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ABSTRACT

The concrete construction industry is governed by a network of codes and standards that ensure safety and quality. This study evaluates two central concrete construction industry standards related to bridge construction to determine if these standards inhibit more sustainable concrete bridge construction. Using social networking tools, ASTM C150-05: Standard Specification for Portland Cement and American Concrete Institute (ACI) 211.1-91/09 Standard Practice for Proportioning Normal, Heavyweight, and Mass Concrete, were identified as "central" concrete industry standards and were evaluated to test whether central concrete industry standards pose institutional barriers to innovation for sustainable concrete construction. Results indicate that while these standards do not explicitly inhibit more sustainable concrete practice, the manner in which they are used implicitly impedes more sustainable concrete construction and innovation for sustainability. Specifically, ASTM C150-05 does not inhibit the use of cement materials with lower environmental impact, but industry demand for rapid construction and institutionalized use of C150-05 to the exclusion of other environmentally preferable products does inhibit more sustainable concrete construction. Similarly, mixes designed for durability using performance-based specifications exhibit reduced annual energy and material impacts compared to mixtures traditionally designed using ACI 211.1-91/09.

Introduction

Construction industries are under increasing pressure to reduce energy and material intensity, greenhouse gas emissions, and other environmental impacts. The cement industry is continually seeking process efficiency due to constant internal financial pressures and external social pressures to reduce energy and material consumption and CO_2 emissions [1]. To achieve lower carbon emissions in cement products, the cement industry currently markets alternatives to ordinary portland cement by intergrinding supplementary cementitious materials (SCMs) with cement clinker to reduce energy costs and CO_2 emissions per ton of cement produced. Common SCMs include, coal fly ash, ground-granulated blast furnace slag (GGBFS), and silica fume.

Architects and engineers (A/Es) have specified SCMs since the 1950s to improve workability, reduce heat of hydration, and provide a cost effective cement replacement in mass concrete [2]. More recently, concrete incorporating SCMs is promoted as "green" due to cement replacement with industrial waste streams and improved overall durability. Such "green building" is becoming prevalent as federal, state, and local governments not only require Leadership in Energy and Environmental Design (LEED) certification [3], but adherence to form-based building codes, which specify urban form including building aesthetics and energy and environmental performance [4].

Consensus material and practice standards govern all phases of concrete production and construction to maintain uniformity, quality, and safety. The U.S. concrete industry organized itself around consensus technical standards in the early 1900s. Early standards from the ASTM were established to standardize the material and expanded the domestic market. Concurrently, construction standards by the National Association of Cement Users, later renamed the American Concrete Institute (ACI), helped engineers communicate and prescribe new construction concepts to provide conformity in construction. Within 10 years of developing U.S. standards, sales of domestic cement surpassed imports [5]. ASTM and ACI documents still provide the foundation for most concrete construction codes including those by the International Code Council (ICC) or the American Association of State Highway and Transportation Officials (AASHTO).

While industry-wide standards assure product standardization, quality, and safety, they can also create institutional inertia around specific materials and practices. Mechanistic, rather than organic, organizational structures can hinder successful innovation [6]. Due to their hierarchical, rigid, mechanistic nature, standard specifications can entrench economic interests, which may resist change and innovation for an entire market. Over time, the mechanistic structure of concrete industry standards may shift from fostering development and innovation (as in the early US cement market) to inhibiting change and innovation.

A number of researchers have looked at the broader cement and concrete industry and have identified challenges and opportunities in sustainable practice. Meyer [7] noted that a changing political landscape has spurred innovation in the use of supplementary cementitious materials (SCMs) and recommends policies to encourage research and development of new SCMs. Rehan et al. [8] examined policy and market-based approaches to "greening" the concrete industry in Canada, finding that when combined with appropriate technological innovations such as fly ash or recycled materials, such approaches are a viable way to improve concrete sustainability. Along these lines, other researchers have focused on technological innovations such as SCMs or other recycled products [9–11] and their limitations rather than potential barriers to sustainability innovation within the organization of the industry itself.

The objective of this research is to evaluate potential institutional barriers or opportunities for innovation in sustainable concrete construction. Concrete can be used to construct many parts of the built environment. These can include, for example, marine structures, railway structures, residential foundations and structures, precast tilt-up construction, water management infrastructure, and automobile transportation infrastructure. Due to industry idiosyncrasies (e.g., specialized building codes for each of these infrastructure types, specialized contractors, and contracts for many of these infrastructure types) only one infrastructure type was chosen for investigation. Due to the extensive highway network and large number of concrete bridge structures in the US, this study focuses on standards related to concrete bridge construction. While concrete bridge construction only represents part of the concrete construction market, similarities between concrete infrastructure types (e.g., concrete mix proportioning methods are consistent throughout the concrete industry, ASTM standards for cement are used throughout the industry) allow the method and findings to be more broadly applied. Within this work, social networking tools were applied to develop a network of concrete industry standards to identify "central" industry standards. This networking served as a means to select and determine how the most influential standards impact innovation for sustainability in concrete bridge construction industry. It is hypothesized that the most central concrete industry standards are the most influential and create institutional barriers to innovation for sustainable concrete mixture design and construction.

