

Sustainable Concrete Pavements with Blended Cements

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Transportation infrastructure management has traditionally focused on the safety and reliability without deliberately incorporating sustainability considerations. Recently, national, state and municipal governing bodies, the engineering community and society as a whole, are realizing the enormous investment of materials, energy, capital, and social costs affiliated with infrastructure system design, construction and maintenance. Approaches to help achieve higher infrastructure sustainability and resiliency include design and construction techniques to provide longer-lasting pavements, use of recycled materials in construction, and increasing the use of supplemental cementitious materials (SCMs) and portland limestone cements in concrete mixture designs. Concrete materials manufactured with blended cements intrinsically reduce greenhouse gas emissions by reducing portland cement usage. In addition, blended cement concretes containing SCMs may substantially increase the pavement service life providing the most cost-effective method to reducing the economic, environmental and societal impacts (triple bottom line) of surface transportation.

Introduction

Infrastructure is the backbone of our modern society: roads, airports, railroads, buildings, bridges, water and wastewater treatment plants, sewers, drainage, flood control, water supply, landfills, and many other facilities are crucial to our society's prosperity. The key requirement for economic growth and development as well as for the well-being of communities is an efficient transportation system. America's transportation network is an important tie as it provides businesses with access to materials and markets; people with access to goods, services, recreation, jobs; and a societal link to communities. Transportation is a strategic investment that is essential to strengthening America for the challenges and opportunities of the 21st century.

The United States highway network consists of four million miles of roads and streets. Highway bridges also make up a critical link in the Nation's infrastructure, and at present number 600,000 on the entire highway network (US Department of the Interior, 2011). However, these critical intermodal transportation structures have been evaluated by the American Society of Civil Engineers in their quadrennial report card as poor and almost failing in 2009. According to the U.S. Department of Transportation, of the 600,905 bridges across the country as of December 2008, 72,868 (12.1%) were categorized as structurally deficient and 89,024 (14.8%) were categorized as functionally obsolete. Americans spend 4.2 billion hours a year stuck in traffic at a cost to the economy of \$78.2 billion, or \$710 per motorist. Poor road conditions cost motorists \$67 billion a year in repairs and operating costs, and cost 14,000 Americans their lives. One-third of America's major roads are in poor or mediocre condition and 36% of major urban highways are congested. The current

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spending level of \$70.3 billion per year for highway capital improvements is well below the estimated \$186 billion needed annually to substantially improve the nation's highways (American Society of Civil Engineers, 2009; AASHTO, 2008).

Sustainability and Material Selection

Infrastructure systems represent an enormous investment of materials, energy, and capital, resulting in significant environmental burdens and social costs. As the world's developing economies grow, so does the need for civil infrastructure to serve the expanding urban populations. This growth is reflected in construction materials consumption rates. The main element of highway and road infrastructure is the pavement, which can be either asphalt or hydraulic cement concrete. With increasing oil prices, the cost of future of asphaltic concrete pavements is almost certain to rise rapidly; whereas the cost hydraulic cement concrete pavements appears to be more stable (Massachusetts Institute of Technology, 2011).

The primary measure of sustainability is the energy consumption required to manufacture the end product and the energy produced during its use. Embodied energy (measured in CO₂ equivalents, CO₂-e,) distinctly measures how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO₂) as the reference. Embodied energy is divided into two main areas, namely the initial embodied energy and the operational energy. Simply put, initial embodied energy is the total energy consumed during resource extraction, transportation, manufacturing, and fabrication of a product; and is typically calculated within the boundaries of Cradle-to-Gate (factory gate) or Cradle-to-Site (site of use) to separate it from operational impacts. Operational energy is non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the structure's life span. Operational energy is heavily influenced by the durability and maintenance of construction materials, systems and components installed in the structure, and the life span of the structure.

As the life span of the structure increases, the ratio of the initial embodied energy to total energy decreases and becomes less significant in comparison (Figure 1). Research conducted on high-volume roads (major highways) have shown the use phase can account up to 85% of greenhouse gas emissions where the effects of traffic-related emissions are magnified (Massachusetts Institute of Technology, 2010). In addition, varying scheduled maintenance and associated lane closures can reduce CO₂ emissions for concrete pavements over the life cycle of the pavement.

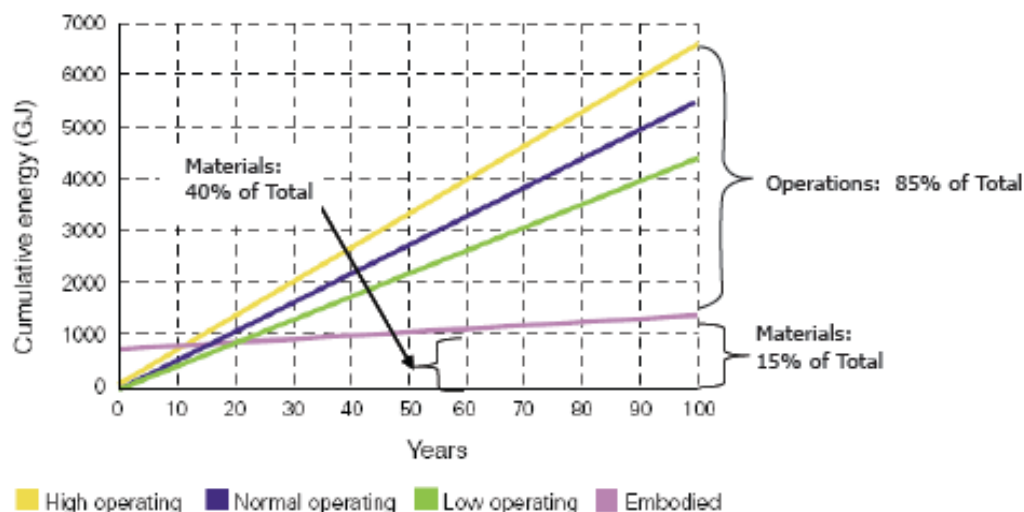


Figure 1. Temporal Relationship of Embodied Energy to Operational Energy (Symbiotic Engineering, 2007)

Concrete and Embodied Energy

Concrete, by volume, is the most common manmade material in the world and provides an essential building block for strong, durable and resilient infrastructure. Concrete has a relatively low embodied energy coefficient ranging from 2.0 to 0.94 CO₂-e depending upon geographical location, technology employed in the manufacturing process and methods of manufacture (Alcorn, 2001). Despite this, proponents of sustainable design have criticized the use of concrete because portland cement, comprising approximately 7-15% volume in concrete (Kosmatka et al. 2002), is energy-intensive and generates carbon dioxide (CO₂) in its manufacturing process.

