Silica Fume's Contribution to Sustainability

by Eckart Bühler, Norchem-Ferroglobe

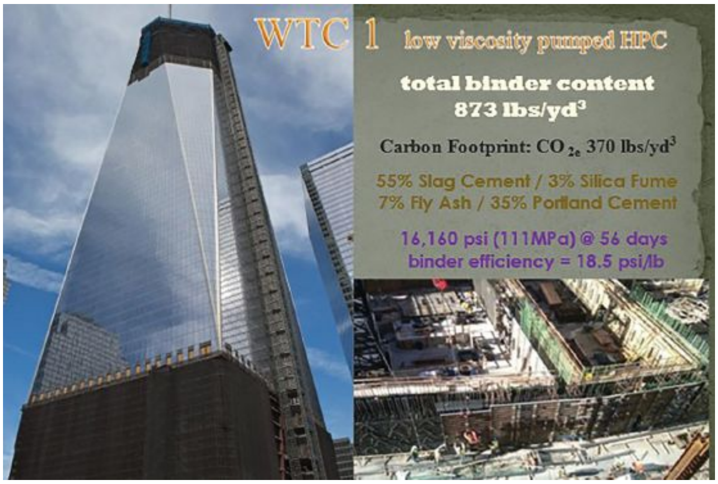
Sustainability, resilience, carbon footprint, and life-cycle analysis are becoming keywords in everyday conversation, whether related to energy consumption, food supply, global warming, or human expansion in general. These also extend to concrete, the most commonly used building material on the globe. Ordinary portland cement (OPC), historically the key ingredient in concrete, comes with a relatively high carbon footprint of approximately 1 ton of carbon dioxide (CO_2) per ton of cement produced; thus significant pollution status has been assigned to concrete.[1] Industrial processes and fine-tuning of cement production with alternative ingredients, additives, and energy supplies have been able to lower concrete's carbon footprint by up to 20%, and additional tools are available to go even further.

As stated in the article "Road Map to Carbon Neutrality for Concrete Materials" in the Winter 2022 issue of *ASPIRE*®, "the single greatest opportunity for CO_2 reductions in concrete as a material remains with mixture optimization. Concrete mixtures can be optimized by increasing the use of SCMs [supplementary cementitious materials]."[2] There are various SCMs, including three that the U.S. Environmental Protection Agency identified as recovered mineral components (RMCs) in 2008.[3] These three RMCs—slag cement, fly ash, and silica fume—are designated preconsumer waste materials whose application in concrete removes materials from the national waste stream. They have been used as alternatives to cement in concrete for decades, but traditionally not for the purpose of carbon-footprint reduction.

Slag cement and fly ash can be used in place of OPC at large replacement percentages (at roughly a 1:1 ratio), significantly reducing the OPC content in a concrete mixture. The contributions of slag cement and fly ash to the durability and life-cycle extension of concrete structures have also been noted.

Silica fume is included in much smaller percentages than slag cement or fly ash, but it has a powerful synergistic effect that allows concrete to achieve very high strengths as well as durability characteristics that can facilitate 100-year or more life-cycle performance of structural concrete. From a purely compressive strength perspective, each pound of silica fume can compensate for 3 to 4 pounds of OPC. Silica fume is also uniquely positioned as a borderline nanomaterial, making it an important tool for optimizing concrete mixture proportions by enabling ternary and quaternary binder formulations that provide desirable mechanics for ideal rheology of complex concrete mixtures.

Higher concrete performance requirements are well known to the bridge-building industry, where they are routinely employed. The 2008–2009 reconstruction of the collapsed Interstate 35W bridge in Minneapolis, Minn., is an example where combinations of these three SCMs/RMCs were ingeniously employed in ternary blended concrete mixture proportions to achieve not only a fast-track rebuild in a 14-month span but also, and more importantly, a 100-year design life for the replacement structure with a reduced carbon footprint.[4] The 4000-psi concrete designed for the piers employed a mere 15% of OPC, whereas silica fume application in the superstructure concrete achieved compressive strengths greater than 8000 psi and a very low permeability rating; the resulting increased concrete impedance will inhibit corrosion of the embedded steel reinforcement.



