DEVELOPMENT AND GUIDANCE OF GREEN CONCRETE FOR LEED™ APPLICATIONS

John T. Kevern[1]

ABSTRACT

As green building rating systems such as LEED™ become more popular, the use of recycled materials in construction is increasing. Concrete can be produced with significant quantities of supplementary cementitious materials or recycled aggregate materials. However, modifying concrete mixture proportions for improved recycled content credits also impacts strength and long-term durability. Without properly understanding the effects recycled materials have on concrete, greener concrete can be less desirable from a lifecycle perspective from poor durability. This research investigates the impacts different types and quantities of supplementary cementitious materials and recycled concrete aggregate have on strength development and concrete durability, specifically deicer scaling. Improvements to deicer scaling resistance were investigated using a novel soybean oil sealer. The concrete mixtures were also evaluated within the LEED™ recycled materials criteria for selection based on economy and total contribution value. Considerations are included to assist designers in the selection of greener concrete mixtures for appropriate applications.

KEYWORDS

LEED, concrete, recycled materials

INTRODUCTION

The recent upswing in green building and sustainable infrastructure in general has seen the proliferation of green building rating systems. The largest and most widely-used is the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED™) program where points are awarded in various categories to define a building's greenness (Haselbach 2008). The danger with a point-based system is the specifier selecting very green materials to achieve the desired rating without consideration for performance over the long term. Unfortunately this has become apparent in the Portland Cement Concrete (PCC) arena where concrete containing high levels of recycled/reused materials are becoming specified at an increasingly alarming rate without proper considerations and expectations to allow success with the non-traditional concrete mixtures. A majority of ready-mixed concrete in the U.S. already contain supplementary cementitious materials (SCMs), such as fly ash and blast furnace slag, but only up to 25% replacement for cement (FHWA 1996). Concrete can be produced with much higher amounts of recycled materials with the proper understanding of expected differences in placing and finishing, strength gain, permeability, and long-term durability (Mehta and Manmohan 2006).

Concrete is the most durable man-made building material on earth and allows a designer a great deal of flexibility. Concrete is produced most basically by combining Portland cement, sand, gravel, and water. Portland cement is hydraulic, setting within the presence of water, through an exothermic process called hydration. Cement is produced in a highly controlled process that combines, most often, limestone, clay, and sand at high temperature 2300°C (~4300°F) to produce clinker (Kosmatka et al. 2002). The clinker is then ground to produce Portland cement. While cement production does initially produce significant quantities of carbon dioxide, cement production utilizes many waste materials from other other industrial process. The raw materials can include hazardous waste, fly ash, foundry sand, and unrecyclable glass bottles. The kiln can be heated by landfill gases, industrial wastes such as

[1]Ph.D., LEED AP, Assistant Professor of Civil Engineering, University of Missouri-Kansas City, kevernj@umkc.edu.

coffee, or wrapping paper, as well as waste tires. If the chemistry and heat value is known, almost anything can be utilized as raw material or fuel. However in the concrete process, the highly controlled cement is then shipped to tens of thousands of concrete plants for incorporation into concrete containing various local materials produced with different mixture proportions. The fresh concrete is then sent to a variety of construction projects with different durability criteria and placed by contractors with various levels of experience. Consequently there are a plethora of poorly-performing concrete examples throughout current infrastructure.

Concrete is rarely taken out of service because of issues related to low compressive strength. Many times poor concrete performance is caused by inadequate subgrade support leading to overloading. Failure from overloading occurs as corner or mid-panel cracking and eventually leads to deterioration such as potholes. Deterioration from overloading is due to inadequate structural design or poor construction practices, but not from low compressive strength (Miller and Bellinger 2003). True concrete failures are most often material-related durability issues, controlled by the mixture components and ultimately the concrete paste permeability. Durability distresses such as sulfate deterioration, durability cracking, steel corrosion, and alkali silica reaction are caused by water as an agent of deterioration or when water carries unwanted components into the concrete or leaches out hydration products. Compressive strength is measured because concrete cylinders are inexpensive, easy to produce, easy to test, and results are repeatable. Data from compressive strength is used to determine product variability and because compressive strength can be correlated to important design properties such as flexural strength (Weiss 2008). SCMs generally gain strength through slower cementitious or secondary pozzolanic reactions. While the concrete is undergoing the slower reactions the hydrated (hard) cement paste is less dense and more permeable, on a microscopic level, than concrete produced with only Portland cement. So while concrete containing SCMs is greener, stronger, and more durable at latter ages, at early ages the concrete may be more susceptible to durability related material distresses if treated the same as concrete containing only Portland cement.