The calcination of limestone ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) in combination with fossil fuel combustion in the production of portland cement clinker produces significant CO₂ emissions. Approximately one ton of CO₂ is produced for each ton of cement clinker, although the level of CO₂ emissions from fuels depends on the cement process and the fuels used (US Department of Energy, 2003).

Through the cement industry's aggressive efforts to reduce emissions through innovations in manufacturing, usage of waste derived raw materials and the extraction of energy from industrial waste fuel or bio-fuels, anthropogenic (man-made) CO₂ emissions have been reduced by 33 percent, while energy efficiency has increased by the same amount.

Yet despite such innovations, portland cement remains an energy intensive building material. As the largest single source of global anthropogenic emissions, at 5%, and being the most widely used building material, even small reductions in cement and concrete emissions can have large environmental impacts. (World Business Council on Sustainable Development and International Energy Agency, 2009).

Blended Cements and Sustainability

The most effective means of decreasing both energy consumption and the production of greenhouse gases is to substitute supplementary cementitious materials (SCMs) for a portion of the portland cement. The increasing use of alternative raw materials as a partial replacement for portland cement in concrete mixtures today has had a positive environmental impact. Supplementary Cementitious Materials (SCMs) may enhance the strength and durability of concretes and the use of these materials in cement and

concrete production yields a number of environmental and economic benefits as seen in Table 1. These values are derived from life cycle inventory data and represent the total life cycle savings of using SCMs as a replacement for one metric ton of finished portland cement in concrete.

SCMs reduce the initial embodied energy as they are reclaimed, recycled industrial by-products. Slag cement is a reclaimed by-product from an iron blast furnace; fly ash is a by-product of coal-fired furnaces at power generation facilities; and, silica fume is a by-product of the production of silicon metal or ferrosilicon alloys.

SCMs incorporated into cement-based building materials are added individually, blended, or interground with portland cement. As recycled industrial materials, SCMs enable the concrete industry to employ millions of tons of by-product that would otherwise be landfilled. Moreover, SCM use reduces the volume of portland cement required to make concrete, thereby lowering emissions of greenhouse gases and reducing the amount of virgin material required for the manufacture of cement and concrete.

A life cycle inventory performed by Construction Technology Laboratories, Skokie, IL, found that when slag cement replaces 50% of the portland cement in 51.72 MPa (7,500 psi) concrete, the energy required to produce one cubic yard of concrete is reduced by 37%; carbon dioxide emissions are reduced by 46%; and virgin material used is reduced by 15% (Figure 2).

In general, SCMs can enhance the plastic properties improving workability and placeability (Bradley and Wilson, 2005; ACI, 2003a, ACI, 2003b, ACI 2006). SCMs may also lower the yield stress in concrete mixtures to improve workability and flow through a slipform paver and around reinforcing steel, dowel baskets and other embedded fixtures. More importantly, SCMs enhance the hardened properties of concrete by increasing ultimate compressive strength, decreasing permeability, and enhancing long-term durability, which is the single most important factor in reducing the impact of embodied energy.

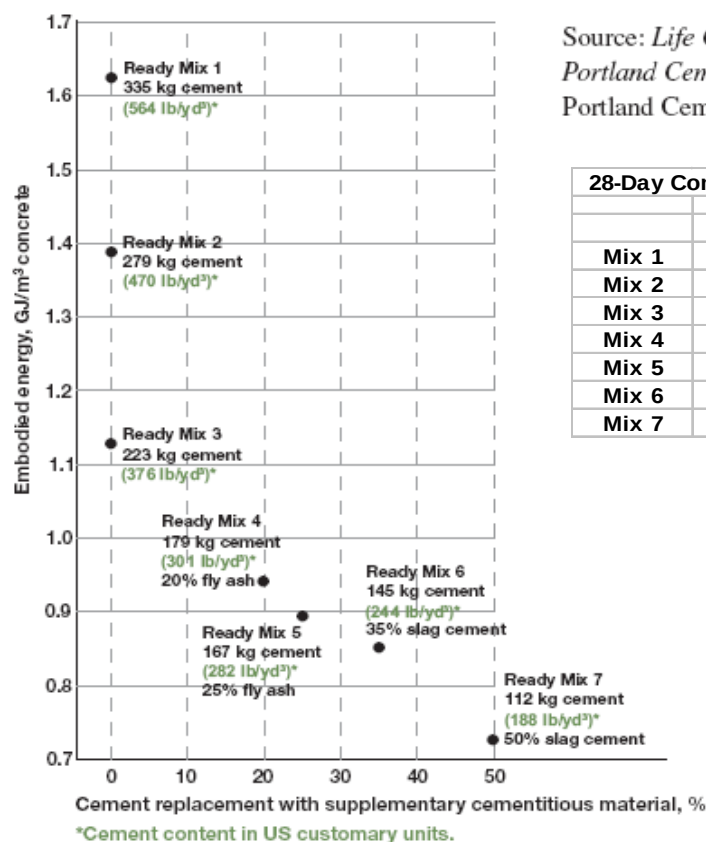
While use of SCMs in concrete mixtures constitutes a sustainable best practice in the concrete construction industry, many barriers to usage include: technical limitations; perceived safety and health risks; economic; and legal, regulatory, and contractual limits. (US EPA and US DOT, 2008).

