NORCHEM, INC.
www.norchem.com
985 Seaway Drive, Suite A • Ft. Pierce, Florida 34949-2744
Tel (772) 468-6110 • Fax (772) 468-8702

P.O. Box 5537 • Hauppauge, New York 11788-0132
Tel (631) 724-8639 • Fax (631) 724-8645

Eckart Bühler

eckart@norchem.com phone: 561-575-7092

Green Concrete Design Incorporating Life Cycle Assessment & Service Life Prediction and the Effect of Lowering the Carbon Footprint with High Performance Concrete

INTRODUCTION

To the public at large, two words are synonymous: Concrete & Cement. We often see concrete described as cement in large circulation periodicals or hear it on the national evening news. No surprise actually, as cement has been historically viewed as the primary ingredient in concrete. The higher concrete strength is desired; usually cement content is increased to achieve that. Volumetrically speaking, cement is a minor ingredient, as per quantity of a concrete unit (m^3 or yd^3). In the currently very active Sustainability mindset however the opposite applies, cement is a major ingredient, when considering the carbon footprint of concrete.

The average 28 MPa (4,000 psi) conventional concrete mix design, with 297 kg/m^3 (500 lbs/yd^3) of Ordinary Portland Cement (OPC), has a carbon footprint of approximately 300 kg/m^3 (230 kg/yd^3). The carbon footprint of the OPC alone contained within such a cubic yard of concrete is 285 kg/m^3 (218 kg/yd^3). Typically, as in any concrete utilizing OPC as the exclusive binder, OPC produces 95% of the total carbon footprint of all the ingredients in concrete, yet the OPC quantity as an ingredient makes up less than 10% of the total concrete volume.

When considering High Performance Concrete (HPC), historically the necessary material selection, i.e. higher cement factors, would indicate a higher carbon footprint. Not necessarily so, if not the opposite. When predicting service life of any concrete and assigning a carbon footprint value per year of life before replacement is needed, HPC is can be surprisingly efficient, to the extent that it may be considered that a relatively small cost increase of HPC at the time of construction, easily pays off over the long run, not only in economic terms but especially when considering Sustainability.

CEMENT SUBSTITUTION

There are various ways to reduce the carbon footprint of concrete by material substitution of any constituents, but none have an impact as large as substituting OPC. The Leadership in Energy & Environmental Design (LEED) for example, awards points towards certification status for material substitutions that lower the carbon footprint of concrete. For OPC substitution such alternative materials have been labeled Supplemental Cementitious Materials (SCM). Some three decades ago SCM were increasingly utilized in concrete mix designs as lower cost OPC replacement. Initial challenges due to SCM incorporations such as delayed setting times, possible color and air-entrainment fluctuations were controlled with innovative chemical admixture advances and more focused quality control. As SCM utilization became more commonplace, unique valuable and marketable engineered properties that SCM can bring about in concrete also became evident. These properties include, but are not limited to: heat of hydration control, compressive and flexural strength increases, but most importantly durability improvements that could greatly enhance service life of concrete structures built with SCM incorporated in the mix design.

RECYCLED MINERAL COMPONENTS

The U.S. Environmental Protection Agency (EPA) has furthered the designation of SCM, for sustainability language, to Recovered Mineral Components (RMC). Three RMC, coal fly ash, ground granulated blast furnace slag and silica fume, are designated as meeting the requirements of the Resource Conservation & Recovery Act (RCRA), when included in the concrete mix design. RMC are pre-consumer waste materials originating from mineral conversion industries that initially had been land-filled exclusively until their beneficial characteristics to concrete had been discovered. What differentiates RMC from SCM is that RMC utilization directly eliminates landfill storage of waste materials. In 2008 a report to Congress [EPA 530-R-08-007] identifies the positive environmental impacts per metric ton of RMC substituted for OPC:

EPA Report to Congress 530-R-08-007, June 2008

Impact of RMC substituted for Portland cement, per metric ton

RMC	Fly Ash	GGBFS	Silica Fume
Energy Savings (MJ)	4,696	4,221	32,915
Energy Savings (USD)	129	116	905
Avoided CO2 Emissions (g)	701,378	668,889	699,876

[Table 1]

The figures represented in Table 1 are selected from the EPA report in Chapter 3, page 8, Table 3-3 and incorporate most prominently the BEES model (Building for Environmental and Economic Sustainability) including life cycle inventory. Table 2 below simply breaks down these values further into SI and metric units that we are familiar with in concrete mix designs, and which will be used to evaluate upcoming project case studies.

