Discovering Institutional Barriers and Opportunities for Sustainable Concrete Construction

By

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Abstract

Using industry standards to commodify cement beginning in 1904, the cement and concrete industry surrendered control of their product to the market and the concrete industry as a whole developed a technocratic and conservative culture. Both industry standards and the culture which they have created have had lasting impacts on the industry with respect to innovation and potentially more sustainable concrete construction. Industry standards and project specifications have institutionalized concrete optimized for high early strength and rapid construction rather than durability. The objective of this research is to identify specific points at which industry standards can limit innovation and more sustainable concrete construction and then demonstrate the benefits of concrete optimized for durability.

This thesis was tested using social networking tools to inform case study analysis. Networking results generated a ranking of the most central U.S. industry standards related to concrete bridge construction, providing a framework for case study analysis. The highest ranked standards, American Society for Testing and Materials (ASTM) C 150 “Standard Specification for Portland Cement” and American Concrete Institute (ACI) 211.1 “Standard Practice for Proportioning Normal, Heavyweight, and Mass Concrete,” were then evaluated using sustainability metrics.

These documents do not explicitly limit innovation or more sustainable construction, but it is the way these documents are used that impacts sustainable concrete construction. C 150 itself does not inhibit more sustainable material, but the way in which it is used by architects and engineers to garner high early strength renders concrete with heavier environmental impacts than necessary. Even though ACI 211.1 is not a legally binding document, it has established the status quo for proportioning concrete for high early strength. The industry has evolved under pressure to optimize for high early strength at the cost of durability. Industry standardization has developed a conservative culture, but it is actually the individual project specifications rather than industry standards that explicitly inhibit sustainable concrete construction.

This study also demonstrates the benefits of optimizing for durability. Designing a durable concrete using well-graded aggregates and performance-based specifications significantly reduced cement paste requirements in nearly all cases, which showed reduced material impact of fresh mixes. Durability projections augmented the sustainability benefits dramatically. Well-graded mix designs with 6% air entrainment categorically showed longer service lives and reduced annual material impact compared to their gap graded counterparts. Mixes designed using National Ready-Mixed Concrete Association model performance based specifications similarly demonstrated drastic environmental and durability improvements.

Acknowledgements

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My research was largely based on primary research and many of my finding were derived from conversations with concrete industry insiders. I would like to acknowledge Jim Olshefsky, American Society of Testing and Materials (ASTM), for providing me with industry contacts with expertise on specific standards and sectors of the industry. Two concrete industry veterans, Joe Lamond, United States Army Corp of Engineers, Chief Materials Engineer-Retired, and Lou Spellman Atlantic Cement-Retired, provided invaluable historical context of the evolution of industry consciousness, practical technical expertise, and referrals to fantastic resources. Lastly, several other industry insiders, Paul Tennis and Steve Kosmatka, Portland Cement Association, Karthik Obla, National Ready Mixed Concrete Association, and Jim Shilstone were helpful in understanding eminent problems, initiatives, and developments in the industry.

1 Introduction

Within two decades of organizing itself around industry standards for cement material and practice in 1904, the United States cement industry became the world's largest producer. As U.S. cement products struggled against foreign competition in the late 19th century, the industry used material standards to commodify cement and expand the market for domestic product. However, by organizing itself around consensus industry standards, cement producers surrendered control of their product to the market and standards institutionalized scientific reduction of concrete developing a technocratic and conservative culture, both of which slow innovation and consequently, introduction more sustainable concrete construction. While industry standards stimulated extraordinary development and economic growth within the concrete industry, and established concrete as the building material of choice, the long-term impacts of industry standards are profound and can be counter-productive in many several ways.

Deliberately commodifying a product creates both market opportunities and risks. Cement producers allowed industry-wide product homogenization according to strict material and practice standards to expedite the cement purchasing process. Industry standards became legal documents that guaranteed quality and protected buyers and sellers during each transaction, expanding the market that the product might reach. But by using consensus standards to homogenize cement products across the industry, cement producers surrendered product differentiation and ultimate control of their product to standards writing commitees.

Perhaps the most subtle impact of industry standardization is that it stimulated the scientific study of concrete. As the material became increasingly subject to reductionist science, concrete construction transitioned from an art to a science. Understanding of the composite was reduced to that of its components and as understanding of concrete's constituent parts emerged, standards were written to prescriptively specify for those constituents and rather than the entire composite. Consequently, standards have effectively institutionalized mix designs optimized for singular performance measures, which have unintended impacts quality and durability. For example, industry standards have evolved to institutionalize high early strength concrete at the cost of durability and environmental performance.

Industry standards have also created a system and culture which provides few incentives for innovation. Standards are designed to homogenize competitive products, discouraging producers from investing in new products. As a firm releases a new product, and industry organizations develop new standards for that product, the time and information sharing required by the standards development process can lead to the firm losing its competitive advantage in the market. However, the most significant barriers to innovation in the concrete industry are cultural and institutional. The standardization process has created culture and institutions that tend to resist change.

Mix designs optimized for early strength and rapid construction can have significant environmental impacts with respect to the material and durability. Concrete's environmental impacts are largely attributable to cement production. Industry standards have institutionalized cement intensive mix designs with unnecessary environmental impacts, which also exhibit poor long-term performance. Therefore, standards present the most significant barriers to sustainable concrete construction and innovation, but because the concrete industry has organized itself around consensus standards, these will be the most powerful leverage points for incorporating more sustainable practice. The objective of this research is to illustrate the institutional barriers to sustainable concrete construction created by industry standards and use sustainability metrics to demonstrate the benefits of modifying standards to support concrete optimized for durability.

1.1 Terminology

It is important to establish the terminology used to discuss industry standards in this study. Proper terminology must be defined in the context of typical contracting processes as specifications are a part of legal construction contracting documents. There are several types of standards and specifications related to a construction project that will be discussed here including, drawings and specifications, project specifications, technical specifications, material and product standards, industry standards, guidance documents, and standard specifications, that must be differentiated from each other. Figure 1 illustrates how these terms are related to each other and how they are nested in the contracting process.

The contracting process hinges on the project Architect or Engineer (A/E) which is hired by the owner to design, specify, and perhaps oversee construction. **Drawings and Specifications** are the core set of documents that are developed by the A/E and used to bid projects, guide construction and manage contractors. The drawings pictorially portray the extent and arrangement of the components of the structure. The specifications verbally describe the materials and workmanship required. These documents serve three important functions: a basis for competitive bidding or contract negotiation, a framework for contract administration, and constitute the basis for settlement of claims disputes and breeches of contract (Clough and Sears, 1994).

While detailed drawings show what is to be built, the specifications describe how the project is to be constructed and what results are to be achieved. The term “specifications” specifically refers to the technical requirements of materials, workmanship, and operations. However, the industry commonly refers to the aggregation of all construction documents, drawings and bidding and contract documents, as “specifications” (Clough and Sears 1994). These **technical specifications** that are developed by the A/E will be referred to herein as **project specifications** because these technical specifications are project specific, and not standardized across the industry.

The next level within the contracting hierarchy after drawings and specifications and project specifications is **material and product standards**. These specifications have been devised by specialists and are accepted as authoritative, regulating documents by the construction industry (Clough and Sears 1994). These specifications will be referred to as **industry standards** in this study, as they are developed by industry associations like the American Society of Testing and Materials (ASTM), the American National Standards Institute (ANSI), or the American Association of State Highway Transportation Officials (AASHTO). Industry standards are used or referenced by name when appropriate in the project specifications to communicate that specific types of materials are to be used. Industry standards also allow engineers to rely on the expertise of other industry professionals so that they do not have to recreate material specifications for individual projects and still protect themselves against liability.

A fourth definition that will be heavily used refers to the documents developed by the American Concrete Institute (ACI). ACI develops what could be called general specifications, but other than ACI 318 Building Code Requirements for Structural

Concrete and a few other standard specifications, they are not legal documents and cannot be directly referenced in project specifications. For example, an ASTM specification can be explicitly referenced in project specification and the contractor is bound to comply with that ASTM specification in its entirety. A general specification or guidance document cannot be explicitly referenced in the legal contract documents, but the A/E can draw upon it to develop project specifications using exerpts.