Networking U.S. Concrete Standards

Social networking tools are used in a variety of applications and industries from determining influential people within organizations to characterizing the flow of information [12] such as in public opinion formation as done by Watts and Dodds [13]. Specifically, Tenkasi and Chesmore [14], along with Krackhardt [15] have used social network analysis to identify barriers in implementing organizational change. A number of classical social network analyses can assess basic network characteristics. These methods include positional analysis, reputational/attributional analysis, decisional analysis, or interactional analysis [16,17]. Positional analysis is used to analyze prescribed communication lines in formal organizational structures. Reputational/attributional methods identify specific influential individuals to gain insight into network performance. Decisional analysis tools examine individuals who play key roles in decision-making. Finally, interactional methods examine the flow of interactions and their feedback and assign power as a measure of constraint.

To determine the most central industry standards for concrete, a network was constructed to examine U.S. concrete industry standards and guidance documents related to the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications [18] and Construction Specifications [19]. As a highly static network which sees little change over time (e.g., most standards have been cross-referenced for decades) and comprised of individual standards that have no independent decision-making capability, positional analysis was chosen to examine the respective location and "in-degree centrality" of each document in the network. Each industry standard or guidance document contains a list of "Referenced Documents" to assure that new products and methods are produced or tested in a uniform manner. For each industry document, references to other documents were recorded in a symmetric, binary matrix. "Centrality" was determined based on the frequency that a document was referenced by another document. The network of standards evaluated includes all AASHTO, ASTM, and ACI standards directly and indirectly referenced by the AASHTO LRFD Specifications. Positional analysis tools UCINET 6.135 and NETDRAW 2.41 [20] were used to network the documents. These tools were used to construct network connectivity datasets in matrix format and graphically depict network connections to compute connectivity and in-degree centrality, the frequency that a particular document is referenced throughout the network.

SOCIAL NETWORKING FINDINGS

An aggregated, ordinal list based on "in-degree" centrality, the frequency that a document is referenced by another, for the AASHTO BLRFD Bridge Design and Construction Standard Specifications is shown in **Table 1**. Aggregation results, shown in **Table 1**, were used to inform case-study analysis of the most central standards to understand their role in driving more sustainable concrete construction.

ACI 318-11 Building Code Requirements for Structural Concrete [21] was the most frequently referenced document. However, for the bridge systems studied, it is superseded by the AASHTO LRFD Bridge Design Specifications and therefore was not selected as a case study in this work. The second and third most central standards, ASTM C150-05 [22] and ACI 211.1-91 [23], were selected as case studies to test the hypothesis that the most influential standards, as indicated by the frequency the standards are referenced, inhibit innovation for more sustainable concrete construction.

TABLE 1

Aggregated results for the most referenced concrete design and construction standards.

Designation	Description	% of Total References
ACI 318 [21]	ACI Building Code Requirements for Structural Concrete	4.62 %
ASTM C150/M85 [22]	Standard Specification for Portland Cement	4.4 %
ACI 211.1 [23]	Standard Practice for Proportioning Normal, Heavyweight, and Mass Concrete	4 %
ASTM C33 [24]	Standard Specification for Concrete Aggregates	3.29 %
ASTM C595/M240 [25]	Standard Specification for Blended Hydraulic Cements	3.2 %
ACI 306 [26]	Guidance for Cold Weather Concreting	2.84 %
ACI 305 [27]	Guidance for Hot Weather Concreting	2.58 %
ASTM C494/M94 [28]	Standard Specification for Chemical Admixtures	2.58 %
ACI 308 [29]	Standard Practice for Curing Concrete	2.44 %
ACI 116 [30]	ACI Terminology	2.27 %
	Sum	**32.22 %**

Note: References cited in the table are Refs. [24,26–30].

Case Study I: ASTM C150-05

The role of cement in sustainable construction occurs in both cement production and concrete mixture design. The objective of this case study was to determine if the material requirements in ASTM C150-05 explicitly jeopardize concrete durability and therefore the sustainability of concrete bridge construction. Concrete durability is closely connected to overall concrete bridge construction. Keoleian [31] established that improved concrete bridge durability and fewer subsequent service events improved life-cycle sustainability of bridge infrastructure in terms of cost, environmental impact, and public health.