Problems further arise when high levels of recycled materials are specified without consideration on how the new material properties will impact placement and ultimate durability. While LEED™ certification is achieved a few months after project completion, ideally the projects will last 50 to 100 years. Even poorly durable concrete will perform well for several years, however replacing even highly greened concrete after a few years is much less sustainable than a traditional concrete design with durability for many years. The American Concrete Institute (ACI) 318 Building Code for Structural Concrete only places limits on SCM replacement for exposure class F3 severe exposure conditions. Severe exposure is defined by cycles of moist freezing and thawing where deicer contact is anticipated. Concrete with F3 exposure is limited to a maximum of 25% fly ash, 50% blast furnace slag, or 50% of a combination of SCMs with a maximum of 25% being fly ash. The other requirements for F3 exposure concrete is a maximum water-to-cement of 0.45, around 6% air depending on coarse aggregate size, and minimum compressive strength of 31 MPa (4500 psi) (ACI 2008).

The research presented herein examines a variety of concrete mixtures that may be incorporated within the LEED™ certification process. Concrete mixtures were based on a standard ready-mixed concrete baseline mixture used for a wide-variety of applications. Variations included up to an 80% replacement for cement with SCMs with parallel mixtures containing100% replacement of virgin coarse aggregate (VA) with recycled concrete aggregate (RCA). Since SCMs are commonly used in concrete up to 50% replacement for Portland cement, the testing program began at 50% cement replacement (Tikalsky et al. 2007). Testing examined the strength, economy, and deicer freeze-thaw resistance. As 100% replacement for virgin aggregate with recycled concrete aggregate is not always an option or practical, recycled material values were evaluated within the LEED™ Materials and Resources Credit 4: Recycled Content requirements using both the SCM only option or total weight option (USGBC 2007). For the mixtures produced with VA, a cross-over replacement rate was calculated to assist in selection of most appropriate LEED™ reporting method. In order to reduce the potential for early-age deicer scaling damage common with high SCM concrete, a natural soybean oil coating was also investigated. Results show concrete produced with recycled concrete aggregate and up to 75% replacement for Portland cement can have performance and strength equal to standard concrete. Soybean oil appears as a viable option to protect high recycled material concrete from deicer damage.

CONCRETE MIXTURES AND TESTING METHODS

The mixture proportions used in the study were based on a standard concrete baseline mixture suitable for exterior flatwork or structural load-carrying members. The baseline mixture contained 330 kg/m^3 (564 lb/cy) of cement at a 0.5 water-to-cement ratio. A standard vinsol resin air entraining admixture was dosed to achieve 5-8% air, common for exterior concrete (Kosmatka et al 2002). The combined aggregate gradation was 1:1 coarse to fine aggregate. The baseline mixture contained Type II (marketed as Type I/II) ordinary Portland cement (OPC), virgin coarse aggregate, sand, and air entraining admixture and is designated OPC-VA. SCMs were included in binary or ternary combinations with the OPC. The ground-granulated blast furnace slag (S) was grade 120 and fly ash (FA) used was Class C. Mixtures with SCMs are designated by a replacement amount for OPC along with the type of SCM. For example a mixture containing 50% replacement for cement with slag and 25% replacement for cement with fly ash, by mass, is designated 50S-25FA-VA. Mixtures containing RCA instead of VA replace the VA term with RCA. One additional mixture was included in the testing program that used the standard Type II cement interground with 18% limestone, which is outside allowable limits for ASTM C150 cements, while meeting ASTM C1157 requirements (ASTM 2007a, ASTM 2003b). The high limestone cement was included with 75% replacement with SCMs and RCA and is designated as 25HS-50S-25FA-RCA for an 80% replacement for OPC.