ACI is an industry association that issues Guides, Commentary, Case Studies, State-of-the-Art reports, and Recommended and Standard best practices documents. ACI's major objective is information dissemination and education to promote innovative practice so that concrete remains competitive with other building materials. ASTM and ACI are recognized as central regulatory bodies within the concrete industry. ASTM specifications are narrowly focused on materials and test methods and ACI documents are generally focused on practice. AASHTO has also established its own set of material and testing specifications, but most of them are based on ASTM. Even though ACI **guidance documents**, as they will be referred to here, cannot be directly referenced by the A/E in project specifications, they are recognized as authoritative and are generally used as part of project specifications.

The final class of specifications that will be mentioned is **standard specifications**. Standards specifications are generally issued by government, state, and city agencies for highway, bridge, and utility work (Clough and Sears 1994). They provide the general framework for all jobs contracted by the agency and can be modified on a case by case basis. So **standard specifications** are simply standardized **project specifications** as defined earlier, which apply for a large number of similar projects. For example, AASHTO has developed standard “Load and Resistance Factor Design” Specifications for Bridge Design and Construction, upon which state departments of transportation base their customized specifications for bridge design and construction. AASHTO standard specifications will be used to evaluate industry standards and guidance documents for bridge construction which are nested within them.

Figure 1. Concrete Specifications Terminology Hierarchy

2 Standards Establish Industry Institutions

2.1 Industry Standards Created Commodity Cement

Throughout the 19th century, the United States cement industry languished against foreign competition mainly because of real or perceived problems with domestic material quality control and consistency. Foreign governments invested vast resources into research and development which spawned the first national cement standards. These standards provided customers with the first assurances of quality control and uniformity. Material standardization provided customers with quality assurance without having to test each procurement, reducing the costs of each transaction. Thus, foreign cement companies were able to dominate the United States cement market. The United States industry followed suit to be competitive and self-imposed an industry-wide cement material specification. Standardizing cement products turned them into commodities and improved quality assurance growing the market for domestic product by creating a commodity. Even though conscious agreement to homogenize cement grew the market, cement producers relinquished control of their products to consensus industry organizations.

2.1.1 Cement Quality

In the late 19th century, cement quality posed problems for the United States industry. Inconsistent quality made it difficult for domestic producers to compete with foreign imports, particularly those from Germany (Prentice 2006). Until 1871, United States cement manufactures only produced natural cement, which was prepared “directly from rock” with little processing. Natural cement performance was variable and United

States purchasers could not be assured that domestic product was of consistent quality, unlike the intensively processed portland cement with strict quality control of foreign producers. In fact, in 1887 the United States imported six times more portland cement than it produced. This discrepancy was largely due to the perception of a quality gap between standardized foreign product and variable domestic product . Whether or not the quality gap was perceived or real is difficult to surmise, but domestic production increased by 75% from 1886 to 1887 (Lesley 1898), attributable to the 1885 American Society of Engineers (ASCE) recommendations on testing and performance (Slaton 2001), which signified the beginning of standardization in the United States. Within 10 years of developing U.S. standards, sales of domestic product surpassed those of foreign imports (Abrams 1925).

ASTM Specification

The United States cement industry adopted the German model, moving toward a national standard beginning in 1885. The industry still remained fragmented at the turn of the century, with several organizations writing specifications independently. ASCE, American Society of Testing and Materials (ASTM), the American Railway Engineering Society, the National Bureau of Standards (NBS) (Slaton 2001), and the American Portland Cement Manufacturers in addition to disparate users continued to develop specifications well into the 1900s. At the time, there were literally hundreds of cement specifications in the United States.

It was the ASTM Standard Specification for Cement, ASTM C-1, issued in 1904 that emerged to represent a private, proactive centralized source for standards of best practice (Mowry and Rosenberg 1922) with considerable industry support as an alternative to government regulation. As the NBS began to promulgate standards for many things, including mucilage, fire brick, rubber tires, shoe leather, and asphalt (Slaton 2001), the cement industry became uncomfortable with having the government regulate their product and grew to actively self-regulate using consensus standards (Slaton 2001). ASTM so effectively organized the industry and developed credibility that the ASTM C-1 Standard Specification for Portland and Natural Cement soon came to be recognized as the National cement standard. Various federal entities including the Army Corp of Engineers and the National Bureau of Standards had concurrently developed their own cement specifications, but in 1917 committed to refer to ASTM C-1 as their central cement specification (Prentice 2006). Government participation consummated the success of the ASTM specification and developing a self regulated industry.

ACI Guidance

The ASTM material specification for cement spawned standardization activities across the entire industry. Evolving out of a 1904 movement to form an association of concrete block machine manufacturers, the National Association of Cement Users (NACU), held its first convention in Indianapolis in 1905. From its inception, the NACU and ASTM were closely aligned. NACU was founded only a few years after ASTM and its first president, Richard L. Humphrey, is also recognized as one of the founders of ASTM.

ASTM emerged to develop material specifications for cement, while the objective of the NACU was, “to disseminate information and experience upon and promote the best methods to be employed in the various uses of cement by means of conventions, the reading of discussion papers upon materials of a cement nature and their uses, by social and friendly intercourse at such conventions, the exhibition and study of materials , machinery and methods, and circulate among its members, by means of publications and the information obtained (Wilde 2004)." Where ASTM was established to specify materials, the NACU was established to provide guidance on the application of these materials. There was some early overlap in the activities of these two organizations. The NACU adopted the ASTM Standard Specification for Portland and Natural Cement, until 1936, when ACI (formerly NACU) and ASTM entered formal agreement to eliminate overlapping specifications. ACI dropped its material specifications and ASTM ceased to standardize design and construction practice. NACU had officially changed its name to the American Concrete Institute in 1913 to reflect the scope of its interests, which were beyond the application of cement and more heavily focused on structural applications of concrete.

ASTM and ACI still maintain this relationship and are considered the authoritative bodies of concrete materials and practice. ASTM focuses mainly on materials; ACI on concrete practice. ASTM remains focused on developing material standards and test methods and ACI on disseminating technical information through education and outreach. Early on, NACU adopted the agricultural extension model, providing training and short courses, which eventually evolved into full University level courses on structural engineering and concrete practice at the University of Wisconsin in 1910. Similar programs were also established the University of Pennsylvania and Iowa State University.

AASHTO Specification

The American Association of State Highway Transportation Officials (AASHTO) emerged as a leading standardization organization after the Federal Aid Highway Act of 1956. Prior to 1956, the organization that became AASHTO was a small affiliation of state roads and highway officials, but the Highway Act placed increased importance on this organization which represents the state transportation departments that built, owned, and continue to operate the Interstate Highway System. Thus, AASHTO has evolved to set transportation industry policy and regulate the industry using consensus standards in the same way that ASTM and ACI have. In fact, AASHTO largely uses ASTM and ACI documents to inform its own policy for concrete construction. Many AASHTO standards for concrete construction have been designed based on ASTM and ACI documents.

2.1.2 Standards Shape Industry

As collaborative, consensus standards, their development required information sharing between industry members at the committee meetings of NACU and ASTM. At the time, many felt that sharing information worked against what they considered healthy capitalist competition, but most industrialists saw that standardization and homogenization of product saved duplication of effort and created consumer confidence (Slaton 2001). It was widely believed that even though firms may lose the competitive advantages of product differentiation, greater gains could be made from their share of a much larger market created by standard specifications and homogenous products (Prentice 2006). Thus, ASTM, ACI, and to a certain extent, AASHTO have become the institutions that govern the concrete industry.

2.1.3 Resource Commodification

There is a clear trade-off in creating a commodity product to expand the market; sacrificing product and service differentiation to develop a high volume market. Product standards are an essential first step to creating a commodity product as evidenced by the development of commodity grain in 1856. The Chicago Board of Trade developed policies to standardize the shipment of wheat from Chicago's hinterland into the city to be traded and distributed throughout the country. The essential feature in making a commodity product is homogenizing the products of many producers. Grain had typically been shipped from the farm in individual sacks, but with rail car innovation and the grain elevator, grain could be transported loosely and flowed from the hinterland like a river through the grain elevator. The Board of Trade used product classification and rating standards to channel the river and assure buyers that they were actually getting the product they bought even though the producer became anonymous. Therefore, a refinery could confidently purchase a gross of #1 White Winter to make flour without having to actually see the product. However, the grading system allowed grain elevators to sever the link between ownership rights and the physical grain, with a host of unanticipated consequences (Cronon 116).

