Pelletization," FEECO International, https://feeco.com/iron-ore-pelletization/ Accessed 18 July 2023.
[20] Teo, P. T. et al. (2020) "Assessment of Electric Arc Furnace (EAF) Steel Slag Waste's Recycling Option into Value Added Green Products: A Review" Metals 10 (10), 1347.
[21] ACI (American Concrete Institute) Committee 232, Obla, K. H., Chair (2012) "Report on the Use of Raw or Processed Natural Pozzolans in Concrete" ACI 232.1R-12
[22] GCCA (Global Cement and Concrete Association) Author Unknown (2023) "Natural Pozzolans" https://gccassociation.org/cement-and-concrete-innovation/clinker-substitutes/natural-pozzolans/ Accessed 22 June 2023.
[23] ASTM International (2021) ASTM C595/C595M-21 Standard Specification for Blended Hydraulic Cement.
[24] Zunino, F., Martirena, F., and Scrivener, K. (2021) "Limestone Calcined Clay Cements (LC3)" ACI Materials Journal, V. 118 No. 3.
[25] ASTM International (2022) ASTM C1866/C1866M-22 Standard Specification for Ground-Glass Pozzolan for Use in Concrete.
[26] Krstic, M. and Davalos, J. F. (2019) "Field Application of Recycled Glass Pozzolan for Concrete" ACI Materials Journal, V116 (4)
[27] Kaminsky, A., Krstic, M., Rangaraju, P., Tagnit-Hamou, A., and Thomas, M. D. A. (2020) "Ground-Glass Pozzolan for Use in Concrete" Concrete International November 2020.
[28] Anson-Cartwright, M. (2011) Optimization of Aggregate Gradation Combinations to Improve Concrete Sustainability, Master's Thesis, University of Toronto.
[29] PCA (Portland Cement Association) Author Unknown (2023) "Portland Limestone Cement and Sustainability" https://www.cement.org/sustainability/portland-limestone-cement accessed 22 June 2023.
[30] Owens, K., Russell, M. I., Donnelly, G., Kirk, A., & Basheer, P. A. M. (2014) "Use of nanocrystal seeding chemical admixture in improving Portland cement strength development: application for precast concrete industry" Advances in Applied Ceramics, V. 118 (8).
[31] National Grid (2023) "National Grid completes record-breaking pour of cement-free concrete at London Power Tunnels," https://www.nationalgrid.com/national-grid-completes-record-breaking-pour-cement-free-concrete-london-power-tunnels, Accessed 15 July 2023.
[32] Green Steel World (2022) "Green Steel Partnerships: A lynchpin for auto industry's real transformation" https://greensteelworld.com/green-steel-partnerships-a-lynchpin-for-auto-industrys-real-transformation accessed 23 June 2023.
[33] Pagnotta, A. and Somboonyanon, P. (2021) "Embracing Carbon Abatement in Concrete for the Construction of Electrical utility Networks" Grid of the Future Symposium, CIGRE US National Committee