EVALUATION METHOD

ASTM C150-05 defines Portland cement through baseline material chemistries and physical properties. To evaluate the potential of ASTM C150-05 as a driver or barrier to more sustainable concrete construction, its current and historical chemical and physical property requirements were compared to actual formulations of cement currently sold in the U.S., along with changes in these requirements and industry products over time. By analyzing the discrepancies between the requirements of C150-05 and the actual properties of Portland cement used in practice, along with the potential ramifications of these discrepancies on sustainability metrics of life-cycle global warming potential (CO_2-eq emissions) and primary energy consumption (MJ), this case study demonstrates whether C150-05 can serve as a driver or a barrier to more sustainable concrete construction.

FINDINGS

The chemical requirements of C150-05 have changed little since its establishment in 1942. Minor adjustments have been made to Magnesium Oxide (MgO) and Sulfur Trioxide (SO_3) limits. The physical requirements of portland cement concrete however, have been significantly modified since 1942, specifically the rate of compressive strength gain. A comparison of C150-05 early age compressive strength requirements and actual concrete compressive strength gain in practice, over time shows that early age strengths exceed requirements of C150-05. **Figure 1** shows that actual compressive strengths dramatically exceed compressive strengths required in C150-05. Actual 3-day compressive strengths in 2005 are similar to 28-day compressive strengths required in 1930.

FIG. 1 Comparison of required and actual trends in concrete compressive strength 1920–2005.

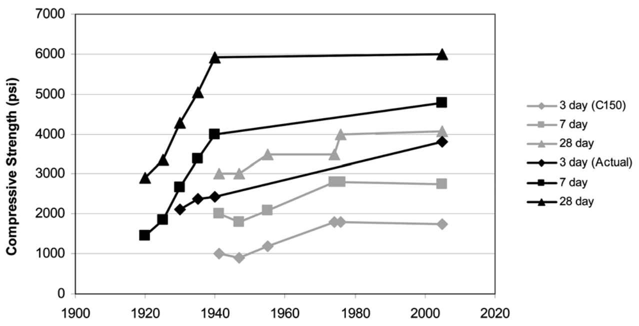
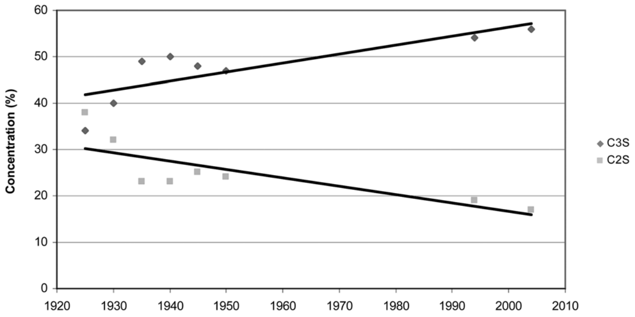


FIG. 2
Cement C_3S and C_2S fractions 1925–2005.



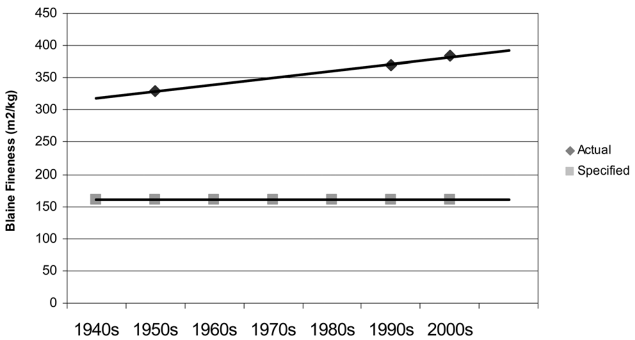
Fueling this rapid compressive strength gain is tri-calcium silicates (C_3S), often expressed in a ratio to di-calcium silicate (C_2S), which govern the rate of hydration. Higher levels of C_3S promote faster hydration and strength gain. Since 1925, the C_3S/C_2S ratio, which is unregulated by C150-05 for most types of portland cement, has increased, resulting in higher strength concretes at earlier age (C150-05 does specify C_3S limits for Type IV Low Heat of Hydration cement, but not others). Between 1925 and 1950, C_3S concentrations increased by 28 % [32]. Since 1950, it has increased an additional 16 %. Presently, the C_3S/C_2S ratio is over 56 % for most types of cement (**Fig. 2**) [33].