The impact of product standardization and commodification on the agricultural industry was profound. Farmers became beholden to the grain elevators and market, which sets prices without regard to the full cost of the product. Farmers were then forced to focus on minimizing production costs; maximizing efficiency and productivity. As such, agriculture evolved from an art, where farmers utilize experiential knowledge and intuition to maintain a productive system, to a science, where they deconstruct the system into components to understand the individual inputs that lead to one valued output: productivity.

Optimizing for a singular output like agricultural productivity in the short-term usually leads to unintended long-term impacts. In the case of agriculture, as farmers were forced to maximize yield and develop economies of scale, they developed very resource intensive methods. Advances in petroleum-based nitrogen fertilizers afforded them the capability to grow large monoculture crops that could be efficiently harvested and transported. Reduced biodiversity requires elevated pesticide application. Run-off from these systems causes nutrient loading and stream and groundwater contamination, but affects on the system itself are perverse. Resource intensive techniques lead to soil degradation and loss, crop diseases, and general loss of ecosystem services (Tilman et al. 671).

2.1.3.1 Commodity Cement

Agricultural commodities are fundamentally different than mineral commodities in that they are renewable and extraction leads to temporal concerns of renewing the system. The nature and dynamics of commodity resources is complex. The aim of this discussion is not to convey the details of commodity markets, but to highlight the role industry material standards play in creating a commodity and the long-term impacts of those standards. The major underlying similarity between agricultural commodities and cement product is the desire for quality control and transaction security achieved through standardization. As the United States cement industry struggled to establish itself around the turn of the 20th century, industry participants made a deliberate decision to homogenize cement product across the industry so producers could expand their markets to users that could not afford those transaction costs.

As the Chicago Board of Trade's action to develop grain standards marginalized its producers and subjugated them to the whims of traders, cement standards also made producers beholden to the market. The standard locked producers into producing a specific type of cement with a minimum set of attributes. Furthermore, the nature of the consensus organization is that its representatives consist of producers, consumers, and third parties, including academics, consultants, and other tangentially interested parties. Therefore, cement producers do not have control over their product at a very basic level. Producers of any type of product are subject to the whims of their consumers based on demand for the application, but cement products themselves are actually defined by the rest of the industry. So the type of cement actually produced is defined largely by users, but also by people and organizations representing other interests. ASTM C-09 for Concrete and Concrete Aggregates includes members for government organizations like the National Institute of Standardization and Technology and the U.S. Army Corp of Engineers; industry associations like the Portland Cement Associate; independent laboratories like the Concrete Testing Laboratory (CTL); concrete products companies like Grace Construction Products; Ready-Mixed Concrete producers; and academia. Cement producers then are legally bound to produce cement according to the demands of their consumers and external interests (Tennis 2006). Beyond the impact of standardization on cement products specifically, the technocratic culture created by the standardization process has had a profound impact on the development of concrete construction.

2.2 Standardization Created Technocratic Culture

Establishing industry material and practice standards for concrete in the early 1900s created a technocratic culture, by which the concrete composite was reduced and studied by its component parts. ASTM C-1 institutionalized a scientific culture and marked the transformation of concrete construction from an art to a science. The significance of this is profound because as concrete was reduced and studied by its component parts, standards were developed to specify the characteristics of those component parts rather than the performance of the mixture as a whole. Over time, prescriptive standards developed for the concrete constituents which are optimized for early strength have overlaid to limit the ability to design concrete optimized for durability.

2.2.1 "Technikers"

As standards and quality control came into focus, portland cement became preferred over natural cement for the consistency of quality achieved through material processing. Portland cement is a very specific type of hydraulic cement made by finely pulverizing clinker formed when a mixture of calcium and silica-containing minerals is heated to the point of fusion and usually as added gypsum interground to control setting and hardening (ACI 1993). In Germany, standardization and chemical investigation of portland cement created an industry led by chemists and engineers, "technikers." As the United States cement industry began to transition from natural cement to portland cement, chemical analysis and manipulation also became an integral part of quality assurance and control.

Initially, there were very few people with any significant knowledge of portland cement chemistry in the United States industry. At the end of the 19th century only two companies, the American Cement Company and Atlas Cement company had hired scientists with the chemical expertise commensurate with the German technikers (Prentice 2006). As previously stated, the United States industry was modeled after the German industry and as the 1878 National Standard and cement chemical investigation coevolved in the German industry, the 1904 ASTM standard similarly established a scientific culture in the United States industry. The standards and committees were designed such that chemists and engineers were required to design and write the material and test specifications. There were so few people with technical expertise that it was absolutely necessary for scientists to provide explicit guidance for contractors and laborers. Thus, industrial specifications are also means of social organization (Slaton 2001). As standard test methods and specifications proliferated, employment for scientist trained to run testing procedures became readily available with cement producers, independent testing laboratories, and even at the construction site. Indeed, beginning around 1900, old-fashioned artisans and skilled tradesman faced obsolescence as concrete began to dominate building materials and then concrete practice transitioned from an art to a science. Industry standards effectively institutionalized a technical and scientific culture and perpetuated the importance of scientists and engineers in the industry (Slaton 2001). The scientific nature of the concrete industry persists today. ASTM, ACI, and AASHTO, which are comprised mostly of engineers representing industry, academia, and government, regulate concrete practice with formal industry standards, which reflect the legacy of reductionist science.

2.2.2 Concrete Reduction

In Germany, extensive chemical analysis of cement led to the development of their national standard. The ASTM standard was based on a growing body of scientific research, andestablishing the standard stimulated extensive research and development. In 1915 that extensive laboratory testing of the “design of concrete mixtures” was executed by Duff Abrams, researching at the Structural Materials Research Laboratory at the Lewis Institute. The laboratory carried-out over 50,000 tests as part of a comprehensive study of proportioning concrete. Abrams’ exhaustive study established the initial relationship between strength and water to cement ratio (w/c ratio) (Figure 2).