Average Environmental Impact & Energy Savings of RMC

Recovered Mineral Component	Fly Ash	GGBFS	Silica Fume
	per metric ton:		
Avoided CO2 Emissions	701 kg	669 kg	700 kg
Energy Savings	$ 129.-	$ 116.-	$ 905.-
	per pound:		
Avoided CO2 Emissions	0.318 lbs	0.304 lbs	0.318 lbs
Energy Savings	$ 0.059	$ 0.053	$ 0.411
	per kilogram:		
Avoided CO2 Emissions	0.70 kg	0.67 kg	0.70 kg
Energy Savings	$ 0.129	$ 0.116	$ 0.905

[Table 2]

CASE STUDIES

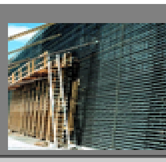
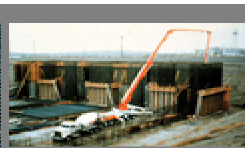
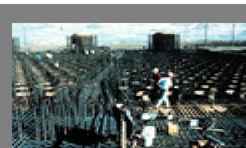
The energy savings and avoided CO2 emission values based on 28 day compressive strength efficiency can provide an insight on sustainability on past projects, where RMC where used not for sustainability measure, but for other engineered concrete properties, such as high compressive strength and modulus of elasticity, mass concrete temperature differential control, abrasion, impact and chemical resistance and extended service life cycle.

1.) The Four Seasons, Miami Florida, 2001. At the time of construction and at 750 feet the tallest-to-be high rise tower south of Atlanta, the HPC employed here had the lowest total cementitious content concrete mix design utilized for this degree of high compressive strength and modulus of elasticity performance. Slag and silica fume both substituted for a large portion of OPC providing extended workability in hot weather climate and achieved high compressive strength. Silica fume directly benefitted the modulus of elasticity requirement, with local coarse aggregate in lieu of imported stone, providing an approximate material savings of $ 150,000.00 over and above the cost premium for this RMC. Also instrumental as a viscosity modifier, silica fume controlled self-consolidating concrete characteristics necessary for dense reinforcement design. This project is presented in Table 3 where the RMC substitution calculates to 200 kg/m^3 Avoided CO2 Emissions and $ 58/m^3 of equivalent Energy Savings, according to the aforementioned EPA report and its efficiency interpretation (Tables 1 & 2).

Mix Design Materials	lbs / yd^3	kg / m^3	substitution	Energy Savings / m^3	Avoided CO2 Emissions / m^3
Cement, Type I	450	267			
Slag (G.G.B.F.S.)	450	267	47.4 %	$ 31	179 kg
Silica Fume	50	30	5.2 %	$ 27	21 kg
Totals:	950	564	52.6 %	$ 58	200 kg
				performance vs. conventional mix*	
Water / Cementitious Ratio	0.29	0.29	(33 gal total)	3 gal over	- 10 %
High Range Water Reducer	1.1 gal	5.4 ltr			
28 day compressive strength	11,700 psi	81 MPa		12.3 psi / lb binder	+ 37 %
modulus of elasticity	5.5 x 10^{6}psi	38 GPa			

[Table 3]

2.) Nuclear Canister Storage Facility, Hanford Washington, 1998. Large volume mass concrete application necessitated low heat of hydration, partially achieved by limiting the concrete temperature in the plastic state but also by substituting OPC with fly ash and silica fume with a low total binder content, yet providing a relatively high compressive strength. As presented in Table 4, the RMC substitution calculates to 87 kg/m^3 avoided CO2 emissions and $ 44/m^3 of equivalent Energy Savings, according to the aforementioned EPA report.


Mix Design Materials	lbs / yd^3	kg / m^3	substitution	Energy Savings / m^3	Avoided CO2 Emissions / m^3
Cement, Type I	391	232			
Fly Ash, Class F	150	89	25 %	$ 11	62 kg
Silica Fume	60	36	10 %	$ 33	25 kg
Totals:	601	357	35 %	$ 44	87 kg
				performance v conventional *	
Water / Cementitious Ratio	0.37	0.37	(26.7 gal total)	3.3 gal saved	+ 11 %
High Range W R	1.7 gal	8.4 ltr			
28 day compressive strength	6,300 psi	43 MPa		10.5 psi / lb binder	+ 17 %
90 day compressive strength	7,500 psi	52 MPa			

[Table 4]

3.) Solid Waste Authority of Palm Beach County, Florida, 1993. This rehabilitation project included a complete 6-inch deep replacement of the existing, worn-down transfer floor. In choosing this ultra-durable concrete design over the traditionally utilized 2-inch industrial floor overlays, this facility not only cut cost and construction time in half, but also nearly tripled the useful floor life. Extreme abrasion resistance as well as chemical resistance is paramount to obtain an extended service life for this transfer floor, in operation 24/7. As presented in Table 5, the RMC substitution calculates to 188 kg/m^3 avoided CO2 emissions and $ 86/m^3 of equivalent Energy Savings, according to the aforementioned EPA report.