Along with C_3S ratio, changes in the fineness of cement products since the 1940s have also impacted concrete practice. Changes in C150-05 fineness requirements between 1941 and 2012 are negligible. Actual trends in cement fineness do not reflect this constant value since 1941. A comparison of 1950 and current cement fineness show that fineness of cement used in practice has increased over time (**Fig. 3**) [33]. As seen, cement fineness has increased and is currently over two times finer than the level specified by C150-05. As grinding technology has improved, actual fineness dramatically exceeds the minimums set by C150-05. Therefore, fineness minimums set by C150-05 simply remain to ensure a minimum rate of strength gain.

ASTM C150-05 CASE STUDY DISCUSSION

With the objective of determining if the material requirements in ASTM C150-05 explicitly jeopardize concrete durability, and therefore concrete bridge sustainability,

FIG. 3
Cement blaine fineness trends relative to C150 requirements 1941–2005.



this case study indicates that industry demand for rapid construction has driven increased C_3S/C_2S ratios and finer cements, not ASTM C150-05. Project owners, engineers, and contractors demand high early strength. Such demands can yield concrete with higher life cycle environmental impacts. Cements designed to be used in concrete proportioned for speed of construction, through such mechanisms as C_3S/C_2S ratio and cement fineness, are particularly vulnerable to early age thermal and shrinkage cracking [34]. Such cracking expedites steel corrosion in reinforced concrete and consequent failure. Specifically, Keoleian [31] found that crack resistant, durable cementitious composites used in bridge structures reduced life cycle global warming potential (CO_2-eq) emissions by 31 % and life cycle primary energy consumption by 41 % over conventional concrete. However, project schedule constraints and contract incentives for rapid construction demand cement chemistry and fineness characteristics can lead to less sustainable concrete materials and structures [34].

These case study findings indicate that ASTM C150-05 is not a major barrier to more sustainable concrete construction practices. Rather, demand for higher rates of strength gain at the cost of durability, is a barrier. However, C150-05 remains a partial barrier in some respects. While individual project specifications which demand rapid construction represent the greatest hurdle to more sustainable practice, the institutionalized use of C150-05 as a conventionally referenced standard in project specifications curbs the use of alternative and more sustainable cement products such as ordinary portland cement interground with limestone, ASTM C1157 [35]-Performance Specification for Portland Cement or C595 [25] - Specification for Blended Cement.

C150-05 currently allows for interground limestone, up to about 3.5 %, to displace cement within "Portland cement." However, this is significantly less than European cements that can contain as much as 15 %–20 % interground limestone. ASTM C1157 [35] or ASTM C595 [25] can be specified equivalent to C150-05 with the interground limestone option. With regard to ASTM C1157 specifically, Braselton and Blair [36] note that while the industry is moving towards performance specifications for concrete to improve overall quality, in reality there are few purely performance-based specifications actually written for concrete. Often hybrid specifications are used that can stifle the concrete producers or contractor's own expertise and prevent achievement of high quality concrete field results. Performance-based specifications can be written such that any alternative or innovative approach that meets the specification may be used (not just SCMs). Lightweight aggregate, for example, can effectively reduce cracking due to autogeneous shrinkage. High early strength, durability, and environmental impact should not be seen as competing objectives. Performance-based specifications allow users to accomplish all three objectives in creating more sustainable concrete infrastructure.

Case Study II: ACI 211.1-91/09

Originating in the 1930s, ACI 211.1 is consistent with the proportioning method developed by the Portland Cement Association (PCA), which evolved into the, "Design and Control of Concrete Mixtures." Together, ACI 211.1-91/09 and PCA prescribe proportioning methods that render a "gap graded" concrete mix in which intermediate sized aggregates are excluded. Gap gradation evolved due to possible improvements in density, permeability, shrinkage, creep, strength, consolidation, and to permit the use of local aggregate gradations [37]. This case study evaluates alternative proportioning methods and quantifies the environmental benefits of mixes designed with optimized aggregate gradations and model performance specifications.

Optimized aggregate gradation incorporating intermediate aggregate sizes (3/8 in. through #16 sieve) increases matrix density and reduces chloride diffusion by reducing the mortar volume through which chlorides percolate [38]. While meeting standard requirements, this concrete cures more slowly due to reduced cement content. A number of state departments of transportation and federal government agencies have formally adopted or have used some form of aggregate optimization including Iowa, MN, KS, WA, CO, and the US Air Force [39].