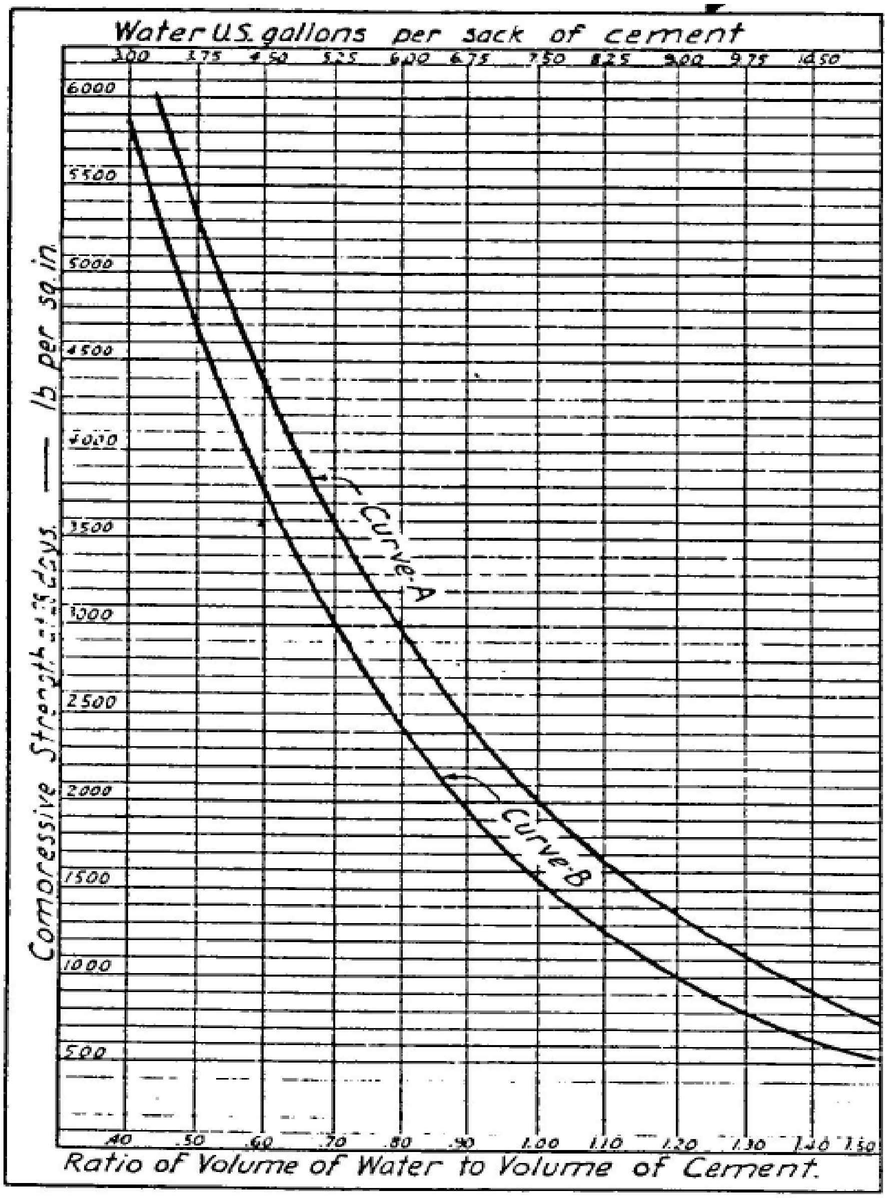

Figure 2. Compressive Strength-Water/Cement Ratio Relationship

This was the seminal study on concrete mix design philosophy in the United States and its impacts on concrete practice were enormous. While understanding the relationship between strength and w/c ratio improved industry-wide concrete performance, it also established "compressive strength" as the central performance metric for concrete. Because compressive strength became the most well understood measure of performance and easiest to test, it also became the singular measure of concrete performance. Abrams published this work in an article called "Design of Concrete Mixtures" where he made an explicit distinction between "proportioning" and the "intention to imply that each element of the problem is approached with a deliberate purpose in view which is guided by a rational method of accomplishment (Abrams 1925)." He made clear the value of defining concrete by its constituent parts and in his study institutionalized the importance of compressive strength. Abrams' publication was the precursor to the Portland Cement Association's (PCA) concrete proportioning guidance now called, "Design and Control of Concrete Mixtures," which is one of the authoritative sources on mix design and still uses compressive strength and w/c ratio as the foundation of mix design. In fact, contemporary concrete project specifications begin by prescribing desired compressive strength.

This newfound knowledge of how to control compressive strength quickly led to innovations in strength gain. In the mid-1920s, the definition of cement performance shifted from overall tensile strength and durability to high early strength (Anderson). The 1904 Standard Specification for Natural and Portland Cement focused principally on long-term strength. But in the 1920s, following Abrams' work, manufacturers began pushing high early strength product achieved through increased fineness created by wet processing techniques for cement production (Anderson 292)[1]. However, as early as 1927, observers began to understand that high early strength was achieved at the cost of durability. A leading trade journal of the time stated that, "There are certainly other qualities desirable in portland cement besides early hardening ability, especially in the view of the facts, apparently well established, that the early strength cements do not have

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[1] Note: Increasing the fineness of cement particles increases chemical reaction rates and expedites the curing process.

good keeping qualities, require more gypsum, make concrete more subject to shrinkage, and do not make so permanent a concrete when exposed to seawater, or perhaps any water (Anderson, 293)." This was an early example of how controlling for a singular characteristic of concrete led to unintended consequences in performance. Designing for high early strength requires high heat of hydration, which can lead to early age shrinkage and thermal cracking. Cracking expedites failure in reinforced concrete by mechanisms discussed later. By 1939 the drawbacks of high early strength concrete were apparent and ASTM reworked C01 to differentiate between five types of cements, including Type III High Early Strength Cement.

This modification was important because it demonstrated the understanding that fineness and high early strength can reduce durability and was not appropriate in all projects. But more significantly, in addition to Abrams' work, it more broadly signified the shift from the art of concrete practice to subjecting concrete to reductionist science. Portland cement was now broken down into five categories based on five different performance characteristics. Beginning with w/c ratio and compressive strength, concrete mix designs have continually been evaluated and specified with respect to its constituent parts rather than the attributes of mix as a whole.

2.2.3 Prescriptive Standards

As concrete became increasingly subject to reductionist science, prescriptive specifications also emerged for its components and additives. A prescriptive specification specifies particular materials, quantities, and methods rather than intended performance. For example, ASTM C 150 Standard Specification for Portland Cement has very specific chemical requirements that all portland cement must meet.

As discussed earlier, industry standards are part of the legal framework that specifies a construction project. In a time when quality assurance and control was much more tenuous, industry standards were written to require very specific materials and practices. As experiential knowledge based on project results accumulated, industry engineers oversaw the development of prescriptive specifications to ensure that contractors with little technical knowledge of concrete could effectively complete complex projects. In the early years the gap in technical knowledge between engineers and contractors was vast and it was necessary to make prescriptions in project specifications, industry standards, and guidance documents to make sure the job was completed properly (Karthik Obla interview). However, over time prescriptive standards “lock-in” legacy state of the art and as knowledge and technology develop, prescriptive standards overlay and conflict with each other. Therefore, prescriptive industry standards, project specifications, and guidance documents layer upon each other to inhibit the ability to optimize concrete materials and construction methods using innovative techniques.

Beginning with Abrams’ developing the relationship between w/c ratio and compressive strength and then the mid-1920s movement to high early strength cement, the industry has gravitated toward compressive strength as the prime metric for concrete quality. In 1941 ASTM C 150 began the shift to focus mostly on 3, 7, and 28 day compressive strength as its primary performance metric. The move to compressive strength was largely due to the reliability and precision of concrete compressive strength test ASTM C 39-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens and cement compressive strength test ASTM C 109-34T- Test for

Compressive Strength of Portland Cement Mortar. "Though the compressive strength test was late in arriving, its strong entrance in use with Type III (High Early Strength) cements as the governing test method eventually caused it to be the governing strength test method for all cements, and it has been that since 1953 (Isberner and Klieger 1978)"

Concrete is a complex material in which a change in one component material or the proportion of the materials can cause large performance variations and generally requires a change in another material or constituent to maintain consistent performance. Concrete is a composite or cocktail of cement, water, aggregate, air and specified chemicals in which each component is related and affects one or several other components. For example, adjusting w/c ratio affects the amount of aggregate required both of which impact the strength performance of the concrete. Figure 3 illustrates that prescriptive specifications can actually end up conflicting with intended performance. Controlling for one material or performance criteria without respect for others can lead to conflicts related to proportioning and performance (Figure 3).

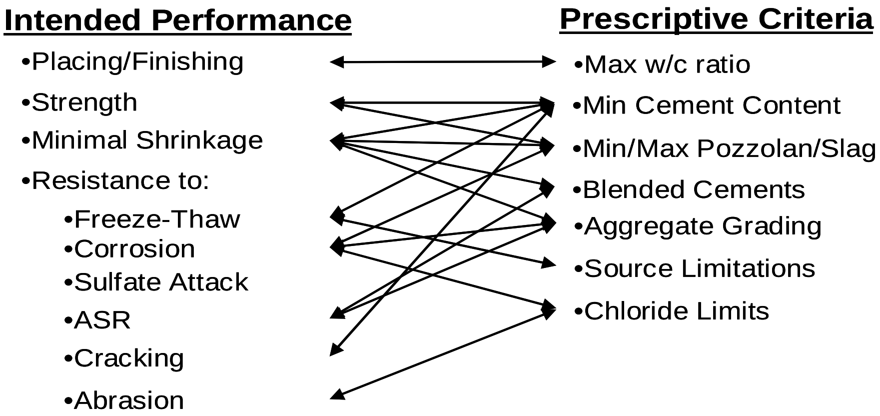

Figure 3. Representation of Interconnections of Physical and Performance Characteristics (Figure from Karthik Obla, National Ready Mixed Concrete Association)

Even though the relationship between w/c ratio and compressive strength has been well established, categorically requiring a specific w/c ratio in an industry standard or project specification might lead to a poor performing concrete if compressive strength is not the only concern on the project. Most importantly, developing prescriptive specifications for certain components of concrete mix (i.e. cement) have served to "lock-in" requirements for each addition, requiring producers to provide users with concrete that meets minimum material requirements even if producers can provide higher quality concrete with alternative material compositions. Since 1934, perceived optimal w/c ratio has fallen from 0.53 to nearly 0.35. Based on Duff Abrams' exhaustive work on the relationship of w/c ratio and compressive strength, prevailing sentiment is that minimizing w/c ratio maximizes strength. As this information has propagated, project specifications have institutionalized and locked-in specified w/c ratio and minimum cement requirements to assure strength performance. Specifying concrete with high cement content may yield high early strength, but subsequent rate and heat of hydration can lead to early age shrinkage and thermal cracking that actually reduce the service-life of reinforced concrete (Mehta 2001).

