January 2023

Summary of Glass as an SCM and Pozzolan

What is an SCM? What is a Pozzolan?

Definition and Types

Supplementary cementitious materials (SCM) and Pozzolans are:

- mineral admixtures
- finely divided materials having cementitious properties
- an addition to or replacement for cement in concrete mixes
- generally, a by-product of a manufacturing process (but can be naturally occurring materials as well)

Supplementary cementitious materials (SCMs) contribute to the properties of hardened concrete through hydraulic or pozzolanic activity. Typical and most used examples are fly ashes, slag cement (ground, granulated blast-furnace slag), and silica fume. These can be used individually with portland or blended cement or in different combinations. Supplementary cementing materials are often added to concrete to make concrete mixtures more economical, reduce permeability, increase strength, or influence other concrete properties.

A **pozzolan** is a siliceous or silico-aluminous material that by itself possesses little or no cementitious values but will, in finely divided form and in the presence of water, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Generally, a pozzolan is an SCM and the terms can be used interchangeably. A few examples exist where they are not the same, but it is rare (limestone additive being one). To confuse even further at times, slag has both a pozzolanic and hydraulic function (see cement hydration equations below).

Main Types of SCM's/Pozzolan's

Flyash: Type C and Type F

Silica Fume: densified and undensified

Slag: ground granulated blast furnace slag – three main types 80, 100, 120

Natural pozzolans

- ✓ Minerals of volcanic origin (rhyolite for example)
- ✓ Rice husks
- ✓ Pumice
- ✓ others

Ground glass

- ✓ From plate, container (or E-Glass, low volumes exist)

Calcined Clay/Metakaolin (some define this as a natural pozzolan as well)

Others under development

- ✓ Natural pozzolan/glass blends
- ✓ Corn husks
- ✓ Carbon capture grades
- ✓ Blends
- ✓ ???? (Unknown as of today)

And some cement hydration basics to be technical ….

Two main types of reactions in cement hardening: hydraulic and pozzolanic
Portland cement consists of about 80% calcium silicates: alite (C_3S) and belite (C_2S)

These will react with water according to the following hydraulic reactions.

$C_3S + 3H = CSH + 2\ CH$
$C_2S + 2H = CSH + CH$

The final structure consists of about 75% calcium silicate hydrate (CSH – gives the strength) and 25% hydrated lime (CH).

The hydrated lime (CH) also called calcium hydroxide or Portlandite will react with pozzolan, forming more CSH-phases:

CH + S -> CSH gel-like structures

Glass as a Pozzolan: a brief history

At the beginning ….

A) Ground glass was thought to be an effective sand substitute in concrete. The issue was the alkali level (Na and K) is too high in container and pane glass and the coarse particles of glass (relative to cement) led to expansive concrete.
B) Similar approach was to try glass as a concrete aggregate. Concerns about the use of glass aggregate in concrete relates to its susceptibility to alkali-aggregate-reaction (AAR) in concrete, and this aspect was also recognised and studied several decades ago.
C) Then the potential use of ground glass as a pozzolan was reported by Pattengil & Shutt (1973) who tested soda-lime container glass crushed and milled to a pass 325 mesh (45-microns sieve). Since this time other groups have confirmed that ground glass exhibits good pozzolanic provided it is ground to sufficient fineness. Little pozzolanic reaction is evident for glass above 300 microns but the pozzolanic activity increases as the particle size is reduced below this size with good pozzolanic properties generally being achieved below about 45 microns (Federico & Chidiac 2009)

And finally, after a few passes at ASTM, ASTM C1866 in 2020 set the first major specification for use of glass as a pozzolan. CSA A3000 followed. Here is an example Press release of the day …

NEWS BRIEF

A New Standard for Replacing Cement with Recycled Glass

ASTM C1866 will make it easier to specify low-embodied-carbon recycled ground glass as a supplementary cementitious material.

by Brent Ehrlich

Ground glass can be a low-global-warming-potential replacement for Portland cement, but using it on a project has been difficult because there has been no standard way to specify the material. ASTM has published ASTM C1866, Standard Specification for Recycled Ground-Glass Pozzolan for Use in Concrete. ASTM C1866 will make it easier for building teams to replace a percentage of Portland cement with recycled ground glass supplementary cementitious materials (SCMs, sometimes called *pozzolans*)—an important step forward for the green building industry.

Publication of ASTM C1866 makes it easier to specify post-consumer recycled ground glass as a replacement for high-global warming potential Portland cement.

Photo: Urban Mining Northeast

The production of Portland cement used in concrete is responsible for approximately 5% of total global CO_2 emissions, so replacing some of the Portland cement with post-consumer ground glass can significantly reduce concrete's carbon footprint. As a bonus, ground-glass pozzolans make use of a readily available regional waste material that is often landfilled instead of recycled, and it can be used in place of fly ash (which can contain toxic heavy metals) and ground granulated blast furnace slag, both of which are byproducts of carbon-intensive industries.