In the context of sustainability, other research has demonstrated the durability benefits of paste reduction and decreased permeability [40–42]. Reducing cement paste economizes mix designs and intuitively reduces environmental impacts associated with cement production. Decreased permeability limits carbon dioxide or chloride transport through the concrete protecting the reinforcement against corrosion. The National Ready Mixed Concrete Association (NRMCA) [43] has developed several model performance-based specifications for concrete mixes optimized for durability using existing proportioning methods to reduce cement content and chloride diffusion potentials. While these specifications still abide by ACI 211.1-91/09, they demonstrate the limits of prescriptive guidance like ACI 211.1-91/09 and the benefits of mixture optimization. Within this case study, ACI 211.1-91/09 is evaluated against alternative grading methods and performance based specifications to determine if ACI 211.1-91/09 presents an obstacle to more sustainable concrete construction as measured by sustainability metrics of annualized energy consumption, CO_2 emissions, and water use.

EVALUATION METHOD

Thirty-one mix designs were gathered from existing studies to evaluate the sustainability benefits of mixes intentionally designed for high durability. Twenty-eight mixes (using 4 aggregate sources named Rolag, Klocke, Glendive, and Riverdale) were designed by the Univ. of North Dakota (UND) to study the effect of dense graded aggregate proportioning, or the Shilstone Method, for combined aggregate gradation [44]. Three other mixes were designed by NRMCA using model performance-based specifications which allow more optimal aggregate proportioning. Gap graded mixes were produced by UND using North Dakota DOT Standard Specifications for Road and Bridge Construction. Dense graded mixes were produced using the Shilstone *seeMix* design tool. Mix proportions are given in **Table 2**.

To test the environmental benefits of durability design, a two-step analysis was conducted. Primary energy consumption, CO_2 emissions, and water use associated with producing gap graded concrete mixes and dense graded (UND and NRMCA) concrete mixes were calculated. This resulted in a set of “plastic” material environmental impact metrics per liter of concrete. Subsequently, environmental impact results from plastic mixes were normalized over the projected service life of the application to estimate “material impact by volume per year.” This normalization

TABLE 2

Case study concrete mixture proportions.

Mix Design		Cement (lbs)	Fly Ash (lbs)	Silica Fume (lbs)	Ground Granulated Blast Furnace Slag (lbs)	Sand (lbs)	Intermediate Agregate (lbs)	Course Aggregate (lbs)	Water (lbs)	Air Entraining Admixture (oz)	Water Reducing Admixture (oz)	High Range Water Reducing Admixture (oz)
Rolag	Gap	394.8	169.2	—	—	1222	—	1874	224	10.7	—	—
	Dense	315	135	—	—	1457	90	1747	217	8.6	—	—
Klocke	Gap	394.8	169.2	—	—	1284.7	—	1824	225.4	8.5	—	—
	Dense	389.4	166.9	—	—	1099	380	1631	222	14	—	—
Glendive	Gap	394.8	169.2	—	—	1508	—	1577	233.3	9.5	—	—
	Dense	354	151.7	—	—	1598	230	1303	222.5	7.1	—	—
Riverdale	Gap	394.8	169.2	—	—	1326	—	1881	187.7	10	—	—
	Dense	305.9	131.1	—	—	1465	282	1592	179	4.7	—	—
NRMCA	BR-1	550	105	20	—	1121	—	1800	275	0.4	4	13
	BR-2	426	150	24	—	1199	—	1922	234	0.45	4	9.4
	BR-3	300	—	—	300	1209	—	1940	234	0.4	4	18.4

allows for a more direct comparison of concrete mixes taking into account impacts on sustainability associated with higher durability.

Mix design sustainability indicators were evaluated using a concrete material intensity calculator [45]. Building from a life cycle inventory of concrete components and processes, mega joules of primary energy consumed, grams of CO_2 emitted, and kilograms of water consumed per liter of concrete produced are calculated. For energy and CO_2, all upstream inputs, processes, and emissions are considered.

Following material environmental impact evaluation, LIFE-365 service life prediction software was used to determine the service life of concrete mixes. Holding all other inputs equal and assuming one-dimensional Fickian diffusion of chlorides as the primary deterioration mode, service life projections for mix designs were based on experimental chloride diffusion coefficients for each mix. Experimental chloride diffusion values were used as determined by ASTM C1202 [46] "Test Method for Rapid Ion Chloride Permeability." A relationship between charge passed and diffusion coefficient (Eq 1) [47] was used to calculate the diffusion coefficient for UND mixes.

$$\frac{P_e - 400}{12.76} = D_c \quad (1)$$

where:

P_e = charge passed in coulombs and diffusion coefficient, and

D_c = measured in mm per year.

NRMCA diffusion coefficients were used as reported by Lobo and Obla [43]. Diffusion coefficients allow for calculation of time-to-corrosion based on chloride diffusion [48]. This time serves to normalize environmental impact results for each mix design to determine "material impact by volume per year" over the projected service life of the concrete.