On a job-specific basis, the A/E generally relies heavily upon industry standards and guidance documents developed by consensus organizations to specify materials and practices in contract documents and rarely develops his/her own specifications to ensure safety and limit personal liability. Existing methods have been used with great success for many years and assuming additional liability for unspecified products is not worth the increased risk. The A/E tends to use the specifications they have always used to mitigate risks by ensuring reliable materials and proper completion of the job (Obla 2007).

As industry standards have evolved to be prescriptive, so too have contract specifications. The A/E does not have incentives to innovate or create less prescriptive project specifications which might allow contractors to innovate. Historically, project specifications have needed to be prescriptive to ensure that contractors, who have less technical knowledge, can complete the job properly. However, now that the industry has matured, the knowledge gap between the A/E and the contractor is less pronounced and prescriptive specifications are less important and can actually create a barrier to innovation and more sustainable concrete construction (Obla 2007).

2.2.4 Performance-Based Standards

In the last 20 years a movement to transform industry reliance on prescriptive documents to performance-based industry standards, project specifications, and guidance documents reflects industry producers' (concrete and cement producers') desire to deconstruct the institutional layering created by prescription and gain control of their production processes and provide optimized concrete products. The National Ready Mixed Concrete Association (NRMCA) is leading the initiative to move the industry toward "performance-based" specifications that do not prescribe materials or methods, but specify the intended physical and functional character of the concrete. Knowledgeable ready-mixed concrete producers can now design high quality and optimized concrete that is compliant with industry standards without having the materials and proportions of that mix explicitly prescribed. While industry standards prescribe the materials that should be used, contract specifications frequently prescribe the amount of such materials that should be used in the job (i.e. concrete mix design). As stated earlier, most project specifications require a minimum requirement of cement to be used per unit of concrete. Experiential data show that given compressive strength requirements and w/c ratio, a minimum cement content is an easy prescription to ensure that the desired strength requirements are met. However, a knowledgeable concrete producer can design a mix with optimal proportions that will easily meet desired strength requirements, but also provide reduced material impact (environmental impact per liter of material) and better long-term performance and reduced material impact. Concrete material impact is defined as the environmental impact per liter of material.

Therefore, the movement away from prescription also reflects a movement toward optimizing concrete proportions, which simply enables efficient material usage. Prescriptive specification, particularly in project specifications, has led to proportioning concrete with excess cement content that might meet short-term strength performance metrics, but have not demonstrated long-term durability performance. Mix optimization as discussed in this study, refers to reducing cement content; designing concrete for strength and durability rather than rapid construction. Over the years, concrete has been optimized for high early strength by increasing cement content. This study will demonstrate the benefits of optimizing for durability.

Industry trends reflecting the desire for concrete optimized for durability is embodied in recent pressures for “high performance” concrete (HPC) (Lamond 2007). The industry has developed this idea of HPC as mix designs optimized for durability. HPC can mean many things, but generally denotes concrete designed with specific attributes for specific functions. Originally, HPC mix designs specified for very high compressive strength with the intention of optimizing for durability. Extremely high compressive strength and subsequent improvements in permeability have been thought to enhance durability. However, field data indicate that extraordinarily high compressive strength does not necessarily yield durable concrete (Mehta 57). Alternative definitions and methods of optimization, focusing on metrics other than compressive strength, are emerging to demonstrate that optimizing the entire mix rather than focusing on w/c ratio and compressive strength can produce high quality and durable concrete. William Phelan, Euclid Chemical, refers to HPC as an optimally proportioned, “lean,” “athletic” concrete mix based on optimizing aggregate gradation and low water content. Athletic concrete is founded on a robust frame of well-graded aggregate, high quality paste with low mortar and water content, proportioned to achieve an appropriate w/c ratio, while providing two-tiered high performance: proper workability/plastic properties and hardened properties focusing on durability (Phelan 2004). Phelan’s outlook on HPC and mix optimization, whereby optimization is achieved with all components rather individual or sets of components, is emerging throughout concrete industry sectors.

The fundamental goal of performance specifications is to create flexibility for optimizing mix designs, deconstructing some of the institutional and technological layers created over the years by prescriptive standards for individual concrete constituents. Concrete users have become set in their ways, using standards that ensure reliable outcomes. The transition to performance specifications might be very logical to an industry outsider, but in actuality it will require a tremendous transformation in the concrete industry. A transition to performance oriented standards will require A/Es to relinquish control of the material used in construction, allowing the contractor to choose specific materials, but also require an entirely new language by which to discuss standardization (Dick Wing 2006).

2.3 Impact of Standardization on Innovation

The industry made several trade-offs in deliberately transforming a natural resource based product into a commodity using consensus industry standards. As argued above, by homogenizing cement products the industry was able to expand its market, but producers relinquished control of their products to consensus organizations ASTM, ACI, and AASHTO. These organizations are comprised of members from government, academia, and various sectors of the concrete industry representing disparate interests. Not only does making products homogenous create disincentives for innovation, but so too does the arduous consensus process. The conservative technocratic culture represented in the contracting process also inhibits innovation. A/Es have come to rely so heavily on industry standards to protect themselves against liability that changing standardization theory from prescription to performance, let alone the standards themselves, is a monumental task. Prescriptive industry standards and project specifications have “locked-in” the status quo, because the demand side of the industry has little incentive to innovate. Lastly, geographic variability of materials and agent-based fragmentation makes establishing, changing, and disseminating standards very difficult. Regional producers stake their interests in assuring that standards do not exclude their products and then disseminating industry state of the art to those disparate regional engineers, producers, and contractors to the point where they feel comfortable with new practices takes many years.

2.3.1 Consensus Process

In addition to stimulating demand for a particular product by expanding the market, standard specifications stimulate supply by allowing new producers to enter the market and supply specified products. Thus, standards are frequently used as marketing tools. In the same way that the cement industry used standards to reach new markets in the early 1900s, individual concrete products producers seek to develop standards so that their innovations might reach new markets. Again, individual producers face the same dilemma that the industry faced in 1904. Establishing a standard for an innovative product or practice, jeopardizes competitive advantage because establishing a standard requires a certain amount of information sharing. However, in the concrete industry, marketing a product without a standard specification is nearly impossible due to the culture of an industry founded upon technical standards.

The standardization process, however, is extremely time consuming due to the conservative nature of the participating organizations and their members. ASTM, ACI, AASHTO and other industry organizations are consensus organizations that require committees composed evenly of producers, service providers, contractors, academics, government and various other interests. When casting ballots for new specifications or amendments to existing specifications committees must meet minimum levels of approval. With representation from such disparate interests gaining committee consensus is very difficult. In ASTM for example, developing a new standard will typically require five to ten years. Standards are developed through extensive testing, drafting, and revision processes to create a reliable contract between producers and consumers.

While standards expedite the distribution of existing products, this arduous process can be slow for producers with a product ready for the market. The industry members charged with crafting material specifications in the concrete industry are essentially responsible for public safety related to new products and technology. The industry has been able to avoid government regulation related to public safety, by establishing standards under rigorous testing and scrutiny. Therefore, the standards development process is necessarily slow and conservative and was designed such that the process would exclude products that do not stand the test of time. The consequences of expedience at the cost of rigor can be significant. It is the inherent conservatism in the standards development process that causes standardization to lag 5-10 years behind innovation. After an innovative technology, product, or practice begins to emerge in the marketplace, organizations like ASTM, ACI, or AASHTO take it upon themselves to evaluate the new system and make sure that it is viable and safe before it is widely used.

Theoretically, the standards process is designed to promote innovation by helping distribute knowledge throughout the fragmented industry, but industry competition and conservatism can actually have the opposite effect. The standardization process can take so long that companies miss their opportunity to innovate, cannot support the business throughout the process, or lose inertia and move-on. In most cases, non-viable innovations are weeded out with time and scrutiny and real improvements are supported by their specification in the market. In rare cases, this is caused by competing industry participants and factions deliberately inhibit innovation for personal or corporate gain.