Table 1. Average Environmental Impacts and Water and Energy Savings for SCMs in Concrete (US EPA and US DOT, 2008)

	Fly Ash	Slag Cement	Silica Fume
	Per metric ton		
Water Savings (Liter)	376.3	145.2	-5111.4
Water Savings, USD	0.20	0.10	-3.20
Energy Savings (megajoules)	4,696	4,221	32,915
Energy Savings, USD	129	116	905
Avoided CO ₂ Emissions (GHG) (grams)	701,378	668,889	699,876
	Per pound		
Energy Savings, USD	0.059	0.053	0.411
Avoided CO ₂ Emissions (GHG) (pounds)	0.318	0.314	0.318
	Per kilogram		
Energy Savings, USD	0.059	0.053	0.411
Avoided CO ₂ Emissions (GHG) (pounds)	0.701	0.669	0.699

Notes:

- Impact Metrics based upon representative concrete products.
- Negative values represent an incremental increase in impacts relative to the use of portland cement.



Source: *Life Cycle Inventory of Portland Cement Concrete*, Portland Cement Association, 2007

28-Day Compressive Strength		
	Mpa	psi
Mix 1	35	5000
Mix 2	25	4000
Mix 3	20	3000
Mix 4	20	3000
Mix 5	20	3000
Mix 6	20	3000
Mix 7	20	3000

Figure 2. Reductions of Embodied Energy with Replacement of Portland Cement with Supplementary Cementitious Materials (Marceau et al. 2007)

Portland Limestone Cement

Another eco-friendly alternative to portland cement is the use of portland-limestone cement (PLC). PLC is produced by blending portland cement and limestone or, preferably, integrating portland cement clinker, limestone, and calcium

sulfate. Equivalent performance to portland cement (PC) is achieved by optimizing the PLC with regards to composition and particle-size distribution by intergrinding clinker with limestone rather than blending portland cement with limestone. (Thomas et al. 2010b, Thomas et al. 2010c) More importantly, reducing the clinker content of cement by intergrinding limestone effectively reduces the CO₂ emissions associated with its production by the same amount. Further reductions are possible by adding SCMs either directly to the cement or by partially replacing cement with SCM at the concrete mixer.

PLC has additional advantages. Limestone is softer than clinker, and when the two are interground the resulting limestone particles are finer than the clinker particles, resulting in improved particle distribution and packing. (Vuk et al. 2001; Tsivilis et al. 1999) The fine limestone particles also act as dispersed sites on which the formation of hydration products initiates, further densifying the microstructure as hydration proceeds. And, as previously mentioned, the limestone is not chemically inert, but instead reacts with the aluminate phases in portland cement and many SCMs to create carbo-aluminate phases (Hertford et al. 2008; Matschei et al. 2007). The net result is that cement manufacturers can optimize the chemical and physical properties of a PLC to achieve equivalent, or even improved, performance to that obtained using conventional portland cement. Several North American field studies have demonstrated that PLC can be used similarly to ASTM C150 and ASTM C595 cements in the construction of concrete pavements (Thomas et al. 2010a; Thomas et al. 2010c; Van Dam et al. 2010). While relatively novel in North America, European countries have utilized PLC for the last three decades at similar replacement levels for portland cement in pavements. (FHWA, 2007; VDZ, 2005).

European cement standard EN197-1 permits two PLC types with 20% and 35% limestone content; and the 2009 edition of the Canadian Standards Association (CSA) A23.1 Concrete Materials and Methods of Concrete Construction Standard references a new class of cement called "Portland-limestone cement" (PLC) containing up to 15% limestone. Limestone can be used up to this level in all types of cement except sulfate-resisting cements. In 2009, CSA permitted the use of PLC in all classes of concrete except for sulfate-exposure classes (Thomas et al. 2010a).

Prior to CSA acceptance, considerable laboratory and field testing was performed to demonstrate that concretes containing PLC containing up to 15% limestone could be manufactured to provide equivalent performance to PC in terms of compressive strength and durability (freeze-thaw and deicer-salt-scaling resistance, chloride permeability, and chloride diffusion) in concrete mixes with and without SCMs (Thomas et al. 2010b; Hooten et al. 2010).

Durability and Service Life of Concretes

The increased emphasis on life-cycle cost analysis for infrastructure projects requires that attention be focused on the service life and durability. Life cycle cost analysis typically includes a net present value tally of the costs of ownership during an analysis period. These costs include initial costs, maintenance, repair, rehabilitation, and salvage value of the structure. In this analysis, a more durable structural system with higher initial cost may prove to be the more cost-effective system as cost of maintenance is reduced; planned repairs are postponed; rehabilitation effort is eliminated; or the salvage value is higher at the end of the evaluation period. Often future repair and replacement costs overwhelm the marginal increase in initial costs associated with more durable systems. The initial selection of a concrete construction material may depend on a number of complex and often intangible factors, but the

total initial and long-term costs of using a construction material is one of the more important considerations for infrastructure asset management.

Durability refers to the ability of concrete to maintain its integrity in service. Concrete in today's society is exposed to increasingly aggressive environments due to urban pollution including carbonation, sulfate attack, de-icing salts, and even bacteria, *Bacillus ferroxidans* and many others (Acitan and Mindess, 2011). Individually and collectively these distress mechanisms shorten the life of a pavement or increase the cost of ownership through increased maintenance or repairs. Fortunately, much of the cost associated with repair can be delayed or eliminated through proper durability design and material selection.

Historically, most concrete mixtures were designed on the basis of 28-day compressive strength, with durability a secondary concern. This strategy has led to many concretes failing prematurely. Fortunately, the realization that more durable structures are more cost effective has promoted the importance of durability and service life analysis during the design phase.

Considerable efforts have been expended in the development of test methods and service life models for predicting the long-term behavior of concrete. These models have been developed to improve concrete performance and to facilitate future repair planning strategies. Accelerated test methods have been developed to generate information on the concrete transport properties of porosity, pore solution chemistry, capillary absorption, bulk diffusion, and ion migration measurements. The information provided by these tests provides input data for concrete service life models such as Life-365 Service Life Prediction Model™ for Reinforced Concrete Exposed to Chlorides, STADIUM® and SUMMA Numerical Model for Concrete Durability.