Processed into a fine powder, ground glass can replace up to 40% of Portland cement in a mix, creating a stronger, denser, less permeable, and more durable concrete while making use of a readily available, inert waste material. Pozzolans such as ground glass can also improve concrete's workability and reduce the amount of water and chemical admixtures required.

The ground glass pozzolan Pozzotive, made by Urban Mining and a former BuildingGreen Top 10 product, has been used successfully in concrete masonry units (CMUs) and bricks for years and is available as an SCM for ready mix. With the adoption of ASTM C1866, products like this can now be used more readily.

Published June 8, 2020 Permalink Citation

Before reviewing competing SCM's, what makes glass as a pozzolan so attractive?

- ✓ Circular economy value play
- ✓ It's an **available** resource due to large diversion to landfill
- ✓ Performance benefits

Ground glass pozzolan makes for the following attractive performance properties

A) Excellent late strength gain and high cement substitution rates
B) Lower water demand
C) Excellent GWP (Greenhouse Warming Potential) reduction
D) Lower concrete permeability and chloride resistance
E) Preferred lighter colour (near white in some cases)
F) Good ASR mitigation
G) Excellent performance blend material partner (with low alkali E-Glass/calcined clays/Silica fume/etc)

Summary Table of Glass Performance versus other SCM's

Glass as a Pozzolan: Features
Rating: 1 poor, 10 excellent
(Three features have double weighting as critical properties)

SCM/Pozzolan	**Overall rate**	Reactivity Early	Reactivity Late (2x factor)	Water Demand (2 x factor)	ASR Mitigation	GWP	Substitute impact (2 x factor)	Price Point (Typ current)	**Perf/Price Ratio**
Glass as Slag Replacement	12.2	5	9	8	6	10	9	180	10.01
Glass Performance (+ E-Glass/Blend)	13.7	6	10	8	10	10	10	265	9.63
Slag 120	11.7	5	9	6	8	9	9	165	9.62
Class C Flyash	9.0	7	6	7	8	7	3	110	6.63
Natural Pozzolans	8.3	5	6	6	5	6	5	120	4.82
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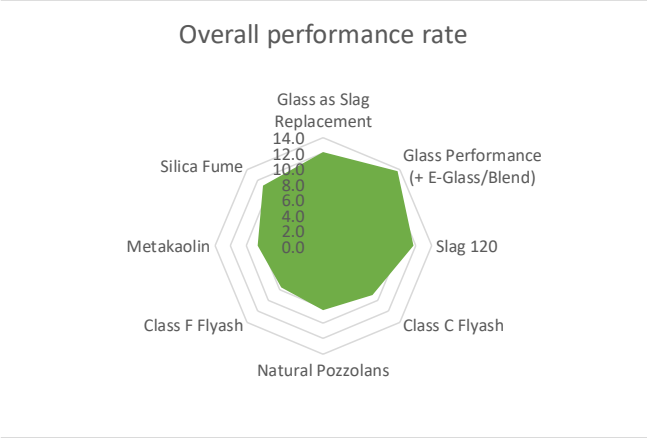

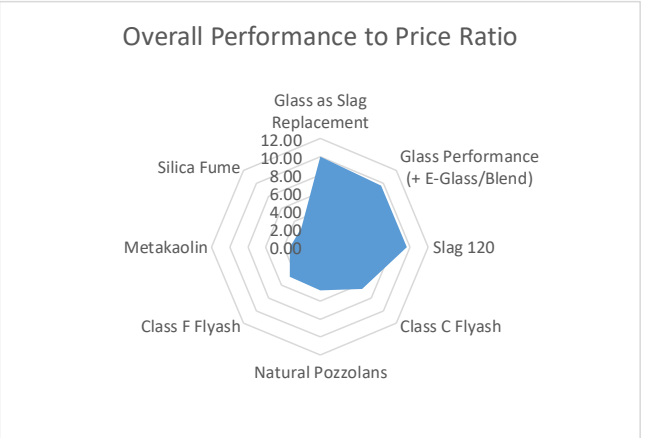

Good recent writing on Glass in Concrete

Open-loop Recycling of Glass in Concrete Provides Upcycling Opportunities

CSHub Research Brief | Hessam AzariJafari, Yiwei Lyu, Ipek Bensu Manav | cshub@mit.edu

CSHub MIT CONCRETE SUSTAINABILITY HUB

Current Status of Glass Recycling

Due to glass' valuable role in advancing civilization and global sustainability, the United Nations deemed 2022 the "International Year of Glass" [1]. Glass is used intensively. In fact, approximately 12 million tons of waste glass are generated in the United States annually, representing more than 4% municipal solid waste [2].