Concrete customers are also very conservative; comfortable with the products they use and hesitant to use new products which may create new risks, even if they have been specified. It is this market “push-pull” dynamic for which the ACI’s Strategic Development Council (SDC) created the Accelerating Technology Acceptance (ATA) Project. The SDC-ATA is an institution designed to guide industry critical innovations through the standardization process, smoothing the obstacles created by these market forces and failures. The overarching goal of ATA is ensuring that concrete remain the material of choice throughout the building industry. ATA is paradoxical in that to ensure that concrete is the building material of choice, it is designed to circumvent the process that made concrete the material of choice in the first place. Implicit in the emergence of the ATA is that the system has broken down. Innovators appreciate peer review, which helps avoid pitfalls of short-cuts, but the lengthy time until the product reaches the market may cost the innovation itself.

The consensus system also has many long-term impacts on the industry. Because the process is so arduous, meticulous, and thorough with respect to verification and certification, ASTM and ACI guidance institutionalizes particular materials and practices. As soon as an innovation or method is institutionalized and customers become comfortable with it, which is what manufacturers want, it is very difficult to displace. One can make the case that an entire market for a material or service revolves around a specification.

As discussed earlier, a new specification provides a framework or contract by which producers and consumers can exchange goods and services. If this contract has been successful, producers and consumers will resist change, as change introduces a new element of risk. The contract itself supports the interests of each party involved in a transaction. Changing the contract is extraordinarily difficult because interested parties have made capital investments to support transactions executed according to each specification. Therefore, standards create institutional layers within an industry or market that are locked-in by capital investment. So, industry standards are designed to over come barriers to innovation related to industry fragmentation and conservatism.

However, over the long-term they create institutional layering and technological lock-in, and might be an even larger barrier to innovation than fragmentation and conservatism.

Evidenced by the existence of the SDC-ATA the consensus process has created stagnant committees. Just as individual specifications are difficult to change, so too is the structure and culture of the organizations that write them. Clearly, new institutions are required to stimulate innovation within the concrete industry. The SDC has already designed an organizational remedy for ACI, producers within the industry are also striving to change the nature of individual specifications to allow greater flexibility in production and provide incentives for innovation.

2.3.2 Industry Fragmentation

Although industry-wide cement standards were designed to create product homogeneity and widespread quality assurance, cement inherently reflects local and regional differences in geologic material; maintaining a certain level of product differentiation. The goal of the standard was to create homogenous product and consequently eliminate brand reputation, but local and regional geologic characteristics have always made eradicating product differentiation impossible. Regional differentiation is less pronounced with portland cement than natural cement and pozzolans (Prentice 2006), but regional material characteristics have defined the industry beginning with the earliest mortars. The most pronounced case of product differentiation from antiquity comes from the reputation for durability of Roman mortars from one region in particular, "The best mortar appears to have been made of lime mixed with a volcanic rock or sand called puzzolona, named after the place where it was first found-Pouzzol, near Vesuvious. This sand contains an aluminum silicate from which the silica is readily liberated by the caustic alkalies, such as calcium hydroxide, and which combines with the lime to form a hard cementing material, and one that will harden under water (Draffin 1942)."

Local and regional differences in concrete materials persist in differentiating concrete more so than cement. The nature of concrete aggregates creates more variability and uncertainty in the concrete mix than any other constituent mainly because there is little that producers can do to control the chemical composition of natural rock. The chemical characteristics of both course and fine aggregates impact the nature of the curing reaction and can either assure or destroy concrete quality. The silica composition of the aggregate surface can react with alkaline cement, resulting in Alkali-Silica Reaction (ASR), which forms a gel layer with an affinity for water on the surface of the aggregate potentially leading to a volume change significant enough to crack the paste matrix and expedite deterioration. Similarly, the regional geologic variability of coal leads to variability in coal fly ash additions to concrete. The chemical composition of fly ash can also lead to undesired reactions that lead to premature deterioration. Both cases demonstrate impacts of geographic material fragmentation on innovation.

Geographic differences are the only means of material differentiation; contemporary concrete producers continue to differentiate their products based on regional variation, particularly in the face of specifications that marginalize product source or regional producer. For example, the 1942 version of C150 reflects a Magnesium-Oxide (MgO) limitation of 2%, while the current version limits MgO at 6%. The old standard set MgO limits low to guard against unsoundness, however, the old specification excluded a prominent producer that registered closer to 4% MgO in its limestone deposit. This single producer was able to demonstrate soundness in their product and lobby the committee to elevate the MgO limitation to 6%, strictly based on the local uniqueness of their product. In this way, geographic product differentiation can have significant affects on the industry standardization process.

Agent-based fragmentation also plays a significant role in the concrete market. Not only are there many interests involved in specification development, but the industry is comprised of many disparate stakeholders in practice. Producers and users of concrete and concrete products are widely distributed geographically, but there are also many different parties handling different aspects of the process: mining, manufacturing, processing, research and development, sales, distribution, project design and specification, mixing, and construction. Salesmen have different interests than buyers; project engineers have interests separate from contractors; research and development/testing laboratories have interests divergent from the sales force. Therefore, geographic information distribution is not the only hurdle to innovation, but industry participants have divergent interests in product development, sales, and procurement.

Barriers to innovation lie in making the divergent stakeholders across a vastly diverse region (the United States) aware of the state of the art and new specification. These are precisely the intended functions of ASTM and particularly ACI. Even if new information is effectively dispersed, the culture of the industry is very conservative and potential users are unlikely to try something new if the current system is reliable.

2.4 Standards Impact on Sustainability

The discussion of sustainability in the concrete industry inevitably begins with cement. Cement production is energy intensive and produces an enormous amount of

CO_2; approximately one pound CO_2 for every pound of cement. The case herein is that the commodification of cement and the development of a conservative, reductionist culture created by industry standardization have led to concrete construction optimized for rapid construction rather than durability. Prescriptive industry standards and project specifications developed under this paradigm have institutionalized inefficient cement usage and material intense concrete with high material impacts. Performance based standards allow producers the flexibility to meet concrete performance requirements with various combinations of materials and techniques for concrete design and placement. Under performance specifications, producers can use materials with lower energy intensity and that lead to greater durability.

As discussed earlier, prescriptive project specifications require minimum cement content to assure minimum specified compressive strength. However, minimum cement contents are much higher than what is actually needed. A/Es specify excessively high cement content to make sure strength is met quickly. In fact, a large percentage of cement in concrete is never hydrated. Paul Tennis, Portland Cement Association, estimates that in high early strength concrete, 20% of the cement is never hydrated because the rapid reaction actually inhibits cement distribution throughout the matrix. High early strength concrete actually ends up weaker than normal concrete in the long-run because it does not allow the curing process to fully hydrate all of the cement. So, prevalent project specifications inhibit optimal cement usage.

Cement producers are under pressure to reduce CO_2 emissions from the cement manufacturing process, but less emphasis has been placed on the demand side of the cement industry. Cement producers have been working for 20 years to institutionalize performance-based standards which allow them to properly design and produce cement materials. Ready-mixed concrete plants seek performance based specifications in their contracting process in order to protect their intellectual property and competitive advantage with respect to mix design (Joe Lamond 2007). While cement producers are certainly under more environmental pressure as the specter of global warming becomes real, they are ultimately motivated by financial returns. Ready-mix and cement producers are driven by financial and competitive forces and while the environmental benefits of mix optimization are enormous, they remain ancillary benefits in the consciousness of the industry.

The industry is well aware of societal sustainability initiatives and their role inreducing environmental impacts. The ASTM Committee on Research has recently begun investigating the need for committee work related to sustainability. ACI has established a Committee on Sustainability and actually reached out to develop a cooperative partnership with the United States Green Building Institute (USGBC) in 2004 (Holland 2006). Sustainability initiatives developed by users are focused on durability performance. Most programs, the Federal Highway Administration’s “Highways for LIFE” for example, foster long-term performance through innovation. Corporate sustainability initiatives generally emphasize improving production efficiency rather than reducing material consumption through product optimization.

However, due the nature of cement and concrete, economic and environmental concerns are closely aligned. Concrete users, producers, and cement manufacturers seek to reduce costs through durability, material and energy consumption, and efficiency. These financial benefits will naturally manifest improved environmental performance.

Cement, for example, is the most expensive and most environmentally damaging constituent of concrete. Optimizing mix design to reduce cement consumption necessarily reduces cost and improves environmental performance of the fresh mix. However, in evaluating sustainability indicators of concrete, long-term performance must also be considered. The long-term performance concrete optimized for durability is thought to be better than that of conventional mixes, but few empirical data points exist. The objective of this research is to provide supporting data for the value of institutionalizing performance-based specifications using sustainability metrics. Reducing costs through mix optimization is well understood, but evaluating the benefits of mix optimization using sustainability metrics is only intuited through reduced cement. Environmental benefits of optimizing for durability have not yet been demonstrated.