These test methods and models demonstrate the durability benefits provided by concrete mixtures containing binary and tertiary blended cements.

Investigation and Evaluation

This paper presents data from two evaluations in which binary and ternary cementitious blends were produced and tested for long-term durability and serviceability.

One evaluation is laboratory-based and the other field-based. In both investigations concrete mixture designs were based upon infrastructure and pavement design considerations. The chosen proportions of portland cement, slag cement and silica fume for the laboratory investigation were based upon concrete mixture proportions accepted by two Midwestern state departments of transportation. Additionally, these departments use some continuously reinforced concrete designs in some heavy urban traffic corridors, bridge decks, off ramps and approaches. The reinforcement allows reductions in concrete thicknesses, longer joint spacing, and crack control providing structural integrity and pavement performance.

Combinations of slag cement and silica fume were used to demonstrate the performance of sustainable ternary-blended cements. By definition, sustainable ternary-blended cements are produced by substituting greater than 40% (by mass) of portland cement by at least two complementary cementitious materials (Mehta, 2008).

The field investigation proportions were chosen to compare portland cement (PC) and portland limestone cement (PLC) with similar SCM replacement levels. The acceptable performance of the concretes in each investigation will permit further reductions in the CO₂ footprint of the concrete. In one concrete mixture, the clinker content was just 41% of the total mass of the cementing material.

Laboratory Evaluation of Blended Cements

Nine concrete mixtures were manufactured using ordinary, binary, and ternary portland cement combinations (Table 2). Specimens were cast for compressive strength, rapid chloride permeability, density, absorption, and voids in hardened concrete, bulk diffusion and ionic diffusion. The concrete specimens were manufactured in accordance with ASTM C192 “Standard practice for Making and Curing Concrete Test Specimens in the Laboratory”.

All mixes contained No. 67 limestone aggregate, natural sand, and proportions of portland cement (ASTM C150), slag cement (ASTM C989) and silica fume (ASTM C1240). The following proportions were all held constant: cementitious materials content of 390 kg/m³ (658 lb/yd³); water-cementitious materials ratio (w/cm) of 0.43; air content between 6.5 to 8%; and slump between 12.7 and 17.8 cm (5 and 7 in); and coarse aggregate content of 1044 kg/m³ [1760 lb/yd³].

Table 2. Binder Proportions

Mixture ID	Alpena Type I/II kg/m ³ [lb/yd ³]	Grade 120 Slag kg/m ³ [lb/yd ³]	Densified SF kg/m ³ [lb/yd ³]	Mix Water kg/m ³ [lb/yd ³]
PCC	390 [658]	0	0	168 [283]
4% SF (96/4/0)	375 [632]	0	16 [26]	168 [283]
6% SF (94/6/0)	367 [619]	0	23 [39]	168 [283]
25% Slag (75/0/25)	293 [494]	98 [165]	0	168 [283]
40% Slag (60/0/40)	234 [395]	156 [263]	0	168 [283]
4/25 Blend (71/4/25)	277 [467]	98 [165]	16 [26]	168 [283]
4/40 Blend (56/4/40)	219 [368]	156 [263]	16 [26]	168 [283]
6/25 Blend (69/6/25)	269 [454]	98 [165]	23 [39]	168 [283]
6/40 Blend (54/6/40)	211 [355]	156 [263]	23 [39]	168 [283]

Results

Compressive Strength

Concrete produced with blended cements had a higher compressive strength at 28 and 365-days of age in comparison with concrete produced with the same quantity of portland cement (PCC) and w/cm ratio (Table 3). As a general rule for normal strength concrete, the use of blended cement typically provides a 10 to 20% increase in the 28-day compressive strength, and a 13% to 24% increase in the 365-day compressive strength compared with PCC concrete. The ternary blends show better strength than the slag cement blends. This impact stems from the synergistic effect of the silica fume/slag cement blend where silica fume increases the early age strength and the slag cement increases the later age strength of concrete.

Permeability

Permeability is a measure of the ease by which water, air and other substances such as chloride, sulfate and other deleterious ions enter concrete through pores and voids in the cement paste fraction. Therefore, lower permeability means it is harder for air, water, or soluble ions to penetrate the concrete.

The permeability of concrete to chloride ions was measured using ASTM C1202 *Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration*. Table 4 shows that the use of blended cements significantly reduces the permeability compared to concrete mixtures with PCC, or blends containing moderate amounts of silica fume and portland cement. Figure 4 shows that the best performance was achieved with ternary blends or higher slag content mixtures.

The smaller particle sizes and chemical reactivity associated with most SCMs greatly reduce permeability. These effects are attributed to the pozzolanic reaction, improved quality of the interface between the cement paste and the aggregate, and reduced internal bleeding. Chemical processes such as the corrosion of embedded steel, sulfate attack, and alkali-silica reaction are greatly reduced when SCMs are incorporated into the binder. The ternary combination of silica fume and slag cement show significant reductions in the permeability of the concrete not only to chloride but to water, gases and other deleterious agents (e.g. sulfates).

Porosity

The blended cements showed porosity results very similar to the PCC mixture (Table 3). This was expected as the w/c ratio was similar for all concretes tested. The incorporation of slag and densified silica fume did not have a noticeable effect on porosity (total volume of voids). This finding is consistent with moderate w/cm concrete where the pores are partially interconnected due to the initial water content. Lower water content <0.42 w/cm concrete normally is required to reduce porosity to <12 percent.

Average porosity varied from 14.3 to 15.2% which is consistent with an average boiled absorption of 6.4-7.0% by mass at two years. These results were typical and considered to be similar to those found in good quality concrete pavements.