Unfortunately, on average, just 33% of waste glass is recycled for new glass production in the U.S. [2]. One key challenge to glass recycling is its low monetary value, currently averaging around $11/ton [3].

However, waste glass has an alternative, currently unexploited value: it can be used as a supplementary cementitious material (SCM) in concrete. This brief explores whether the expanded use of waste glass in concrete provides economic and/or environmental benefit.

Key Takeaways:

- Concrete can enable the upcycling of waste glass powder as a pozzolanic material.
- Glass tower buildings can use three times as much recycled glass in their structural concrete compared to their façades.
- The environmental performance of a mixture replacing 20% of portland cement with glass powder is similar to that of the industry average.
- The annual generation of 12 million tons of glass powder can provide a sustainable source of pozzolan (around 12% of portland cement consumption for concrete in the US).
- Due to its availability in urban areas, glass can partially meet the growing demand for supplementary cementitious materials.

More than four percent of the United States' municipal solid waste is waste glass, but just 33% of it is recycled for new glass production. Rather than ending up in landfills, a much more useful purpose for this waste glass is using it as an SCM in concrete. Image source: Fairfax County, VA.

Another supporting link on glass use in pozzolan (from main competitor Urban Mining)

https://resource-recycling.com/recycling/2023/01/02/experts-tout-the-benefits-of-recycled-glass-pozzolans/

Why SCM's and their Performance matter?

The Net Zero 2025 commitment!

Global Cement and Concrete Association

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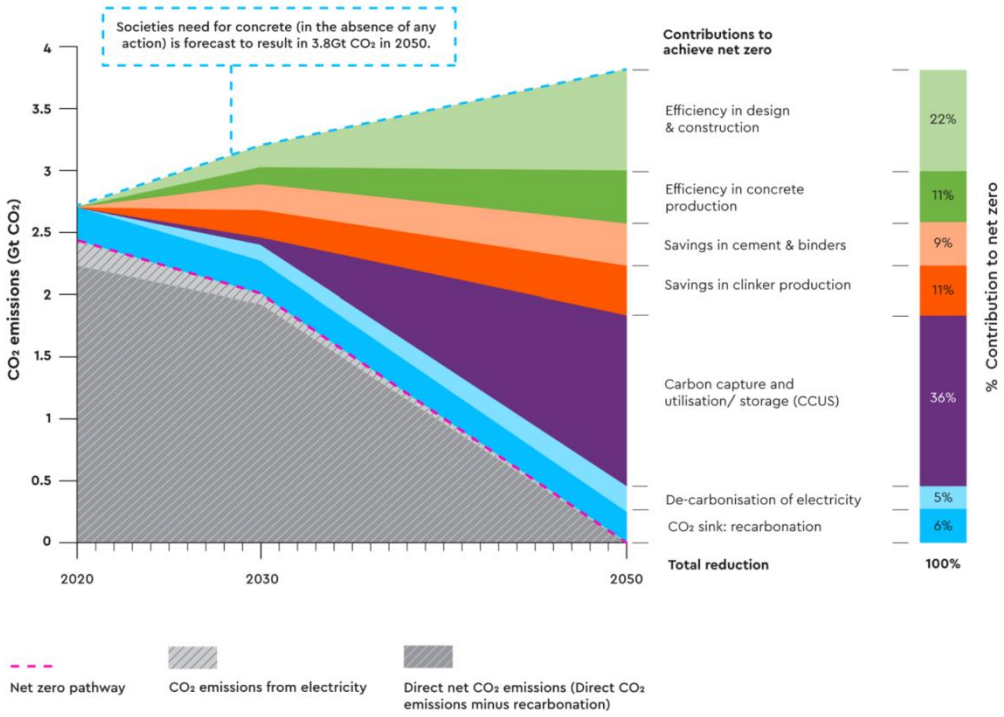
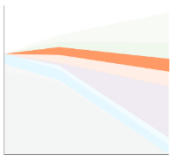
ABOUT US ABOUT CEMENT & CONCRETE NET ZERO INNOVATION ESG NEWS AND EVENTS POLICIES



SCM's form part of two key contribution areas on the road to 0 net CO2 emissions: Efficiency in Concrete Production and binders and savings in cement and binders. The expected contribution to Net Zero is about 19%.