Concrete performance for the gap graded and dense graded mix designs was evaluated for mixes with 2, 4, and 6 % air entrainment. ASTM C1202 [46] measurements at the 0–2 in. depth were input into LIFE-365 simulations for rebar with 2 in. of cover. Emphasis was placed on the mix designs with 6 % air entrainment to reflect typical project air entrainment requirements in northern climates with salt exposure (i.e., harsh exposures).

FINDINGS

Plastic and Annualized Material Impacts—North Dakota Mixes: Plastic material impact results for concrete material with 6 % air entrainment categorically reflect the environmental benefits expected from concrete designed for durability (aggregate optimization and cement paste reduction) including reductions in energy intensity, CO_2 emissions, and water intensity (**Table 3**).

In the cured state, three of the four aggregate sources within the UND study show that concrete designed for durability using well graded aggregates exhibit longer service life. With respect to chloride transport, dense graded mix designs outperformed gap graded mixes from Rolag, Klocke, and Riverdale aggregate sources. UND investigators specifically address inconsistencies with Glendive aggregates and attribute them to laboratory error while executing ASTM C1202 [48]. Annualized material impact reductions comparing gap graded and dense graded mixes are shown in **Table 4**. Dense graded designs with 6 % air entrainment from the Rolag, Riverdale, and Klocke aggregate sources reflected significantly greater service life projections than their gap graded counterparts (**Fig. 4**).

Concrete service life projections and paste content calculations (**Fig. 5**) demonstrate that these two factors work synergistically to reduce annualized environmental impacts. To illustrate this, in the case of the dense graded Klocke mix, a 48 % energy reduction per liter-year relative to its gap graded counterpart is seen despite the

TABLE 3

Environmental impacts of concrete mixes (densely graded (DG) aggregates relative to gap graded (GG) aggregates (6 % air) from four aggregate sources).

Mix Design		Energy Intensity (MJ/L)	CO_2 Emissions (g/L)	Water Intensity (kg/L)
Rolag	Gap	1.68	253.16	0.36
	Dense	1.37	207.14	0.32
	% Δ	18 %	18 %	11 %
Klocke	Gap	1.67	253.25	0.36
	Dense	1.66	250.04	0.36
	% Δ	1 %	1 %	0 %
Glendive	Gap	1.67	253.66	0.37
	Dense	1.51	229.22	0.34
	% Δ	10 %	10 %	8 %
Riverdale	Gap	1.68	253.86	0.34
	Dense	1.33	202.03	0.29
	% Δ	21 %	20 %	15 %

TABLE 4

Annualized impact reduction of dense graded concrete mixtures relative to gap graded concrete mixtures using aggregate from four aggregate sources (6 % air).

Mix Design		Time to Depassivation (Years)	Energy Intensity (MJ/L)	CO_2 Emissions (g/L)	Water Intensity (kg/L)
Rolag	Gap	33.1	0.051	7.65	0.011
	Dense	54.6	0.025	3.79	0.006
	% Δ	65 %	51 %	50 %	45 %
Klocke	Gap	40.1	0.042	6.32	0.009
	Dense	76.5	0.022	3.27	0.005
	% Δ	91 %	48 %	48 %	44 %
Glendive	Gap	40.1	0.042	6.33	0.009
	Dense	28.3	0.054	8.1	0.012
	% Δ	−29 %	−29 %	−28 %	−33 %
Riverdale	Gap	46.1	0.036	5.51	0.007
	Dense	54.6	0.024	3.7	0.005
	% Δ	18 %	33 %	33 %	29 %

FIG. 4 Service life estimates of gap graded concrete mixtures and dense graded concrete mixtures using aggregates from four aggregate sources.

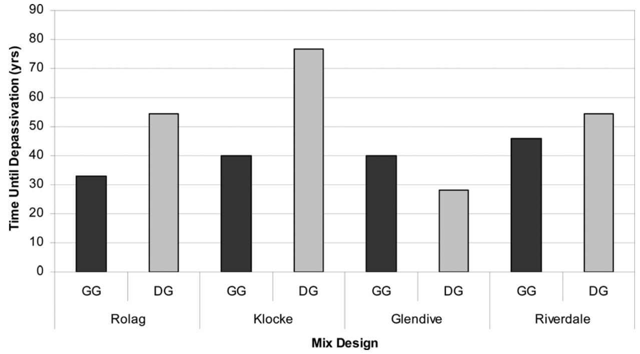
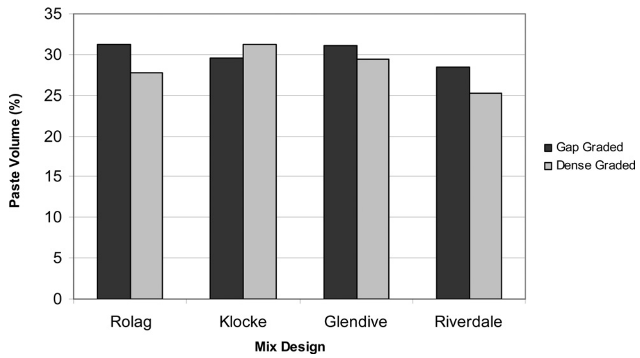