Table 3. Summary of Test Results from Binary/Ternary Blend Laboratory Trial

Mixture ID	PCC (100/0/0)	4% SF (96/4/0)	6% SF (94/6/0)	25% Slag (75/0/25)	40% Slag (60/0/40)	4/25 Blend (71/4/25)	4/40 Blend (56/4/40)	6/25 Blend (71/6/25)	6/40 Blend (54/6/40)
Compressive Strength, ASTM C 39, MPa, (1MPa = 145psi)									
28 Days	37.3	42.8	41.9	44.3	51	45.2	48.6	48.9	50.3
One Year	46.9	48.2	49	52.6	54.2	55.1	58.5	53.6	56.8
Rapid Chloride Permeability Test, ASTM C 1012, Coulombs									
28 Days	3984	2687	1971	2442	1582	1277	845	928	727
One Year	3290	2753	2210	1028	938	734	526	622	444
Two Year	2250	2590	2372	1575	791	772	421	548	360
Boiled Absorption, ASTM C 642, % mass									
28 Days	6.0	5.8	6.0	5.9	5.7	5.8	6.0	5.9	5.8
One Year	5.6	5.6	5.7	5.3	5.1	5.6	5.5	5.6	5.8
Two Year	6.7	6.7	6.9	6.6	6.4	6.8	7	7	6.6
Porosity, ASTM C 642, % Volume									
28 Days	13.1	12.7	13	12.9	12.5	12.7	13.2	12.8	12.8
One Year	12.4	12.3	12.5	11.8	11.2	12.2	12.2	12.2	12.8
Two Year	14.8	14.7	14.9	14.5	14.3	14.7	15.2	15	14.4
Bulk Diffusion Coefficient*, ASTM C 1556, $\times 10^{-12} \text{m}^2/\text{s}$ ($1 \times 10^{-12} \text{m}^2/\text{s} = 0.00124 \times \text{in}^2/\text{y}$)									
28 Days	18.00	13.00	8.40	7.20	6.50	6.10	4.90	3.50	3.60
Two Year	15.70	14.00	7.47	4.04	0.92	1.65	0.76	1.03	0.46
Hydroxide Ion Diffusion Coefficient*, ASTM C 1556, $\times 10^{-11} \text{m}^2/\text{s}$ ($1 \times 10^{-11} \text{m}^2/\text{s} = 0.0124 \times \text{in}^2/\text{y}$)									
28 Days	12.20	11.00	10.30	10.60	7.80	6.80	4.80	6.60	6.50
One Year	12.10	9.60	5.00	5.00	3.20	4.10	2.30	2.80	2.60
Chloride Ion Diffusion Coefficient*, ASTM C 1556, $\times 10^{-11} \text{m}^2/\text{s}$ ($1 \times 10^{-11} \text{m}^2/\text{s} = 0.0124 \times \text{in}^2/\text{y}$)									
28 Days	4.70	4.30	3.90	4.10	3.00	2.70	1.90	2.60	2.50
One Year	4.70	3.70	1.90	1.90	1.20	1.60	0.90	1.10	1.00

Chloride and Ionic Diffusion Coefficients

The bulk and ionic diffusion coefficients (Table 3) were found to decrease with the increase of silica fume and slag cement in the blended cement concretes, similarly to the RCP test results. Smaller diffusion coefficients indicate slower ingress of chloride and deleterious ions with the blended cement concretes than the PCC concrete. After two years, the continued hydration of the blended cement concrete produced an almost impermeable matrix to chloride ingress.

Bulk diffusion coefficients describe the rate at which chloride ion penetrates into concrete. The coefficient is used in service life models based on Fick's Second Law of Diffusion to predict the time that chloride contamination from an exterior source (deicing salts, airborne chlorides, etc.) will reach sufficient levels to initiate corrosion of reinforcing steel. The ionic diffusion coefficient is a measure of the ability of ions to move through the concrete pore structure. This coefficient is used in the proprietary service life models STADIUM[®] and SUMMA[®]. The two measures are not interchangeable, but are related. Note that the ionic diffusion coefficient is approximately an order of magnitude larger than the bulk diffusion coefficient. This distinction is that the ionic diffusion coefficient is a measure of ionic movement through the pores, whereas the bulk diffusion coefficient is a measure of ion movement through the bulk of the concrete.

Service Life

Service life requirements for infrastructure projects are associated with the awareness by governments and owner-operators that the cost of ownership is significantly reduced when a structure is more durable and requires less maintenance. Many owner-operators view service life as the actual duration in which the structure or any of its components performs without unforeseen costs or disruption for maintenance and repair.

For the situation where corrosion of reinforcing limits the service life, the service life is defined by the time it takes chloride ions to penetrate the concrete cover from the environment, and the time it takes for corrosion to cause cracking. The first part is corrosion initiation; that is, the time required for chlorides to diffuse through the concrete cover to the reinforcement in sufficient quantities to initiate corrosion; and the second part, which is normally a fixed period of time based on the rate of corrosion after initiation and the cover depth.

Figure 3 is an example of service life model output showing the chloride concentration as a function of time at a reinforcing depth of 2 inches in a Chicago deicing salt environment. The different lines correspond to different concrete mixtures in Table 2 with their respective ionic diffusion coefficients shown in Table 3. The service life of the concrete mixtures tested is roughly defined by the time it takes for chloride ions to exceed the threshold value of 500 ppm; the dashed horizontal line in the graphic. Figure 3 illustrates that all the more sustainable mixtures containing SCM, had service lives of 2 to 3.5 times that for the PCC concrete mixture, with the longest service life being the ternary blend with 4% silica fume and 40 % slag.