One World Trade Center in New York, N.Y., used a sustainable concrete mixture with an exceptionally high binder efficiency. Figure: Norchem-Ferroglobe.

On the 2008–2013 One World Trade Center reconstruction project in New York, N.Y., a quaternary blended concrete mixture reduced the OPC volume to only 36% of the total binder content. The concrete had a compressive strength greater than 16,000 psi and a carbon footprint as low as a conventional 4000-psi concrete mixture made with straight OPC. Silica fume's main functions in this project scenario were to retain reasonable concrete setting times for timely formwork removal, even with large slag cement and fly ash replacements; achieve very high ultimate strength; and impart favorable rheology to the fresh concrete. The latter allowed single-stage pumping to the full height (1368 ft) of the structure and placement of self-consolidating concrete into densely reinforced areas.

Specifically at low doses—less than 4% by volume of total binder—silica fume introduces hundreds of thousands of minute spherical particles into the concrete, creating a ball-bearing effect that reduces concrete viscosity and negates its own water demand. This effect is more evident at higher percentage inclusions, where the increased water demand can be offset with a high-range water-reducing admixture (HRWRA). Modern HRWRAs can facilitate high workability in concrete, even at extremely low water–cementitious material (*w/cm*) ratios. This allows the total binder contents to be kept to a minimum, which results in a lower carbon footprint.

The bridge and transportation industry seems to be ahead of others in implementing sustainable concrete mixture proportions for achieving long life. The original purpose of these mixtures, however, was to extend the service life for concrete structures that are exposed to more wear and tear and harsher environmental conditions than most other concrete applications. Within the transportation sector, there is room for employing even higher compressive strengths to construct even more slender structures that also excel in long-term durability, leading to excellent sustainability stewardship by using fewer construction materials as well as securing a long structural life.

Table 1 compares three conventional concrete mixture designs with three high-performance concrete mixtures used in projects completed more than two decades ago.[1,5,6] The data demonstrate the advantages of designing for high-strength concrete, which include enabling longer spans and more slender superstructures while using the smallest feasible volume of concrete, as well as extending the service life by requiring less maintenance and delaying replacement work. The table also shows that concrete made with silica fume, slag cement, and fly ash, or any combination thereof, can reduce the carbon footprint of concrete to an average of one-tenth that of conventional mixtures when measured in terms of compressive strength attained and accounting for the expected service life of the structure.

For the projects listed in Table 1, the high-performance concrete mixtures used HRWRAs. Because the binder portions of most concrete represent 90% to 95% of its carbon footprint, only the contributions of those materials are considered in the CO$_2$ equivalent (CO$_2$e) calculations. The life-cycle analysis used a 1.5-in. concrete cover over reinforcing bars for a severe exposure in a southern climate for each of the six concrete mixtures described.[6]

High-performance concrete does not translate to a concrete with a high carbon footprint, although a high cement factor is typically assumed. When accounting for in-service performance, structural life cycle, and the original materials used, high-performance concrete may have a much lower carbon footprint than a conventional 4000-psi design-strength concrete. Incorporating SCMs in concrete mixtures is key in achieving reduced carbon footprints, and the addition of silica fume is particularly critical to maximize concrete resistance to the ingress of deleterious substances that shorten concrete service life. High compressive and flexural strengths, as well as