01 / Binder means all material in concrete such as cement, fly ash, ggbs, limestone fines etc. that is permitted as cementing material in the local jurisdiction

02 / Clinker is produced in a cement kiln and is ground to manufacture ordinary Portland cement. Clinker can be ground with other materials to produce cements with lower CO_2 emissions

Savings in cement and binders [01]

At the cement plant or the concrete plant, fly ash, ggbs, ground limestone and other materials can be added to deliver concretes with reduced CO_2 emissions but still the required performance. In some applications the concrete performance is enhanced. This lever is also referred to as clinker[02] substitution. In this roadmap it is described by clinker binder ratio.

Availability of suitable materials around the world varies now, and will into the future, because for example fly ash comes from coal fired power stations and ggbs from the steel industry's blast furnaces and these industries are also transitioning.

In coming decades there will be increased use of ground limestone and the introduction of calcined clays to both compensate for reduced supply of fly ash and ggbs, and further reduce the clinker binder ratio. Calcined clays rely on clay deposits that are geographically spread and sufficiently abundant to meet projected demand.

Whilst availability of materials can be a limitation on clinker binder ratio, client acceptance is a current barrier in fully exploiting this lever in some developed and emerging economies.

On average globally, the clinker binder factor is currently 0.63. It is projected to reduce to 0.58 and 0.52 by 2030 and 2050 respectively. Regional and even country variations are inevitable due to differing material availability and market requirements.

Alternatives to Portland clinker cements have been the subject of much research but their impact is not forecast to be significant primarily because of fundamental lack of availability of raw materials at the scale required. Furthermore, they also come with CO_2 emissions (about half of common cements).

On average globally it is forecast that alternatives to Portland clinker cements will be 1% and 5% of cement in 2030 and 2050 respectively and in 2050 contribute a 0.5% reduction in overall CO_2 emissions.

The $$$ opportunity for glass pozzolan

Flyash, Slag and Silica Fume: the traditional competition

Market Characteristics

- ✓ Large volumes
- ✓ Established use and specification environments
- ✓ the “original” mass use SCM’s

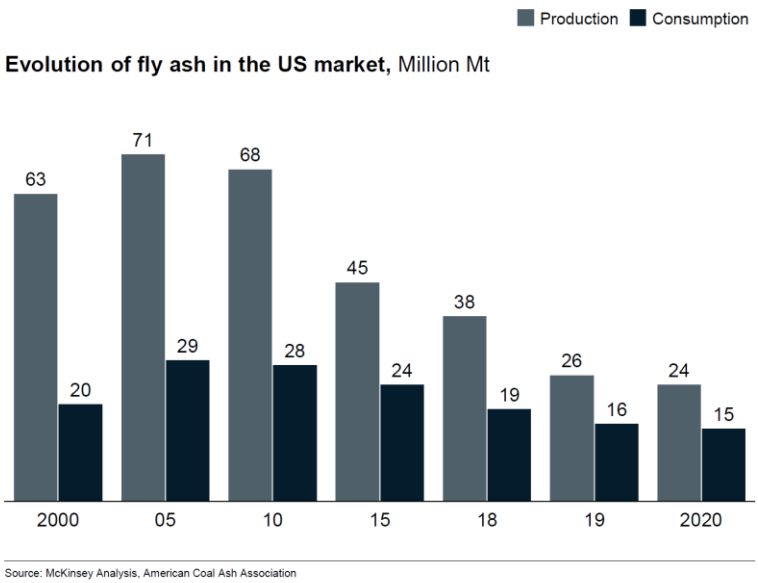
Supply and consumption – defining the market potential for other pozzolans

	Flyash (C and F)	Slag (Type 80, 100, 120)	Silica Fume
Yearly consumption	16 to 20 million tonnes	4.2 million tonnes	450 K tonnes
Supply direction	Declining	Capped to declining	Capped to slight increase
How to attack with glass pozzolan?	Difficult due to low cost of flyash	Finely ground glass with exceptional production cost control + glass blends	Performance grade ground glass

Flyash

Market Excerpts from McKinsey Report (using 2020 Data)

While fly ash production is decreasing in the US…



Source: McKinsey Analysis, American Coal Ash Association

Description of US market

Over past 20 years, fly ash usage has been declining at much slower pace than production (decline due to coal plant closure). This has created shortages in certain areas (e.g., California, New York)

Other SCMs (e.g., slabs, pozzolans, calcinated clay) could capture this opportunity because of their availability, relatively low prices and higher cement replacement percentage. **Silica fume is unlikely to compete with these technologies due to its relatively high price point**

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...other SCMs could capture this opportunity