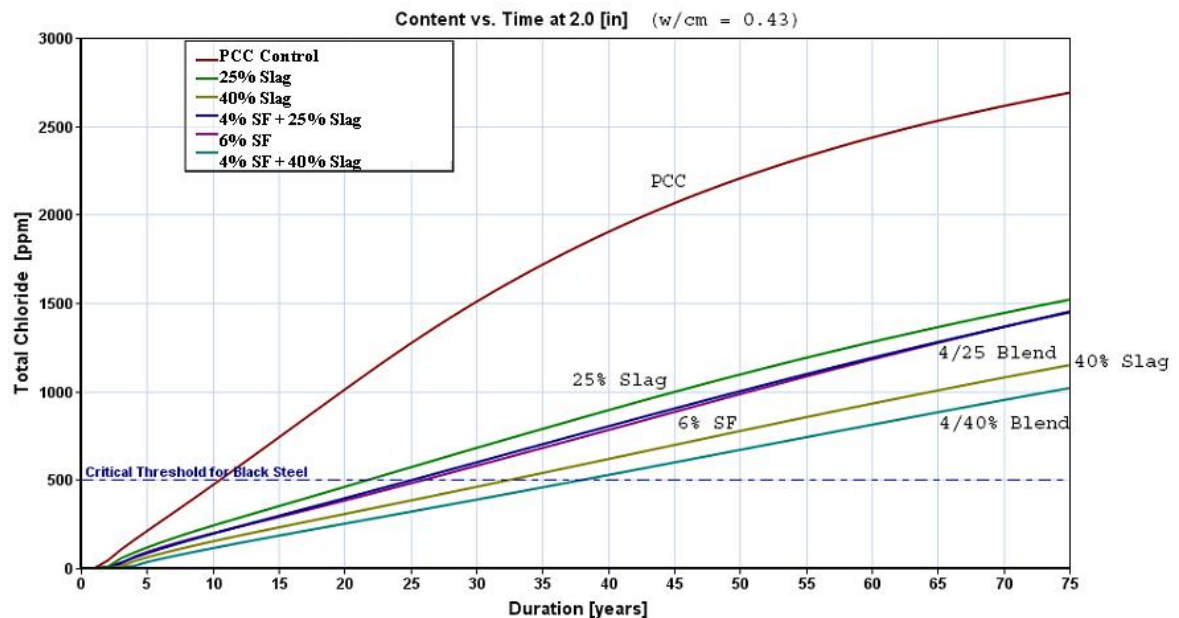


Figure 3. Corrosion Service Life

By inspection, it is clear that using binary and ternary blended cements is an extremely beneficial method to extend the time to corrosion initiation, thus extending time to maintenance and repair. This added service life would eliminate several repairs and possibly a replacement over the normal 75 year service life evaluation period required for federally funded projects.

Field Evaluation: Paving Slab at Gatineau Ready-Mixed Concrete Plant, Quebec

The field evaluation was conducted using a Type GU PC and Type GUL PLC with a blended SCM (currently marketed in Ontario and Quebec) that comprises two parts slag cement and one part fly ash by mass. The PLC was produced by intergrinding limestone with calcium sulfate and the same clinker that was used to produce the PC; the limestone content of the finished PLC was 12%. The PC used in Quebec contains 3-4% limestone and 91% clinker with 5% gypsum content. In the PLC mix with 50% SCM, the clinker only constituted approximately 41% to 42% of the total mass of cementing materials. This compares with about 91% to 92% clinker for the control mix produced with PC and no SCM (PC contains approximately 3% to 4% limestone and 5% gypsum).

A total of eight concrete mixtures were produced, four with PLC and four with PC from the same plant. The total cementitious materials content of all mixtures was 355 kg/m³ (598lb/yd³) and the W/CM = 0.44 to 0.45. A blended SCM (two parts slag and one part fly ash) was added at the ready-mixed concrete plant at cement replacement levels of 0, 25, 40, and 50%. Extensive laboratory testing was conducted on specimens cast during the placing of the concrete and the results were recently reported in a previous paper (Thomas et al. 2010a).

The concrete was used to construct a parking slab at a concrete plant on October 6, 2008. The slab area was about 450 m² (4500 ft²) and the thickness ranged from 150 to 200 mm (6 to 8 in). The concretes were mixed in a truck mixer, placed by direct-chute discharge, consolidated with a hand-held vibratory screed, provided with a bull float and broom finish, and cured under insulated tarps for one day. During the day, the ambient temperature ranged from -2 to 5 °C (28 to 41°F) and the relative humidity ranged from 44 to 93%. No problems were encountered with placing or

finishing the slabs, and no differences were observed in the fresh properties of mixtures with PC or PLC at the same SCM replacement level.

The concrete pavement will be subjected to frequent deicing salts and sand, heavy truck traffic, and severe winter conditions. The pavements will be inspected annually. Extensive laboratory testing was performed during construction. Essentially the results from the field trials confirm that PLC with 12% limestone provides equivalent performance to PC (Table 5).

Field Trial Results

The concrete mixes with PLC generally required more air-entraining admixture than equivalent mixes with PC. No noticeable differences were observed in the water demand, workability, placing or finishing characteristics of similar concrete mixes produced with either PC or PLC; however, mixes with PLC appeared to have higher paste content and were easier to finish. Table 4 illustrates that no differences were observed in the fresh properties of mixtures with PC or PLC at the same SCM replacement level.

Compressive strength values for site-cast, laboratory-cured cylinders and cores are presented in Table 5. The highest strengths (for both PC and PLC mixtures) were recorded for mixtures with 40 and 50% SCM replacement levels. The cylinder results show a reduction in early-age strength with an increase in the level of SCM replacement, but this trend is reversed at later ages. At any particular age or SCM replacement level, the results show no significant or consistent difference between concrete produced with PC or PLC.

Results from the rapid chloride permeability test (ASTM C1202) conducted at 28 and 56-days and on cores cut from the slab at 35 days are shown in Table 5. Values in the range of 3450-3750 coulombs for the PC and PLC mixes without SCMs are expected for concrete that does not contain any SCM and $w/cm = 0.45$. All of the concretes containing SCMs meet the permeability requirements of CSA A23.1 for C-1 exposure class (charge passed < 1500 coulombs at 56 days) and the mixtures with 40 and 50% SCM contents also meet the requirements for a C-XL class of exposure (charge passed < 1000 coulombs at 56 days).

The results from the freeze-thaw (ASTM C666 Procedure A) showed excellent durability factors between 100 to 104%; and the salt scaling tests (ASTM C672) were satisfactory being well below the typical limits used by the Ontario and Quebec Ministries of Transportation agencies in Canada (maximum mass loss in the range of 800 to 1,000 g/m^2 or 23 to 29 oz/yd^2 after 50 cycles). While the data reflects a trend of increasing mass loss as the SCM content increases, especially in the concretes containing 50% SCMs, it must be noted that accelerated laboratory salt scaling tests are extremely aggressive; thus, the poor test performance of concrete containing SCM does not accurately reflect field performance (Thomas, 1997, Boyd and Hooten, 2007).