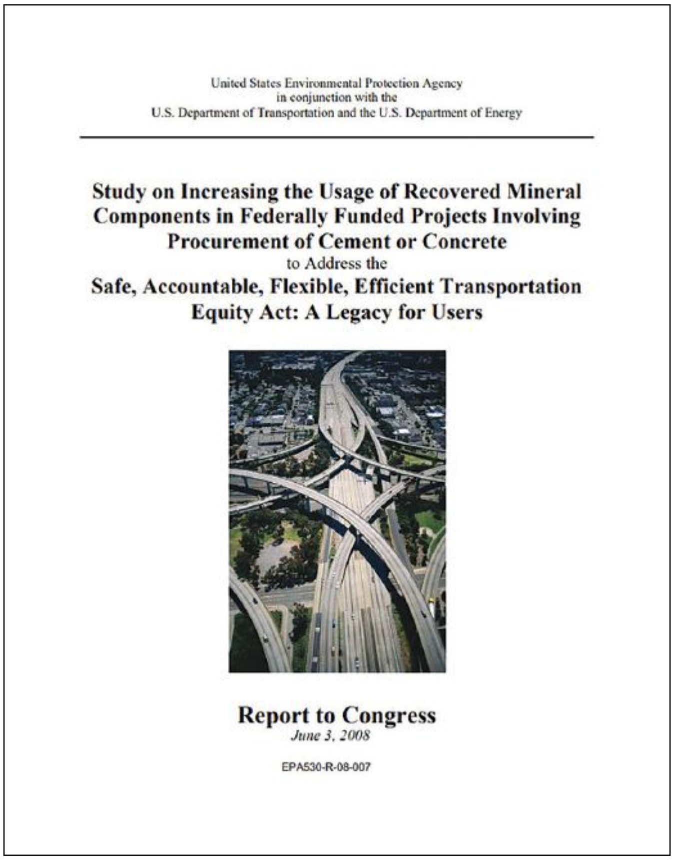
Table 1. Comparison of the carbon footprint of three conventional concrete mixtures with three high-performance concrete mixtures

	Cementitious materials			*w/cm*	CO$_2$e (binder material only), lb/yd^3	Concrete compressive strength,* psi	CO$_2$e per 1000-psi compressive strength, lb	Years to initiation of corrosion	CO$_2$e per year based on initiation of corrosion, per 1000-psi compressive strength, lb	
	Type	Amount	% of total *cm*						Mixture or project	Average for group
Examples of conventional mixtures	**Conventional concrete mixture Design 1**			0.50	375	4500	83	10	8.3	5.97
	OPC	500 lb/yd^3	100%							
	Total *cm*	500 lb/yd^3								
	Conventional concrete mixture Design 2			0.50	305	4500	68	12	5.7	
	OPC	390 lb/yd^3	70%							
	FA	170 lb/yd^3	30%							
	Total *cm*	560 lb/yd^3								
	Conventional concrete mixture Design 3			0.50	231	4500	51	13	3.9	
	OPC	265 lb/yd^3	50%							
	SC	265 lb/yd^3	50%							
	Total *cm*	530 lb/yd^3								
High-performance concrete projects	**Millennium Tower, Miami, Fla.**			0.29	395	11,700	34	62	0.5	0.57
	OPC	456 lb/yd^3	48%							
	SC	446 lb/yd^3	47%							
	SF	48 lb/yd^3	5%							
	Total *cm*	950 lb/yd^3								
	Radioactive Waste Storage Facility, Hanford, Wash.			0.37	305	6300	48	62	0.8	
	OPC	391 lb/yd^3	65%							
	FA	150 lb/yd^3	25%							
	SF	60 lb/yd^3	10%							
	Total *cm*	601 lb/yd^3								
	Solid Waste Authority, Palm Beach County, Fla.			0.34	446	10,300	43	100+	0.4	
	OPC	578 lb/yd^3	68%							
	FA	127 lb/yd^3	15%							
	SF	141 lb/yd^3	17%							
	Total *cm*	846 lb/yd^3								

Source: Norchem-Ferroglobe.

*The concrete compressive strength is the 28-day design value for conventional concrete mixture designs and the actual 28-day value from test specimens for the high-performance concrete projects.

Note: *cm* = cementitious materials; CO$_2$e = carbon dioxide equivalent; FA = fly ash; OPC = ordinary portland cement; SC = slag cement; SF = silica fume; *w/cm* = water–cementitious materials ratio.



United States Environmental Protection Agency
in conjunction with the
U.S. Department of Transportation and the U.S. Department of Energy

Study on Increasing the Usage of Recovered Mineral Components in Federally Funded Projects Involving Procurement of Cement or Concrete
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Report to Congress
June 3, 2008

EPA530-R-08-007

high modulus of elasticity, can optimize designs and reduce the volume of concrete required, thus reducing the use of non-renewable resources.

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