Product	Description	Availability	Selling price, excl. freight	Max. % in cement	CO2 reduction potential[1]
Fly ash (Class F)	Coal combustion product composed of fine particles that are carried out of boiler by flue gases in power plants	Declining availability, stockpiles can be used	$50-$60 per ton	30%	10-30%
Slag (GBFS) and GGBFS	By-product of blast furnace iron- and steelmaking that have been quenched in water or steam to produce sand-like granular product. This is then ground and grinded for mixing into cement or concrete	Declining availability expected	$90-$100 per ton	50 %	Up to 90%
Natural pozzolans (e.g., volcanic ash)	Rocks of volcanic origin, particularly pyroclastic materials resulting from explosive eruptions, exhibit pozzolanic behavior with minimal processing	Depending on local availability	$65-$80 per ton	40 %	30-40%
Calcined clay	Metakaolin is produced by heating sources of kaolin (i.e., clay)	Widely available	$130-150$ per ton	27%	30-40%
Limestone	Sedimentary rock composed mainly of calcium carbonate, usually in form of calcite or aragonite	Widely available	$30-40 per ton	5%	<10%
Silica Fume	Ultrafine powder collected from production of silicon and ferrosilicon alloy – silicon carbide	Mostly used in high-performance concrete (i.e., enhanced strength and durability)	$400 -$1,000 per ton	5%	<10% Additional benefit as total concrete need can be reduced

1. In comparison to conventional (Portland) cement
Source: McKinsey Analysis

Comments

Fly ash is preferred SCM due to low cost and relatively high maximum replacement percentage in cement

Other SCMs are well positioned to bridge expected gap from declining production of fly ash due to their lower cost and higher share of possible cement replacement

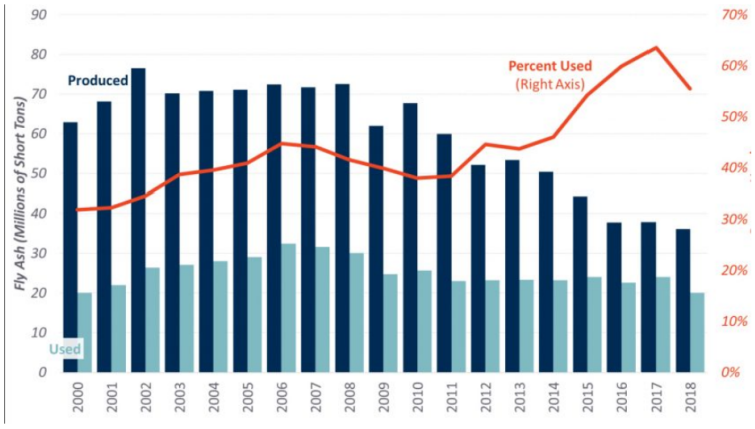
Unless strong new environmental legislation is enacted or additional technical characteristics are required, silica fume is unlikely to replace fly ash

Important take-away: when the previous graphic was created there was no approved specification for glass as a pozzolan. Today's reality is that ground glass is accepted as an alternative SCM that can capture the opportunity of reduced flyash production, let alone the limits identified below in slag supply. In fact when one compares glass to other SCM's in this graphic (per the assessment table on page 4), it becomes evident that a quality glass pozzolan has tremendous opportunity.

Another chart showing change in flyash market conditions

Shifting production, use patterns temper fly ash, CCP recycling rates

January 4, 2020 Concrete News



Supply dynamics in key regional markets, paralleling coal-fueled power plant closures, spurred an 11 percent year over year decline in fly ash consumption in concrete, according to the American Coal Ash Association's (ACAA) just-released "Production and Use Survey" for 2018. Concrete-grade ash accounted for 12.5 million of the 59.4 million tons of coal combustion products (CCP) beneficially used last year, the latter figure down 8 percent or 9.1 million tons from the 2017 ACAA survey. Use of all grades of CCP in cement production declined 26 percent in 2018, to 6.4 million tons.

Slag (GGBFS)

What is blast furnace slag?

- by-product of steel production (BOF furnaces)
- three grades based on reactivity (80, 100, 120)
- can be used at fairly high dosage rates in concrete
- glass phase material
- light grey-white in color

Great link to understand blast furnace slag in cement/concrete

https://theconstructor.org/concrete/blast-furnace-slag-cement/23534/

The slag specification was first set at ASTM in 1982. The uptake in use was slow. The Slag Cement association started in 2002 to represent slag cement producers and make a case for slag use in concrete. Coupled with an environmental push in the late 90's, early 2000's this contributed to a rapid acceptance of slag as an SCM. Glass pozzolan is at a similar tipping point, albeit much closer to its specification approval date (May 2020).

Supply Constraints for Slag

MARKET FORECAST DATA – GGBFS DATA

- **Major global steel producers move away from basic oxygen furnaces (BOFs) to electric arc furnaces (EAFs)**
- **Asia ex-China consumption, however, is forecast to increase by almost 4 million tons by 2027**
- **North America and Europe to drive global EAF production growth by 2027**

Greenwich (CT), USA, February 22, 2022 – Global ground granulated blast furnace slag (GGBFS) demand is forecast to decline by 2027, as China's focuses on the implementation of greenhouse gas emission reduction policies, according to CW Research's 2022 update of the Global Ground Granulated Blast-furnace Slag Market Report and Forecast.