Table 5 provides the results from bulk-diffusion tests (ASTM C 1556) conducted on cores taken at 35 days and immersed in a chloride solution for 42 days. The chloride profiles shown in Figure 4 and the calculated diffusion coefficients presented in Table 3 show increasing resistance to chloride ion penetration with increasing SCM replacement levels up to 40%. There is an insignificant difference in performance between concretes with 40 and 50% SCM replacement levels, but expectations are that concrete with 50% SCM content will provide better resistance at later ages. The profiles and calculated coefficients indicate no consistent difference in

performance between concretes produced with PC or PLC when comparing mixtures with the same SCM replacement levels.

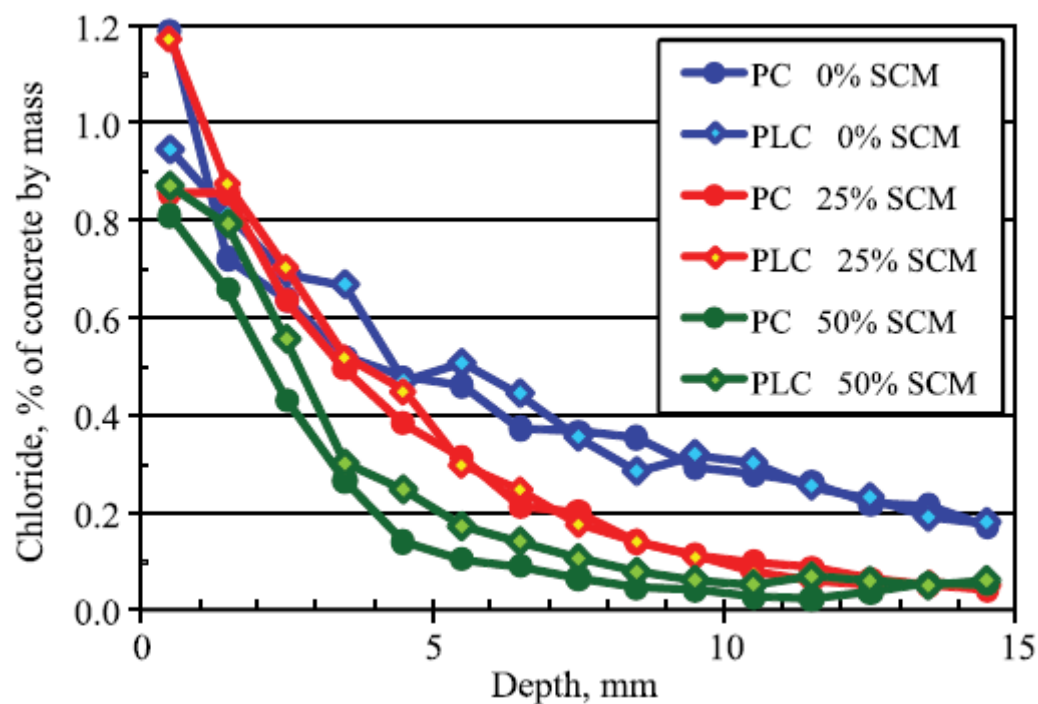
The condition of the concrete pavements was examined visually on April 2, 2009, after a fairly harsh winter and numerous applications of deicing salts. Although there are instances of isolated damage at high points from a front end loader blade used for snow removal, the surfaces of all eight concretes are in excellent condition with no scaling evident.

Table 4. Fresh Properties of PC and PLC Concrete Mixtures

Details of Concrete Mixes Used in Field Trials (1kg/m³ = 1.686 lb/yd³)						
SCM (%, Type)	Cement Type	W/CM	Slump (mm)	Air (%)	Cementing Material (kg/m³)	Clinker Content (kg/m³)
0	GU	0.45	100	6.8	355	323
	GUL	0.44	80	6.0	355	295
25 CI/S	GU	0.44	75	6.2	355	242
	GUL	0.45	100	6.6	355	221
40 CI/S	GU	0.44	95	6.8	355	194
	GUL	0.44	80	6.0	355	177
50 CI/S	GU	0.44	95	6.8	355	162
	GUL	0.44	95	6.5	355	147
Type GU cement used in Quebec contains 3-4% limestone and 91% clinker. Type GUL cement used in Quebec contains 12% limestone and 83% clinker All proportions expressed in notes above are approximate and are based on gypsum content of 5%						

Table 5. Summary of Test Results from Ternary Blend Paving Trial in Quebec

	0% SCM		25% SCM		40% SCM		50% SCM	
	PC	PLC	PC	PLC	PC	PLC	PC	PLC
Compressive Strength, ASTM C 39, MPa, (1MPa = 145psi)								
3 Days	24.2	25.2	21.7	20.7	18.9	19.2	15.3	15.6
7 Days	30.2	30.5	29.8	29.6	30.3	31.1	29.4	28.8
28 Days	37.7	38.2	41.3	39.8	43.5	43.5	43.0	42.5
56 Days	41.3	40.9	45.4	44.7	48.6	48.3	48.7	46.5
Cores at 35 Days	39.7	35.3	35.7	35.5	42.3	43.2	37.6	39.4
Rapid Chloride Permeability Test, ASTM C 1012, Coulombs								
28 Days	3446	3734	2004	1765	1145	1056	1052	932
56 Days	2781	2964	1233	1317	733	666	548	474
Cores at 35 Days	2395	2345	1410	1308	570	617	491	520
Bulk Diffusion Coefficient*, ASTM C 1556, $\times 10^{-12} \text{m}^2/\text{s}$ ($1 \times 10^{-12} \text{m}^2/\text{s} = 0.00124 \times \text{in}^2/\text{y}$)								
40 Days in NaCl	15.00	11.90	3.77	2.91	1.51	1.22	1.25	1.81
Calculated Diffusion Coefficient*, ASTM C 1556, $\times 10^{-12} \text{m}^2/\text{s}$ ($1 \times 10^{-12} \text{m}^2/\text{s} = 0.00124 \times \text{in}^2/\text{y}$)								
	15.00	11.90	3.80	2.90	1.50	1.20	1.30	1.80
Freeze-Thaw Durability Factor, ASTM C 666, %								
300 Cycles	101	100	101	104	101	103	102	100
Deicer-Salt Scaling Mass Loss, ASTM C 672, g/m^2 ($1\text{g}/\text{m}^2 = 0.029\text{oz}/\text{yd}_2$)								
50 Cycles	40	10	30	50	80	230	400	320