Literature review and historical concrete industry research indicate that, for a variety of reasons, concrete mix design and construction has become optimized for rapid construction. The concrete industry has actively organized itself around industry standards, which play a pivotal role in institutionalizing industry culture, behavior, and practice. Further technical evaluation the body of concrete industry standards and identify specific institutions and standards that present barriers to innovation and subsequent transformation to sustainable concrete practice.

3 Methodology

The objective of this research is to test the thesis that concrete industry standards inhibit sustainable concrete construction and innovation. The method by which the thesis was tested was a two-step process. 1) Social network analysis tools have been applied to the body of United States concrete industry standards related to concrete bridge deck construction to identify the most centrally referenced standards. 2) Networking the body of standards in search of the most prominent standards provided a framework for case study analysis of individual standards and insight into the nature of the standards themselves. Network results generated a ranking based on the number of times a standard is referenced or referenced by other standards. Using network results as a guide, case studies demonstrate how a standard might inhibit innovation and sustainable practice based on the evolution of the standard and current committee culture, and how that standard inhibits more sustainable concrete practice from an life environmental impact perspective.

4 Networking Concrete Industry Standards

Social network theory has been applied to concrete industry standards referenced in concrete bridge construction in order to logically evaluate the most prominent standards and identify leverage points where principles of sustainability may be incorporated. Networking the landscape of concrete standards is an important first step toward sorting and understanding their relationships to each other and identifying the most central or prominent standards, which might affect sustainable concrete construction.

4.1 Networking Methodology

Each industry standard and reference document contains a list of “Referenced Documents,” that support the intention of the document, assuring that new products and methods are produced or tested in a uniform manner. For each industry standard or guidance document included in the study, each reference to an industry standard or guidance document was recorded in a square, binary matrix as demonstrated in Figure 4. This matrix was constructed using ASTM data set developed for this study. The standard designations head both the columns and the rows and their references to each other are indicated a “1” in the matrix. Figure 4 shows that ASTM C 94 references ASTM C 33, but not C 91 or itself.

	33	**91**	**94**
33	0	0	0
91	0	0	0
94	1	0	0

Figure 4. Sample Dataset

The matrices were processed using software tools recommended by University of Michigan Business and Sociology faculty: UCINET 6.135 and NETDRAW 2.41 (Borgatti, Everett, and Freeman 2002).

4.1.1 Network Boundaries

The network boundaries have been defined on two conceptual levels: application and network. The application boundaries define a specific application: concrete bridge construction. The network boundaries define the network(s) of industry standards and guidance documents related to concrete bridge deck construction.

Application Boundaries

The application boundaries are defined within the umbrella of ***concrete infrastructure***, primarily focusing on ***bridges and roadways*** rather than Building and Mass Concrete infrastructure standards. Clearly, each classification of concrete infrastructure will reference many of the same standards, but this methodology is focused on the standards related to ***concrete bridges*** in particular.

Network Boundaries

Network boundaries define which specific bridge related standards are evaluated and how each binary matrix (data set) is constructed. Six data sets were constructed based on the AASHTO LRFD (Load and Resistance Factor Design) Bridge Design and Construction Specifications, to remain consistent with application boundaries. AASHTO LRFD specifications are the prominent set of standard specifications for concrete bridge construction. As discussed in section 1.2 “Terminology,” standard specifications are generic project specifications. Each dataset was then built from the industry standards and guidance documents referenced by the AASHTO LRFD standard specifications:

AASHTO’s Standard Specifications for Transportation Materials and Methods of Sampling and Testing (AASHTO standards), ASTM Standard Specifications for Concrete and Concrete Aggregates and Standard Specifications for Cement (ASTM standards), and the ACI Manual of Concrete Practice (ACI Guidance). The scope of the project was confined to the United States concrete industry in order to focus on this new methodology before expanding to include international standards. ASTM and ACI are the most prominent standards writing organizations in the United States and AASHTO specifications are generally based on ASTM and ACI, with occasional modifications.

Figure 5 reflects the application and network boundaries of the analysis. The application illustrates that codes related to bridge decks were evaluated (purple) and roadways were excluded (red). The AASHTO standard specifications served as a guide in defining the boundaries related to which bodies of specifications to evaluate and then how to define the boundaries within each dataset.

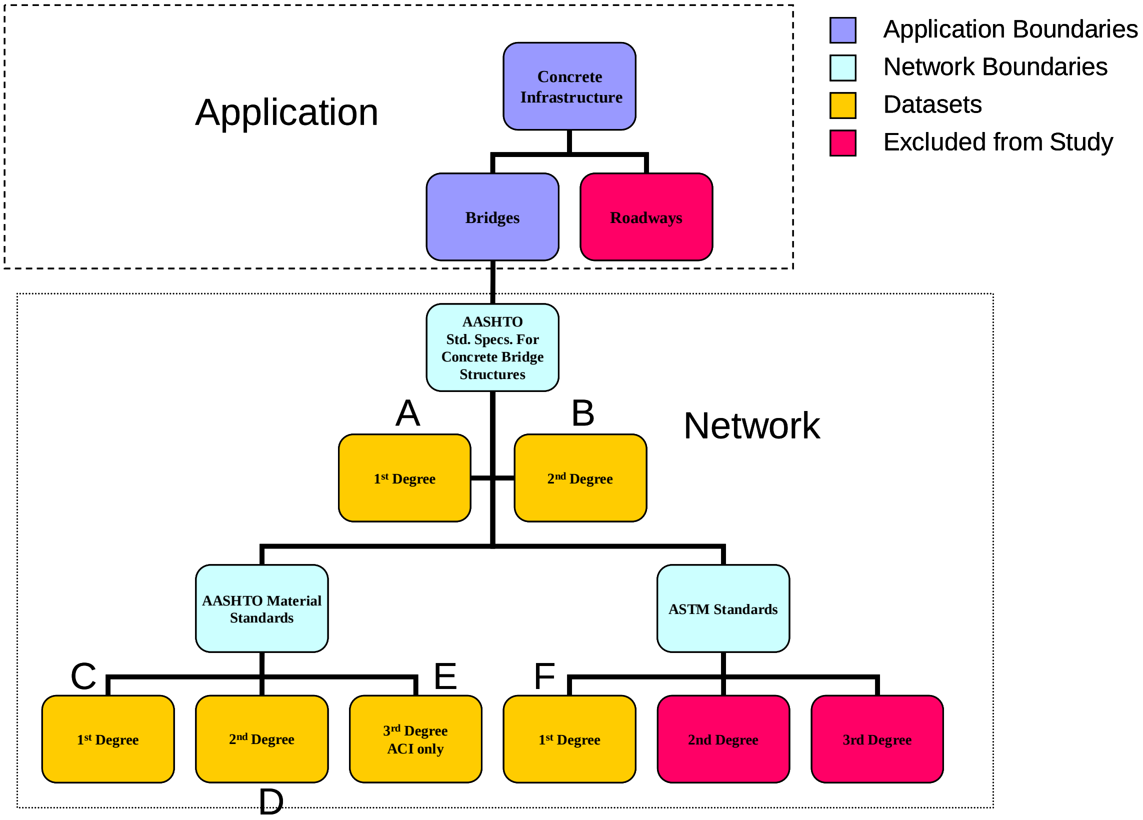

Figure 5. Network Boundaries

Degrees of Separation

Degrees of separation in this project represent the ties from one specification to a second specification and then the second specification to a third. The first tie or relationship is considered to be the first degree and the second tie is considered to be the second degree. For example, ASTM C33 references C150, representing a first-degree connection. C150 then references C219, representing the second-degree connection.

Each data set only represents one degree of separation, meaning that first and second connections were evaluated separately. Initially it appeared logical to build a large network inclusive of each body of standards and each layer of references to each other, but in small networks like these, where there is heavy cross-referencing between standards, it is important keep each degree of separation or level of connection separate

(Mizruchi 2006). Otherwise, the networks might become circular, which dilutes their meaning. For example, ASTM C33 references C150, which in turn references C33. As circular references build on each other among datasets the network risks becoming distorted for certain specifications.

Datasets/Networks

The terms “dataset” and “network” can be used interchangeably here. Each dataset constitutes one network with one degree of separation. For example, the AASHTO standards specifications dataset constitutes their first degree network.