FIG. 5 Cement paste volume of dense graded concrete mixtures relative and gap graded concrete mixtures using aggregate from four aggregate sources.



higher cement paste volume for the Klocke dense graded mix. Since differences in plastic material impacts of the Klocke fresh mix were negligible (**Table 3**), this 48 % reduction in energy intensity per year is due to improved transport properties and longer service life. Such findings demonstrate that in cases where initial material intensity per liter may be high, improved sustainability can be achieved through durable material design. **Table 4** shows the environmental performance of gap versus dense graded mix designs normalized over predicted service life.

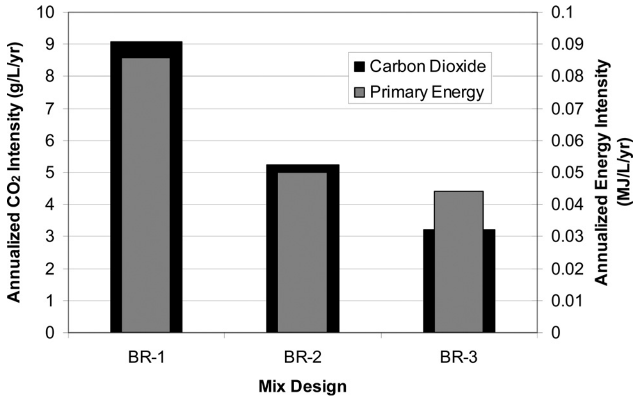
Annualized results demonstrate the environmental benefits of dense graded mix designs incorporating intermediate aggregate, but with more uncertainty than plastic material results. Incorporating service life calculations inherently introduces higher levels of variability due to modeling uncertainty and data uncertainty. Material impact results per volume were discrete, resulting from calculations based on known mix designs with the major source of uncertainty coming from the quality of the life cycle inventory data. Service life projections are subject to laboratory error and material variability in deriving chloride penetration results (within 20 % with 95 % confidence), error in calculating diffusion coefficient (8 % of variation not captured through modeling), along with assumption errors (uni-directional Fickian diffusion). Additionally, LIFE-365 does not account for potential cracking. While not certain to occur, contractors are encouraged to take care in proportioning and placement, particularly with high early strength concretes, to prevent such cracking and improve annualized sustainability metrics. Mehta [49] demonstrated that designing high early strength concrete using high cement content and low w/c ratio can lead to early age cracking and rapid deterioration due to corrosion, thus reducing sustainability performance as computed in this study.

Paste volume comparisons (**Fig. 5**) are largely consistent with energy, CO_2, and water consumption in the plastic mixes (**Table 3**). Annualized Rolag and Riverdale results indicate that durability improves with decreasing paste volume and longer service lives than their gap graded counterparts (**Table 4** and **Fig. 5**). Dense graded Klocke mixes also demonstrated durability improvements over gap graded mixes, though with similar paste volumes. Glendive mixes show decreased paste volume and service life for the dense graded mix designs.

Plastic and Annualized Material Impacts—NRMCA Mixes: Three mixes designed for durability using NRMCA performance-based design methods were also evaluated using annualized environmental impacts. NRMCA mix BR-1 represents high performance concrete (HPC) designed using typical prescriptive bridge deck material specifications used by state DOTs. BR-2 and BR-3 represent mixes designed for the same application based on model performance-based specifications by NRMCA [43]. Plastic material impact results show that relative to BR-1, performance-based BR-2 and BR-3 mixes reduce energy intensity by 23 % and 12 %, CO_2 emissions by 24 % and 40 %, and water intensity by 59 % and 57 %, respectively.

Due to increased durability, mixes BR-2 and BR-3 dramatically reduce annualized primary energy consumption and CO_2 emissions (**Fig. 6**). Carbon dioxide emission reductions for BR-2 over BR-1 proportionally follow energy intensity reductions (42.3 % reduction relative to BR-1). However, CO_2 emission reductions for BR-3 relative to BR-1 were not analogous to energy intensity reductions. BR-3 exhibits CO_2 emissions reductions of 64.7 % relative to BR-1, whereas energy intensity reductions were only by 48 % relative to BR-1.