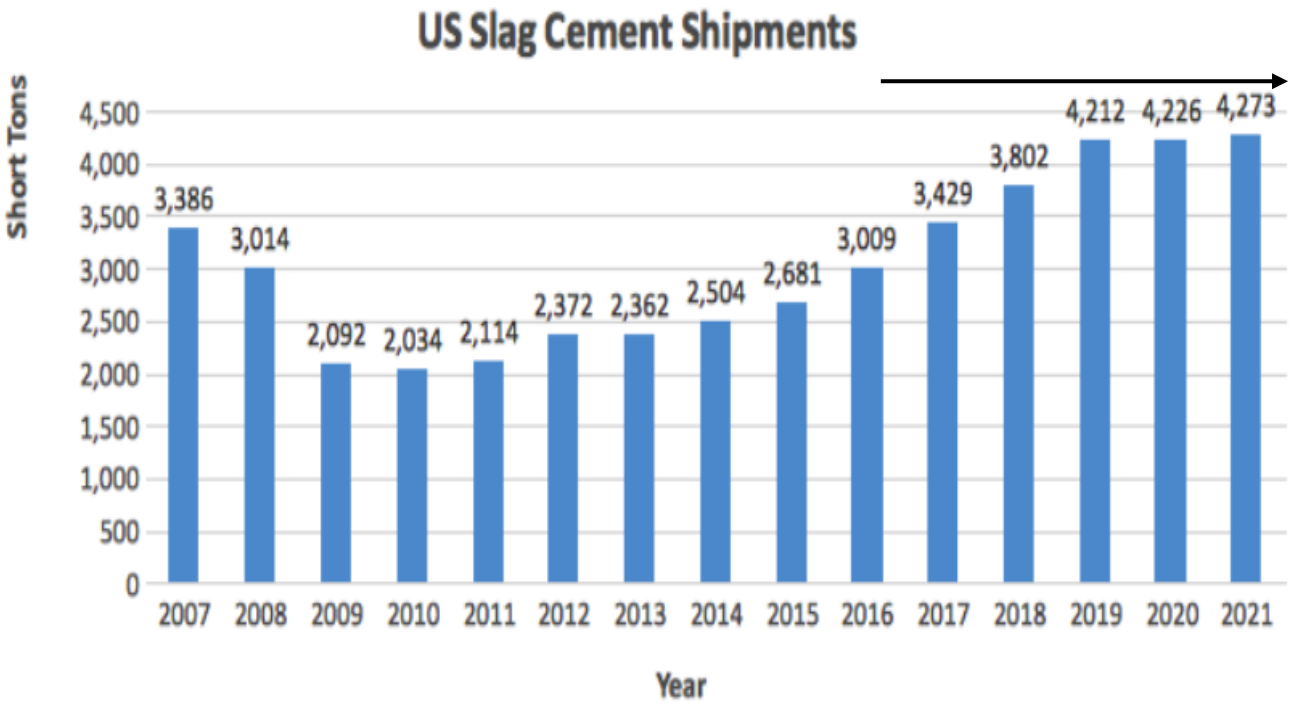
Between 2017 and 2022, global GGBFS consumption grew at a CAGR of 2 percent, however, this trend is expected to change over the next five years as major global steel producers move away from basic oxygen furnaces (BOFs) to electric arc furnaces (EAFs). On the other hand, Asia ex-China consumption is forecast to increase by almost 4 million tons between 2022 and 2027.

"China is set to reduce its steel production intensity gradually and increasingly shift crude steel production towards the EAF process, moving away from a BOF focus. Given that China alone accounts for more than half of global GGBFS demand, this will likely result in a decline of the global market size," writes Prashant Singh, Associate Director at CW Group.