Virgin coarse and fine aggregate and recycled coarse aggregate all met ASTM C33 gradation requirements. Virgin coarse aggregate (VA) was limestone and the recycled concrete aggregate (RCA) was produced from concrete containing limestone from the same source as the virgin material. The concrete used to produce the RCA did not experience any excessive durability issues. Primary durability issues of concern when selecting RCA are durability cracking (d-cracking) or alkali silica reaction (ASR). Pavements that have experienced significant material-related durability distresses should not be used as RCA into new concrete (ACI 2001). Both coarse aggregates met ASTM D67 designated in ASTM C33 (ASTM 2003a). Table 1 shows the coarse and fine aggregate gradations along with the D67 specification limits. As seen in Figure 1, the

TABLE 1. Aggregate Gradations.

Sieve Size, mm (in.)	Percent Passing			ASTM D67
	Virgin CA	Recycled CA	FA	
37.5 (1.5)	100	100	100	
25.0 (1)	100	100	100	100
19.0 (3/4)	100	100	100	90-100
12.5 (1/2)	67	80	100	
9.5 (3/8)	38	58	100	20-55
4.75 (#4)	6	7	99	0-10
2.36 (#8)	2	2	87	0-5
1.18 (#16)	2	2	67	
600 um (#30)	2	1	41	
300 um (#50)	2	1	11	
150 um (#100)	2	1	1	
75 um (#200)	1	0	0	

TABLE 2. Aggregate Properties.

Aggregate	Virgin CA	Recycled CA	FA
SG	2.47	2.25	2.62
Abs (%)	2.87	5.97	0.4
DRUW, kg/m^3 (pcf)	1540 (96)	1310 (82)	—

TABLE 3. Cost Assumptions for LEED™ Calculations.

Average Material Costs	$/ton	$/metric ton
Portland Cement	110	121
Slag	90	99
Fly Ash	45	50
VA - limestone	20	22
Recycled Concrete Agg.	20	22
Fine Aggregate	10	11
Water	1	1

RCA had a slightly finer gradation than the VA. The fine aggregate was a well-graded standard concrete sand sourced from river dredging (Table 1).

The aggregate properties are shown in Table 2. As expected, the RCA had lower specific gravity and higher absorption than the VA. The RCA was slightly more angular than the VA and contained more compacted voids, 42% compared with 38% for the VA. Both aggregates were angular. To minimize the effect aggregate absorption had on fresh concrete properties, such as slump and entrained air, all coarse aggregate was brought to saturated surface dry (SSD) condition before mixing.

The concrete was mixed, placed, and cured according to ASTM C192 (2003c). Compressive strength cylinders were 100 mm by 200 mm (4 in. by 8 in.) and were tested according to ASTM C39 (ASTM 2003b) using unbonded pads conforming to ASTM C1231 (ASTM 2007b). Deicer scaling resistance was performed according to ASTM C672 (2003d).

Table 3 lists the cost assumptions for the purposes of LEED™ recycled material cost calculations. Prices are representative of average concrete supplier costs in the Midwest. Due to the crushing and transportation costs, the VA and RCA were assumed equal. Depending on the distance from source to the concrete production facility and/or economy of scale, the RCA cost may be less than the VA. Since the specific gravity of the RCA is less than the VA, less RCA is required to occupy the original VA volume, so mixtures with RCA are slightly lower cost than VA mixtures.

Cost for the high limestone mixture was determined as equal to the traditional Portland cement. The individual additives were less expensive because the limestone costs less than clinker, but a loss in overall production in the ball mill operations increased manufacturing costs. The difference in the two costs does not result in a cost benefit, although the high limestone cement would have a much lower CO_2 footprint compared to straight Portland cement.