Mix Design Materials	lbs / yd^3	kg / m^3	Substitution	Energy Savings / m^3	Avoided CO2 Emissions / m^3
Cement, Type IP	578	343			
+ interground Fly Ash	127	75	15.0 %	$ 10	89 kg
Silica Fume	141	84	16.7 %	$ 76	99 kg
Totals:	846	502	34.7 %	$ 86	188 kg
				performance v conventional *	
Water / Cementitious Ratio	0.34	0.34	(34.5 gal total)	4.5 gal over	- 15 %
28 day compressive strength	10,280 psi	71 MPa		11.8 psi / lb binder	+ 31 %
NBS Abrasion Resistance .356 mm @ ½ hr. .584 mm @ 1 hr. Rapid Chloride Permeability Aashto T-277 335 coulombs					

[Table 5]

The above three case studies' concrete designs have been compared to a conventional f'c = 28 MPa (4,000 psi) mix design, when calculating the under/overage in water content, as well as the resulting psi/lb of binder ratios shown on the bottom right in the tables above. At an OPC content of 297 kg/m^3 (500 lbs/yd^3) and a W/C=0.50 (148 l/m^3 or 30 gal/yd^3) water content, this design achieve approximately 31 MPa (4,500 psi) in 28 days. This translates into a compressive strength per pound of total binder ratio of 9 psi/lb.

For the forthcoming Carbon Footprint calculations and comparisons only the total binder content of each mix design will be utilized as this typically constitutes 95% of the concrete's total carbon footprint. All other materials such as aggregates, water and admixtures would cause only minor, insignificant variations of the concrete's total carbon footprint between the mix designs, as these are all conventional virgin materials (non-recycled) in very similar amounts. Six total concrete designs, three HPC from the above case studies and three conventional concrete designs, will be compared. Two alternate conventional f'c = 28 MPa (4,000 psi) will also incorporate RMC in the spirit of designing sustainable "green" concrete: 2.alternate will have 30% fly ash substitution [OPC = 231 kg/m^3 (390 lbs/yd^3) + Fly Ash 101 kg/m^3 (170 lbs/yd^3)] and 3.alternate contains 50% slag substitution [OPC = 157 kg/m^3 (265 lbs/yd^3) + Slag 157 kg/m^3 (265 lbs/yd^3)], both with a W/C = 0.50 yielding approximately 31 MPa (4,500 psi) at 28 days of age.

CARBON FOOTPRINT

There are various models in circulation that demonstrate the carbon footprint per metric ton of cementitious materials and RMC. They vary slightly from each other, but in the greater scheme the designations are similar. Figures from the Inventory Of Carbon & Energy (ICE) from the University of Bath and also an independent institution, Enviros, provide us with following figures: CO2 carbon footprint in kilograms (kg) per metric ton of material: OPC – 959 kg, G.G.B.F.Slag – 155 kg, Fly Ash, Class F – 93 kg, and Silica Fume – 14 kg.

In the table below, six concrete designs are compared, three basic F'c = 28 MPa (4,000 psi) and three HPC designs. The first column identifies the origin of each mix design. The second column calculates each concrete design's total binder carbon footprint, according to the above stated values of CO2 (kg) per material. In the third column the resulting 28 day compressive strength for each concrete design is listed, which for the basic concrete is an approximation and for the HPC actual field performance. Since these mix designs are for different applications, in the fourth column, in an attempt to uniformly assign performance with a carbon footprint effect, each 6.9 MPa (1,000 psi) of performance has calculated its respective carbon footprint value.