Figure 4: Chloride Profiles in Concrete Cores Extracted from Pavement Slabs

CO₂ Reduction with Blended Cements

The data from both the laboratory and field evaluations indicates that the content of cement clinker can be substantially reduced with the use of SCMs or PLC/SCM combinations in comparison to PCC concrete mixtures without compromising the performance of the concrete. This reduction in the clinker content of the concrete can be translated directly into reductions in the CO₂ footprint of the concrete.

Life Cycle Balance: Life Cycle Costing and Service Life Performance Requirements

The increased emphasis on life cycle cost analysis (LCCA) for infrastructure projects requires that attention be focused on the service life and durability of concrete structures including costs of initial construction, continued maintenance, habitability, and eventual demolition. The initial selection of a concrete construction material may depend on a number of complex and often intangible factors, but the total initial and long-term costs of using any construction material system is one of the most important parameters for planners and budgeters.

When LCC modeling is used in combination with service life performance requirements (Figure 5), a balanced triple bottom line can be reached by weighting the importance of economics, environmental and societal impacts for material or system selections. For example, the following questions may be answered.

- Which modifiable process or product design variable with the system provides the greatest combined economic and environmental advantage?
- What are the incremental costs of environmental improvement for each option, and which provides the greatest environmental improvement per dollar spent?
- How low must the investment cost be for a particular environmental or service life improvement to become cost effective?

These along with additional critical questions may be answered and lead to a balanced triple bottom line when comparing infrastructure materials and material systems selection, maintenance and rehabilitation schedules, and many other infrastructure design and construction decisions.

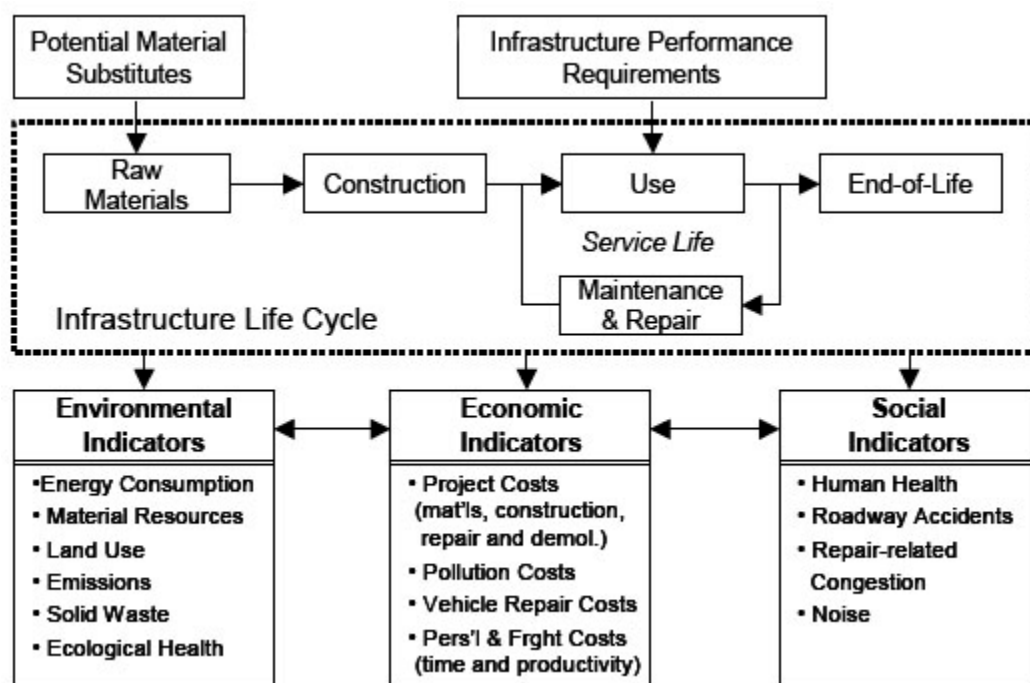


Figure 5. Macroscale Life Cycle Modeling of Infrastructure Systems (University of Michigan, 2006)

Conclusions

The nation's economy and quality of life require highway and roadway systems that provide safe, reliable, efficient, and comfortable driving environments. All around the world and across the U.S., the state of the infrastructure has reached a critical stage. Aging roads, bridges and other assets, many first built in the 1950s, are today supporting the demands of exponential increases in use, far beyond the capacity for which these structures were originally engineered.

With increased capacity and usage comes accelerated deterioration of roadways and bridges and greater wear and tear on vehicles. But even more importantly, when infrastructure is in poor condition, safety could be compromised.

Infrastructure designed and built by civil engineers, construction engineers, and construction managers should be evaluated for service life on associated performance requirements. Service life considerations are essential for sustainable construction of infrastructure. Pavements and bridge decks should be designed to maximize the life of the existing infrastructure. Proper structural design and detailing, material selection, construction practice and maintenance will significantly extend service lives and offer much lower predictable operational energy. This evaluation coupled with life cycle assessment and life cycle cost optimization should become an integral part of a sustainable infrastructure design.

Blended cement concretes rate very highly when the LCA, LCC and service life factors are considered. Concretes fabricated from binary and ternary blended cements offer substantial sustainable benefits over their PCC concrete counterparts. Environmental benefits include reductions in initial and recurring embodied energy and green house gases from reduced portland cement manufacture; economic benefits from lower predicted costs and reduced maintenance expenses due to increased service life performance; and societal benefits of reduced delays from traffic congestion with durable and resilient structures.

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