RESULTS AND DISCUSSION

Strength

The concrete compressive strength results are shown in Table 4. Both blast furnace slag and Class C fly ash contain both cementitious and pozzolanic properties. Since the pozzolanic, lime consuming, reaction requires excess calcium hydroxide, the pozzolanic reaction is secondary to hydraulic reactions (Kosmatka et al. 2002). Consequently, the expected response is a slower strength gain when SCMs are present. All values represent the average of three tests with a coefficient of variation less than 15%. At 7-days the 100% OPC mixtures had the highest strength around 35 MPa (5000 psi) followed by the mixtures containing 50% to 75% slag in either binary or ternary combinations and had strength near 27 MPa (4000 psi). At 7-days the mixtures containing 50% fly ash had about half the compressive strength of the OPC mixtures. The mixtures with 75% fly ash were low at 3 to 5 MPa (500 to 800 psi) at 7-days. At 28-days all mixtures containing at least 50% blast furnace slag in binary or ternary combinations had strength similar to the OPC mixtures, around 42 MPa (6000 psi). Mixtures containing 50% fly ash were again half that of the slag mixtures and the 75% fly ash mixtures much lower. At 56-days many of the mixtures containing blast furnace slag had higher compressive strength than

TABLE 4. Compressive Strength Results.

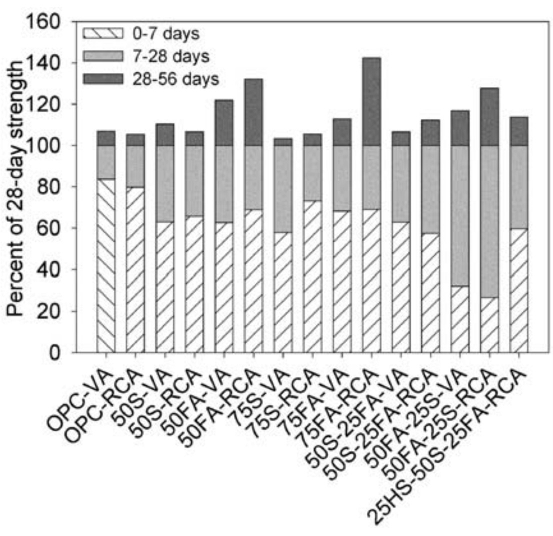
	Compressive Strength		
Mixture	**7-day, MPa (psi)**	**28-day, MPa (psi)**	**56-day, MPa (psi)**
OPC-VA	35.5 (5150)	42.4 (6160)	45.4 (6580)
OPC-RCA	34.4 (4990)	43.1 (6260)	45.5 (6600)
50S-VA	27.9 (4050)	44.3 (6430)	48.9 (8000)
50S-RCA	27.0 (3910)	41.1 (5960)	43.8 (6360)
50FA-VA	17.0 (2470)	27.2 (3940)	33.1 (4810)
50FA-RCA	15.1 (2190)	21.8 (3170)	28.8 (4190)
75S-VA	25.0 (3620)	43.2 (6270)	44.6 (6470)
75S-RCA	28.0 (4070)	38.3 (5560)	40.5 (5880)
75FA-VA	5.3 (760)	7.7 (1120)	8.7 (1260)
75FA-RCA	3.5 (500)	5.0 (730)	7.2 (1040)
50S-25FA-VA	27.5 (3990)	43.8 (6360)	46.7 (6780)
50S-25FA-RCA	24.6 (3560)	42.8 (6210)	48.0 (6970)
50FA-25S-VA	9.3 (1350)	28.9 (4190)	33.7 (4900)
50FA-25S-RCA	6.9 (1000)	25.8 (3750)	33.0 (4790)
25HS-50S-25FA-RCA	23.9 (3470)	40.0 (5810)	45.5 (6610)

the OPC mixtures. All mixtures containing 50% fly ash had similar compressive strengths and were around 70% of the OPC and slag mixtures. All but three of the mixtures (50FA-RCA, 75FA-VA, 75FA-RCA) achieved 31 MPa (4500 psi) by 56-days, with a majority occurring between 7 and 14 days.

The strength development with time expressed as a percentage of 28-day strength is shown in Figure 1. The OPC mixtures had the greatest rate of strength gain from 0 to 7-days. The slag mixtures had the greatest rate of strength gain from 7 to 28 days, while the fly ash mixtures had the greatest strength gain from 28 to 56-days. The OPC mixtures achieved over 80% of 28 day strength at 7-days, gaining only 5-7% additional from 28 to 56-days. All others, except the 75% fly ash mixtures, achieved 60% to 80% of the 28 day strength at 7-days. The ternary blend of high limestone cement, 50% slag, and 25% fly ash had ultimate strength and strength development similar to the other mixtures containing 50% slag.