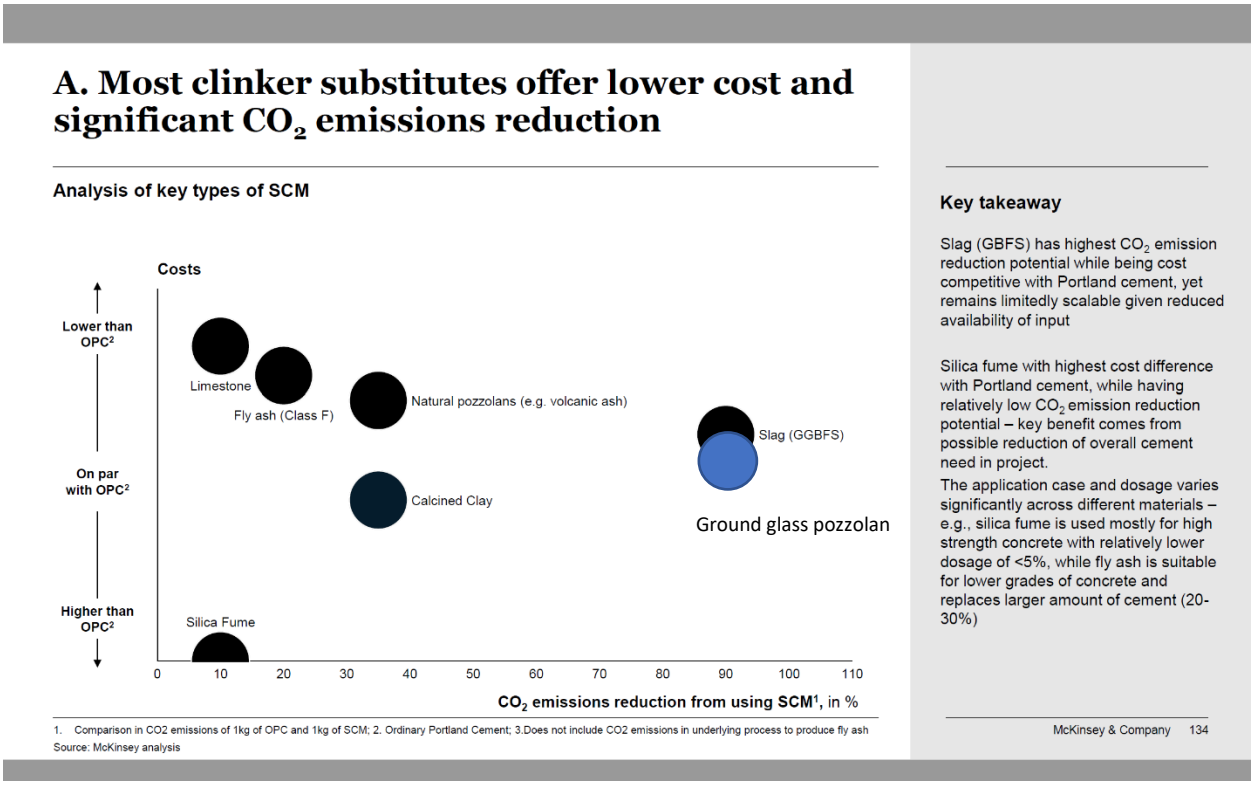
North America and Europe to drive global EAF production growth by 2027

Globally, steel slag production is estimated to slightly increase in the 2022-2027 period, as steel producers are focused on moving towards EAF production to achieve an eco-friendlier steel-making process.

Capacity additions for EAF are expected to be driven mostly by North America and European producers during the forecast period.



Slag has excellent CO2 reduction capability, on par with ground glass pozzolan (note blue circle below)



Silica Fume

What is Silica Fume?

Silica fume, a by-product of the ferrosilicon industry, is a highly pozzolanic material that is used to enhance mechanical and durability properties of concrete. It may be added directly to concrete as an individual ingredient or in a blend of portland cement and silica fume. In the United States, silica fume is used predominantly to produce concrete with greater resistance to chloride penetration for applications such as parking structures, bridges, and bridge decks.

Advantages of Silica Fume

1. Segregation and Bleeding; it reduces the bleeding significantly.
2. It can be used with fly ash or blast furnace slag or **glass** to develop early strength
3. Increase chloride permeability
4. Increase plastic shrinkage
5. Significantly reduce alkali-silica-reactivity
6. Provide excellent resistance to sulphate, seawater attacks and steel corrosion

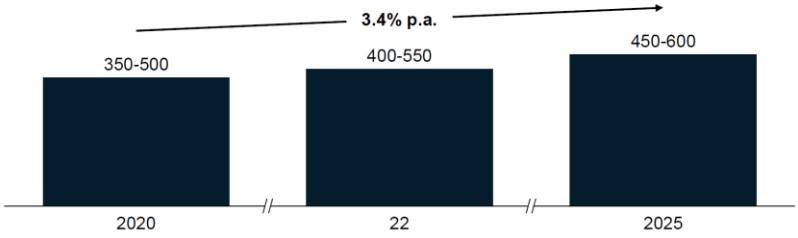
Disadvantages of Silica Fume

1. Workability; due to the fineness of the material, it creates a more cohesive mix. Therefore, there is a higher water demand.
2. Setting Time increases.
3. It requires a longer mixing time
4. Cost

Market Excerpts from McKinsey Report (January 2022)

Total addressable market for silica fume used in concrete is expected to grow at around 1% p.a.