To demonstrate each of the concrete mix designs' durability in a comparative manner, length of time in years-to-initiation-of-corrosion was the selected criteria. Life 365 version 2.0, Service Life Prediction Model for Reinforced Concrete Exposed to Chlorides is one popular model in frequent use in the United States for almost two decades now that was jointly developed by various recognized concrete industry organizations such as NRMCA and others. As common exposure of the concrete to the elements, an average of two more severe conditions were utilized in determining the initiation-to-corrosion time frame:

a parking garage in northern U.S. geography exposed to de-icing salts application during the winter months, as well as a structure exposed to marine environment (salt-spray) in year-round warmer southern U.S. climate. These initiation-to-corrosion results (in years) are shown in column five. When dividing the carbon footprint value (from column two) by the number of years it would take each concrete mix design to initiate corrosion on its embedded reinforcing steel, the values in column six shown represent the carbon footprint value per year of service life of a concrete structure built with each respective concrete mix design. Another selected constant for this evaluation is identical concrete cover over steel, at a thickness of 3.81 centimeters (1.5 inches).

per 1 M^3 *Project :*	CO_2-kg/m^3 (binder only) (kg)	compressive strength Performance @ 28 days	CO_2 / 7 MPa (1000 psi) (kg)	LIFE 365 initiation of corrosion (years)	CO_2 / 1yr Service Life (kg)	CO_2 per year / 1,000 psi (kg)
conventional 297 kg opc	284	*31 MPa 4,500 psi*	64	*10*	28.4	Average 4.60
2.alternate 231 kg opc 101 kg ash	231	*31 MPa 4,500 psi*	52	*12*	19.3	
3.alternate 157 kg opc 157 kg slag	175	*31 MPa 4,500 psi*	40	*13*	13.5	
Miami High Rise	299	*81 MPa 11,700 psi*	26	*62*	4.8	Average 0.45
Nuclear Canister Storage	231	*43 MPa 6,300 psi*	38	*62*	3.7	
Waste Transfer Station	338	*71 MPa 10,280 psi*	33	*100+*	3.4	

[Table 6]

In both cases, measuring the carbon footprint per compressive strength performance, and especially per service life expectancy, HPC vastly out-performs conventional basic 28 MPa (4,000 psi) concrete. When combining performance of compressive strength and structural life cycle, as shown in the last column on the right. The average HPC produces only about one-tenth the carbon footprint as compared to conventional concrete, measured over the anticipated lifecycle and its overall expected durability performance.

Cost-Effective

The significance of the carbon footprint comparisons demonstrated would be that HPC / higher strength concrete could replace more voluminous conventional concrete in many other, more basic applications, such as residential or low-rise institutional construction. In concert with an example from The Sustainable Concrete Guide publication from the U.S. Green Concrete Council as shown below in Table 7, HPC can be more cost-efficient when structures would be re-designed with reduced concrete volume yet match overall structural requirements through higher concrete strength performance, including any expenditures for extra care and time taken to design, produce, place and cure HPC properly.

	4000 psi (28 MPa) concrete	9000 psi (62 MPa) concrete
Total cementitious materials, lb/yd^3 (kg/m^3)	550 (330)	865 (510)
Supplementary cementitious materials, lb/yd^3 (kg/m^3)	110 (65) fly ash	40 (24) silica fume
Portland cement, lb/yd^3 (kg/m^3)	440 (260)	825 (490)
Column dimensions, in. (mm)	36 x 36 (900 x 900)	24 x 24 (600 x 600)
Concrete per column, yd^3	5.0 (3.8)	2.2 (1.7)
Reduced volume of concrete per column, %	—	55
Portland cement per column, lb/column	2200 (1000)	1800 (820)
Reduced volume of cement per column, %	—	18

[Table 7]

Resilience

As for durability of concrete, HPC would make any sort of concrete structure be much more durable, necessitating much less frequent repair or pre-mature replacement. The safety aspect benefit against weather phenomena such as tornadoes and hurricanes or man-made disasters such as collision, explosion and accidents in general, would be evident. Less frequent replacement of concrete structures in itself would tremendously reduce storage of waste or energy to recycle and further the overall concept of sustainability. The aspect of safety to humankind would be immeasurable with stronger and more durable HPC structures. Best of all, HPC with RMC is a proven, global building material, already used for the finest and most visible structures around the globe for decades

Conclusion

In these “slow” times of construction volume, with much equipment running idle and many construction personnel unemployed, it would make sense to dedicate these resources to a more involved, quality-produced and smartly designed High Performance Concrete with Recovered Mineral Components utilized to the fullest possible extent. The potential material and manpower up-charge in cost to expertly execute such HPC would be minimal in the overall of total construction cost. Sustainability however, would be enriched by less immediate and long-term environmental impact, as well as higher quality future concrete structures, built to last. Most important of all, HPC structures could be applied to the bulk of concrete construction, such as in institutional and residential construction where it is rarely used, at a fraction of the carbon footprint conventional and basic concrete produces now.

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