FIG. 6
Annualized material energy intensity (MJ/L/year) and annualized carbon intensity (g CO_2-eq/L/year) of NRMCA concrete mixture designs.



This difference between primary energy consumption and CO_2 emissions stems from mix composition. BR-3 binder material is composed of 50 % portland cement and 50 % GGBFS. This lower cement content in comparison with both BR-1 and BR-2 typically suggests an analogous energy and CO_2 reduction over BR-1 and BR-2, since a majority of primary energy use and CO_2 emissions in concrete are attributed to cement manufacturing. CO_2 emissions for BR-3 followed this expected trend with a 40 % reduction over BR-2 (**Fig. 6**). However, primary energy consumption for BR-2 and BR-3 are similar. This is attributed to additional primary energy consumed by grinding GGBFS, approximately 25 % of the energy required to manufacture Portland cement [50]. The CO_2 displaced through cement replacement outweighs the CO_2 emitted by the GGBFS grinding process (since there is no calcination to emit CO_2), but the energy consumed in grinding granulated blast furnace slag is included. Results remain consistent such that CO_2 emissions associated with grinding are much less than those produced through calcination. Mix designs BR-2 and BR-3 exhibit reduced annualized water intensity by 68.9 and 74.9 % relative to BR-1, respectively.

ACI 211.1-91/09 CASE STUDY DISCUSSION

For all mixes, results for dense graded or performance-based standards showed dramatically improved environmental performance when annualizing results. Dense graded and performance-based mix designs demonstrated lower diffusion coefficients, which improved both their durability and associated annualized impact. Unique to the NRMCA mixes, BR-3 performed the best because of its high GGBFS content, which yields a very dense concrete thus minimizing chloride transport.

This analysis begins to quantify the sustainability benefits of dense and performance-based aggregate gradation in terms of three sustainability metrics. However, energy reductions are on the order of tenths of MJ per liter of concrete. CO_2 emission and water use reductions are on the order of tens of grams per liter of concrete. There has been little attempt to address the marginal economic benefits and costs of these changes, both capital and operational, or the costs of introducing intermediate aggregate into the ready mixed concrete market with perhaps less workable mixes. When extrapolated to large projects, however, the environmental benefits of dense and performance-based aggregate gradations are substantial and may justify significant investments. Results from the Rolag aggregate source indicate that dense graded mixes reduce plastic material energy consumption by 300 GJ in a job requiring 1000 m^3 of concrete compared gap graded mixes, equivalent to approximately 50 barrels of oil. This trend improves after accounting for durability benefits. Hypothetically, considering the 12×10^9 cubic meters of concrete placed globally each year, a worldwide reduction in initial material energy consumption resulting from these mix designs of 60×10^6 barrels of oil could be realized.

Unlike ASTM C150-05, the methods prescribed in ACI 211.1-91/09 inhibit more sustainable concrete construction by institutionalizing proportioning methods that result in higher material intensity and potentially less durable concrete. Seeking to address this shortfall, ACI 211.1-91/09 has since been modified to include "combined aggregate gradations" for well-graded concrete. Such changes are pushing the concrete construction industry toward more sustainable infrastructure.

Conclusions

Social networking analysis proved effective in identifying the most central standards related to concrete bridge design and construction. The standards identified provided good cases for testing the hypothesis that the most central standards inhibit innovation for more sustainable concrete bridge construction. The cases also illustrated particular types of institutional barriers to more sustainable concrete construction. Specifically, ASTM C150-05 does not inhibit the production of more sustainable portland cement concrete. The largest barrier is that few purely performance-based specifications are actually written for concrete that leverage the opportunities of ASTM C595 or ASTM C1157. Therefore, the strongest leverage point for more sustainable practice may occur outside standards writing organizations. Continuing education, project incentives, or industry recognition may press architects and engineers into using alternative standards and products to accelerate sustainable concrete construction innovation. Unlike ASTM C150-05, the proportioning methods prescribed in ACI 211.1-91/09 inhibit more sustainable concrete construction by institutionalizing mixture proportioning methods that result in higher material intensity and potentially less durable concrete. Consequently, ACI 211.1-91/09 was modified in 2002 to include "combined aggregate gradations" for well-graded concrete. Of course, the mix design or concrete material itself is not solely responsible for the durability and sustainability of concrete infrastructure. Durability is mostly influenced by materials selection, environmental loads, and structural design. All of these must be considered while working to improve the sustainability of concrete infrastructure.

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