North America silica fume market, K tons



Key assumptions

- Bulk cement represents ~95% of cement production
- HP / UHPC as share of total concrete – ~2% (2015), ~2.25% (2020), ~2.5% (2025)
- Dosage of Silica Fume in high and ultra-high performance concrete: ~2-3%

Source: McKinsey Analysis, Expert interviews

Key Takeaway

Silica fume allows to strengthen cement for high-performance (55-100 mpa) and ultra-performance concrete (>100 mpa)

Price for silica fume varies from $400 to $1000/ton. At average price of $600 per ton market value is estimated at $200-300M in 2020

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There are four key trends that impact the silica fume and SCM market

Trend	Description	Implication for Opta Group
A Drive for sustainability	Cement production accounts for around 7% of global CO_2 production with CO_2 emissions per $ of revenue at 8x compared to other sectors Silica fume with highest cost difference with Portland cement, while having relatively low CO_2 emission reduction potential – key benefit comes from possible reduction of overall cement need in project	⊕ Opta Group product could be used by cement players to reduce overall concrete usage (i.e., product is used for high strength concrete that reduces overall cement need in project)
B Increase in US infrastructure spending	Infrastructure spending is key part of US government COVID recovery plan with $1.2T in spending pledged over next eight years ($550B over next 5 years) through Infrastructure Investment and Jobs Act (IIJA)	⊕ Increase in construction activity may drive further demand for cement in relevant industries (~$150B in high relevancy sectors for Opta Group)
C Growth in high-performance concrete due to urbanization	People increasingly move to urban areas (global share of urban population increased 10pp between 2000 and 2020). Higher population density drives demand for high-rise buildings and other urban constructions. Typical construction within urban areas needs high performance concrete that includes silica fume to ensure strength and reliability	⊕ Increasing need for urban infrastructure, including high performance and ultra-high performance concrete, drives demand for silica fume
D Feedstock outlook for glass supply	Recycled glass supply in the US varies significantly by region, and growth is primarily flat. On average, 30% of total glass production is recycled. States with container deposit legislation provide 75% of recycled cullets. Some correlation between level of recycling and urbanization although regulation seems to be main driver	= Opta Group would compete with other applications for its glass supply (e.g., container glass, insulation, abrasives). Due to regional nature of market partnership in states with container deposit legislation should be preferred

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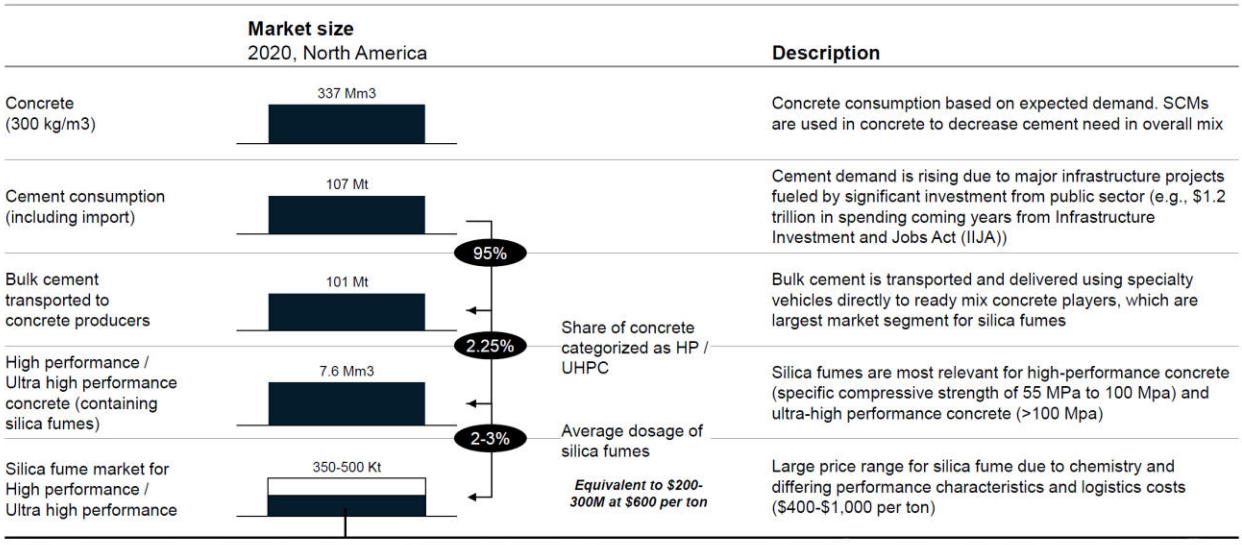
Silica fume addressable market



Source: McKinsey analysis, expert insights

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Glass as a Pozzolan: Features

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