The RCA did not produce a statistically-significant difference in compressive strength for any of the maturity levels, when tested using a paired t-test at P=0.05 level.

FIGURE 1. Percent of 28-day Strength Achieved at 7 and 56 days.



Economy

SCMs and RCA are more environmentally-friendly additions to concrete and help preserve natural resources and lower CO_2 emissions associated with concrete. However, substituting materials with

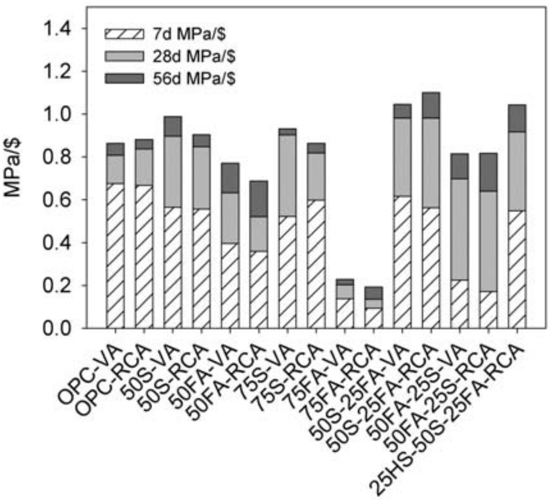


FIGURE 2. Economy of Mixtures at Various Ages.

additional considerations, such as slower strength gain, may have limited use in construction without cost benefits. Figure 2 shows the economy, expressed as strength per dollar, of mixtures at various ages as compared to the baseline mixture. For comparison, mixtures with economy within ±10% of the baseline concrete mixture for a given age are considered similar in economy. Mixtures less than 10% of the baseline mixture are less economical, while those greater than 10%, more economical. At 7-days three mixtures had similar economy to the baseline mixture, two contained RCA and two contained 75% replacement for cement. At 28-days all of the mixtures were similar or more economical than the baseline mixture, except for those mixtures containing 50% or greater fly ash. At 56-days all mixtures were similar or more economical than the baseline mixture except for 50FA-RCA and both mixtures containing 75% fly ash. At 28 and 56-days, the mixtures containing a ternary blend of 50% slag and 25% fly ash were much more economical than the baseline mixture, including the ternary blend produced with the 18% limestone cement. The ternary mixtures cost 18% to 21% less than the baseline mixture and produce greater strength (Table 5).

Since all of the recycled materials used in this study were bulkier and/or cheaper than the original components replaced in the baseline mixture, all combinations cost less (see Table 5). Cost savings for all the mixtures ranged from 2% to 42%, however the performance of the 50% and 75% fly ash mixtures will eliminate usage for most applications.

TABLE 5. Mixture Economies.

Mixture	Mixture Cost	Cost Savings	7-day Economy	28-day Economy	56-day Economy
OPC-VA	$52.59	0.0%	—	—	—
OPC-RCA	$51.57	2.0%	Similar	Similar	Similar
50S-VA	$49.47	6.3%	Less	More	More
50S-RCA	$48.47	8.5%	Less	Similar	Similar
50FA-VA	$42.98	22.4%	Less	Less	Similar
50FA-RCA	$41.96	25.3%	Less	Less	Less
75S-VA	$47.91	9.8%	Less	More	Similar
75S-RCA	$46.89	12.2%	Similar	Similar	Similar
75FA-VA	$38.40	37.0%	Less	Less	Less
75FA-RCA	$37.17	41.5%	Less	Less	Less
50S-25FA-VA	$44.67	17.7%	Similar	More	More
50S-25FA-RCA	$43.66	20.5%	Less	More	More
50FA-25S-VA	$41.39	27.1%	Less	Less	Similar
50FA-25S-RCA	$40.41	30.1%	Less	Less	Similar
25HS-50S-25FA-RCA	$43.66	20.5%	Less	More	More

Cost savings for mixtures which may be considered for construction applications ranged from 2% to 21%. Unfortunately cost savings and accruing points for LEED™ certification have opposing effects. LEED™ Materials and Resources Credit 4: Recycled Content awards 1 point for 10% recycled content based on cost of the total value of the materials on the project, or 2 points for 20% (USGBC 2007). SCMs and/or RCA aids in achieving recycled content credit. Although more recycled content, since recycled materials cost less than virgin, decreases the overall price of the concrete and reduces the recycled material contribution towards LEED™ certification. USGBC has recognized that the cementitious components within concrete makeup a majority of the concrete cost and environmental burden, but are a minority weight fraction. Consequently two options are available for applying concrete within LEED™ MR Credit 4. The standard option applies the recycled material value as a percentage of the total concrete weight. The second option allows the recycled material value to be determined as a fraction of only the cementitious material weight. The second option ignores the aggregate and water contribution due to the relatively low cost and embodied energy. Table 6 presents recycled material value for LEED™ purposes determined using both approaches. Whenever RCA was included in the mixture more benefit was observed with the total weight option. Whenever the mixtures only contained SCMs, more benefit was observed by applying the cementitious materials only option. Since 100% replacement of VA for RCA is often not allowable or practical, a cross-over RCA percentage was calculated to determine when more benefit resulted from the total weight option. While the amount of RCA required for maximum benefit using the total weight option varied based on original mixture cost, around one third replacement with RCA made the total weight option desirable. The most desirable mixtures based on economy and cost contribution were 75S-RCA, OPC-RCA, 50S-RCA, 25HS-50S-25FA-RCA, and 50S-25FA-RCA.

Durability

Blast furnace slag and fly ash improve concrete properties and have been utilized in concrete for many years. However the increased early-age porosity and permeability of concrete containing SCMs often results in deicer scaling during the first winter. Salt in solution is carried into the cement paste

TABLE 6. Comparison of LEED™ Evaluation Techniques.

Mixture	Recycled %, SCM only	Recycled Value, SCM only	Recycled %, Total Wt.	Recycled Value, Total Wt.	Required RCA for Total Wt.
OPC-VA	0.0%	$0	0.0%	$0	any
OPC-RCA	0.0%	$0	38.1%	$20	—
50S-VA	25.0%	$7	3.9%	$2	>27%
50S-RCA	25.0%	$7	42.0%	$20	—
50FA-VA	25.0%	$5	3.9%	$2	>23%
50FA-RCA	25.0%	$5	42.0%	$18	—
75S-VA	37.5%	$10	5.8%	$3	>39%
75S-RCA	37.5%	$10	44.0%	$21	—
75FA-VA	37.5%	$6	5.9%	$2	>31%
75FA-RCA	37.5%	$6	43.9%	$16	—
50S-25FA-VA	37.5%	$9	5.8%	$3	>37%
50S-25FA-RCA	37.5%	$9	44.0%	$19	—
50FA-25S-VA	37.5%	$8	5.8%	$2	>33%
50FA-25S-RCA	37.5%	$8	43.9%	$18	—
25HS-50S-25FA-RCA	37.5%	$9	44.0%	$19	—

pores. The salt increases the degree of saturation in the surface of the concrete creating more severe freeze-thaw damage. As the salt solution dries the salt recrystallizes and expands, further damaging the concrete (Taylor et al. 2006). Sealing agents can be used to slow salt solution ingress, reducing distress (Wang et al. 2006). ASTM C672 tests the deicer scaling resistance of concrete. A 4% calcium chloride salt solution is ponded on the samples. The samples then undergo 50 freeze-thaw cycles at a rate of one cycle per day. The samples are visually evaluated every five cycles. Concrete mixtures containing blast furnace slag are especially susceptible to deicer scaling and often limited to 25% replacement for Portland cement when exposed to deicing salts (FHWA 1996). Reducing the potential for deicer scaling in slag mixtures will allow more wide-spread applications and higher amounts of concrete containing higher amounts of SCMs.

Figure 3 shows the OPC-VA samples a) before any deicer application, b) after 50 cycles with no surface sealer, and c) a sample after 50 cycles with soybean oil applied at 4.9 m^2/L (200 ft^2/gallon) to the hardened concrete. The un-sealed samples had excellent deicer performance with only a few pieces of concrete flaking from the surface. The soybean oil sealed samples had no noticeable scaling after 50 cycles.

Figure 4 shows the 50S-VA samples tested for deicer scaling. The initial samples (Figure 4a) had appearance similar to the 100% Portland cement samples. The unsealed samples (Figure 4b) had severe deicer scaling as expected with high replacement rate slag mixtures (Schlorholtz and Hooton 2008). The entire surface scaled off leaving behind the exposed coarse aggregate. Figure 6c shows a sample that was sealed with soybean oil. After 50 cycles there was no noticeable deicer scaling. The soybean oil fills the surface pores and prevents deicer salts from penetrating the concrete.

CONCRETE SELECTION CONSIDERATIONS FOR LEED™ APPLICATIONS

By better understand the properties of concrete containing SCMs and recycled concrete aggregates, materials can be selected that are economical, help achieve LEED™ requirements, have good performance, and have long lifespans. Through better understanding the relationships between material properties concrete can be created that contains much higher levels of recycled materials than currently utilized while meeting or exceeding current performance. Concrete for LEED™ applications is grouped into three categories:

1. Structural Members
2. Interior Flatwork
3. Exterior Flatwork

The primary consideration for increased recycled content in structural concrete is the slower strength gain compared to 100% Portland cement mixtures. The extra time required to achieved the specified compressive strength may not be appropriate for projects under a short timeframe. However, knowing that the higher recycled material concrete will require longer curing time can be built into the project in the planning stages. Precast concrete is an

FIGURE 3. Baseline Concrete Mixture Deicer Testing Results.

(a) Before Testing (b) After 50 cycles with no sealer (c) After 50 cycles with soybean oil sealer

FIGURE 4. 50S-VA Deicer Testing Results.

(a) Before Testing (b) After 50 cycles with no sealer (c) After 50 cycles with soybean oil sealer

option to allow high amounts of recycled concrete without delaying the project schedule. Concrete members can be placed well in advance to allow strength development before installation.

The primary consideration for increased recycled content in interior flatwork concrete is increased setting time caused by the SCMs (FHWA 1990). The increased setting time can make concrete with higher SCM contents more susceptible to evaporation and plastic shrinkage cracking. Also, higher levels of SCMs can make fresh concrete more difficult to finish (Obla et al. 2008). The contractor should be made aware that the concrete contains higher levels of SCMs than typically used. If possible a contractor that has experience with SCMs should be selected.

The primary consideration for increased recycled content in exterior flatwork is deicer scaling. For best performance, mixtures should have a low water to cement ratio of 0.45 or less (ACI 2008). The considerations mentioned for interior flatwork are more crucial for exterior flatwork as environmental conditions can be more extreme. The mixtures should be properly finished and well-cured. Sealer can be applied to minimize deicer scaling distress.

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effect recycled concrete aggregate and supplementary cementitious materials had on concrete for use towards LEED™ recycled content credits. The concrete mixtures included up to 80% replacement for Portland cement and 100% replacement for virgin coarse aggregate with recycled concrete aggregate. From the study the following conclusions can be made:

- At early ages OPC had higher strength than the SCM mixtures. At later ages the SCM mixtures had equal or greater strength than OPC if slag was present.
- At the included higher replacement rates, there was no difference in later age strength between mixtures containing cement or substituted with slag at 50% or 75% replacement.
- Mixtures containing 75% fly had strength gain too slow for most construction projects.
- For mixtures containing the same cementitious materials, there was no strength difference between virgin aggregate and recycled coarse aggregate produced from the same source with similar gradation.
- At 56-days all mixtures, except those with 75% fly ash and the 50FA-RCA mixture, achieved greater than 31 MPa (4500 psi) suitable for structural concrete.
- Depending on the amount of cementitious materials, between 27% to 39% RCA substituted for VA was required to make the total weight option more desirable than the SCM only option for LEED™ certification purposes.

By identifying and properly planning for the material properties that will be affected by increased recycled material contents, concrete can be created for LEED™ recycled content applications without compromising performance and durability.

ACKNOWLEDGEMENTS

The author would like to thank La Farge North America, Century/Fordyce concrete, BASF admixtures, C2 Products, and Kaw Valley Engineering for providing materials. This research was based in part on work supported by the University of Missouri Research Board. Any opinions, findings, and conclusions or recommendations are those of the author and do not necessarily reflect the views of the project sponsors.

REFERENCES

ACI Committee 318. (2008). "Building Code Requirement for Structural Concrete (ACI 318-08) and Commentary." American Concrete Institute (ACI). Farmington Hills, MI.

ACI Committee 555. (2001). "Removal and Reuse of Hardened Concrete." American Concrete Institute (ACI). Farmington Hills, MI.

ASTM Standard C-33. (2003a). "Standard Specification for Concrete Aggregate." *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 2.

ASTM Standard C-39. (2003b) "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 2.

ASTM Standard C-192. (2003c) "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 2.

ASTM Standard C-672. (2003d). "Standard Test Method for Scaling Resistance Concrete Surfaces Exposed to Deicing Chemicals," *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 2.

ASTM Standard C-1157. (2003b). "Standard Performance Specification for Hydraulic Cement." *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 1.

ASTM Standard C-150. (2007a). "Standard Specification for Portland Cement." *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 1.

ASTM Standard C-1231. (2007b). "Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders." *Annual Book of ASTM Standards,* West Conshohocken, PA, Vol. 4, No. 2.

Federal Highway Administration (FHWA). (1996). "Comprehensive Guidelines for Procurement of Products Containing Recovered Materials." FHWA Policy Memorandum. HNG-23. February 20.

Haselbach, L. (2008). *The Engineering Guide to LEED-New Construction; Sustainable Construction for Engineers*, McGraw-Hill.

Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C. (2002) *Design and Control of Concrete Mixtures.* EB001. Skokie, IL: Portland Cement Association.

Mehta, P.K. and Manmohan, D. (2006). "Sustainable High-Performance Concrete Structures," *Concrete International*. Magazine of the American Concrete Institute. Farmington Hills, MI. July.

Miller, J. S. and Bellinger, W. Y. (2003). "Distress Indentification Manual for the Long-Term Pavement Performance Program." U.S. Department of Transportation Federal Highway Administration. Publication No. FHWA-RD-03-031. June.

Obla, K., Schindler, A., and Carino, N. (2008). "New Technology-Based Approach to Advance Higher Volume Fly Ash Concrete with Acceptable Performance: Guide for the Construction Team." RMC Research and Education Foundation Report No. 07-09. NRMCA. Silver Springs, MD. October.

Schlorholtz, S. and Hooton, D. (2008). "Deicer Scaling Resistance of Concrete Pavements, Bridge Decks, and Other Structures Containing Slag Cement, Phase 1: Site Selection and Analysis of Field Cores. Report by the National Concrete Pavement Technology Center, Ames, IA. CTRE Project 05-202.

Taylor, P.C., Kosmatka, S.H., Voigt, J.F., et al. (2006). "Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual." A Report from the National Concrete Pavement Technology Center and Federal Highway Administration, Ames, IA: Iowa State University. TPF-5(117).

Tikalsky, P. Schaefer, V., Wang, K., Scheetz, B., Rupnow, T., St. Claire, A., Siddiqi, M., and Marquez, S. (2007). "Development of Performance Properties of Ternary Mixtures: Phase 1 Final Report." A Report from the National Concrete Pavement Technology Center, Ames, IA: Iowa State University. [FHWA Publication No. HIF-07-004]

USGBC (2007). *LEED-NC for New Construction, Reference Guide.* Version 2.2, 1st ed. U.S. Green Building Council, Washington, D.C. October 2005 with errata posted through Spring 2007.

Wang, K., Cable, J. K., and Zhi, G. (2006). "Evaluation of Pavement Curing Effectiveness and Curing Effects on Concrete Properties," *Journal of Materials in Civil Engineering*, V.18, No. 3, June 1.

Weiss, J. (2008). "Mechanical Properties and Behavior of Concrete." Course notes Purdue CE530. Lecture 23.