AASHTO Standard Specifications

Two datasets were derived from the AASHTO LRFD Bridge Design and Construction Specifications represented by boxes A and B in Figure 5. References within the standard design specifications were extracted from AASHTO LRFD Bridge Design Specifications Section 5: Concrete Structures and the references within the standard Construction specifications were extracted from AASHTO LRFD Bridge Construction Specifications Section 8: Concrete Structures. Although the Design and Construction specifications are separate documents, they were treated as a single set of specifications and the references within them to AASHTO standards, ASTM standards, and ACI guidance were recorded in two binary matrices.

AASHTO Standards

First-degree references were derived from the M-class specifications relating to Aggregates and Concrete, Curing Materials, and Admixtures. The “M” designations specify only materials as opposed to test methods. The analysis focuses only on material standards under the assumption that test methods are unbiased toward test subjects and should not hinder the introduction of new materials as long as they meet testing requirements. Both the first and second degrees of reference from AASHTO material standards were recorded in two separate binary matrices.

The first degree AASHTO M-class network references (Figure 5-Box C) ASTM and ACI documents relatively evenly, while the majority of second degree references (Figure 5- Box D) are to ACI guidance documents. In fact, the third degree network for AASHTO specifications was dominated by ACI documents. Observing the trend that ACI guidance is generally referenced more heavily in second and third degree networks, AASHTO and ASTM specifications were removed from the AASHTO third degree network to avoid circular references and create an ACI network that is related specifically to bridges.

ACI Guidance Documents

ACI guidance was not networked independently (Figure 5- Box E) from AASHTO standard specifications, AASHTO specifications, or ASTM specifications. The majority of ACI guidance documents specific to concrete bridges were captured in the AASHTO specification third degree network. Networking the entire body of ACI guidance would have proved interesting, but would not generate results consistent within the application boundaries of the analysis.

ACI documents dominate the higher degrees (2nd, 3rd, 4th) of both AASHTO and ASTM networks. Third degree AASHTO and ASTM networks are heavily dominated by ACI documents that become less specific to bridges and begin including specialty specifications that fall outside the scope of this project. For example, third degree networks include guidance on farm silo and nuclear facility construction, which fall outside of the application boundaries of the network.

ASTM Standards

ASTM material specifications were networked independently in addition to their inclusion in the AASHTO standard specifications and AASHTO material standards networks. ASTM first degree specifications (Figure 5- Box F) were networked and included in this analysis even though they fall outside the logical definition of AASHTO bridge specifications, because the ASTM material specifications are heavily referenced within AASHTO and generally applicable to all concrete construction. Furthermore, including the first degree ASTM network also provides a larger sample size from which to evaluate this method. Second and third degree ASTM networks were excluded as they include many ASTM and ACI specifications that fall outside of the application boundaries of this study.

4.1.2 Compiling Network Data

Network data were processed to distill the most central concrete specifications based on the number of times the specification was referenced within each dataset/network (In-degree centrality). The results for all six networks were combined to determine the most central standards across networks related to concrete bridges. An ordinal list based on In-degree centrality for each dataset along with a visual representation of each network is represented in Table 1 and Figure 6, respectively.

Table 1. In-Degree Output for 1st Degree AASHTO Code

Designation	Description	#	% of Total
ACI 318	Building Code	12	12.3711%
ACI 201.2	Guide to Durable Concrete	9	9.2784%
ACI 211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	8	8.2474%
ACI 207.1	Mass Concrete	7	7.2165%
ACI 207.2	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete	6	6.1856%
ACI 306	Cold Weather Concreting	6	6.1856%
ACI305	Hot Weather Concreting	5	5.1546%
ASTM 150/M 85	Portland Cement	4	4.1237%
ASTM E 92	Wire Seive	4	4.1237%
ACI 209	Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures	4	4.1237%
ACI 211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	4	4.1237%
AASHTO M43	Size of Aggregate for Road and Bridge Construction	3	3.0928%
ACI 222	Corrosion of Metals in Concrete	3	3.0928%
ASTM 845	Standard Specification for Expansive Hydraulic Cement	3	3.0928%
AASHTO M6	Fine Aggregate for Portland Cement Concrete	2	2.0619%
AASHTO M80	Course Aggregate for Portland Cement Concrete	2	2.0619%
AASHTO M154	Air Entraining Admixtures	2	2.0619%
ACI 213	Guide to Structural Light Weight Aggregate	2	2.0619%
ASTM 309/M148	Liquid Membrane Forming Compounds for Curing Concrete	1	1.0309%
ASTM 171/M171	Sheet Materials for Curing Concrete (AASHTO)	1	1.0309%
ASTM 494/M194	Chemical Admixtures	1	1.0309%
ASTM 330/M195	Light Weight Aggregates for Structural Concrete	1	1.0309%
ASTM 595/M240	Blended Hydraulic Cement	1	1.0309%
ASTM 618/M295	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	1	1.0309%
ACI 343	Analysis and Design of Reinforced Concrete Bridge Structures	1	1.0309%
ACI 350	Environmental Engineering Concrete Structures	1	1.0309%
ACI 439.3	Mechanical Connections of Reinforcing Bars	1	1.0309%
ABCS	AASHTO Bridge Construction Specifications	1	1.0309%
ABDS	AASHTO Bridge Design Specifications	1	1.0309%
	Sum	**97**	100.00%

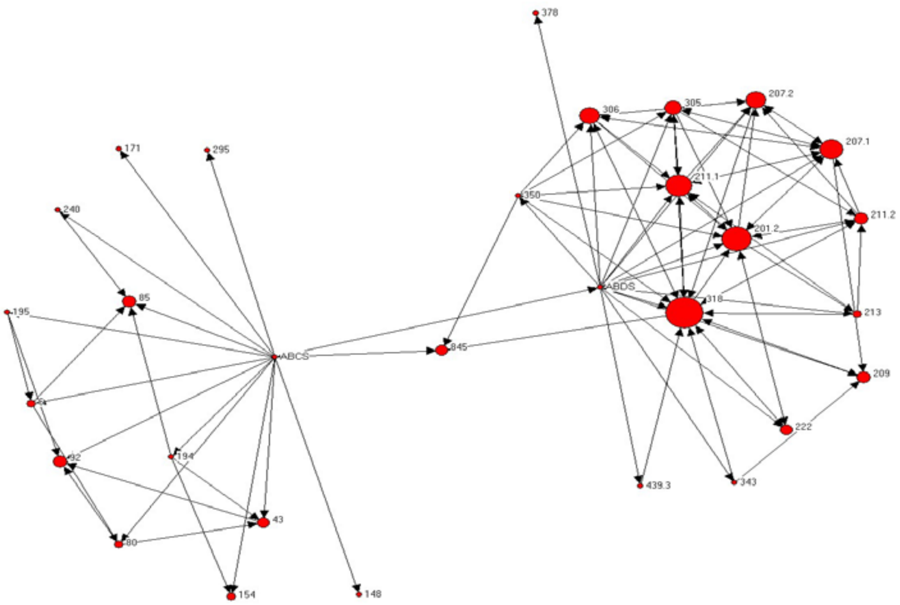

Figure 6. Graphic Representation of 1st Degree AASHTO Standard Specifications

Figure 6 illustrates the references emanating from the AASHTO Bridge Construction (ABCS) and Design (ABDS) Specifications demonstrating that ACI 318 Building Code is the most central standard in the network, based in the number of times it is referenced.

Specifications were ranked in terms of In-degree centrality by aggregating the number of in-degree references for each specification in each network (Table 1) and then dividing the number of references for each specification by the total number of references in all six networks. The result is the total percentage that each standard is referenced with respect to all six networks. Aggregating the results in this way effectively shows results as if it were one network for concrete bridge construction rather than six separate networks. Table 2 provides an example of how the data were compiled and ranked for ASTM C 33 Standard Specification for Aggregates.

Table 2. Sample Aggregation of In-Degree References for ASTM C33

ASTM C 33- Standard Specification for Concrete Aggregates

AASHTO Standard Specifications- 1st Degree	0
AASHTO Standard Specifications- 2nd Degree	15
AASHTO Standards- 1st Degree	10
AASHTO Standards- 2nd Degree	24
AASHTO Standards- 3rd Degree	0
ASTM Specifications- 1st Degree	25
SUM	**74**
Total # of References- All Networks	2255
ASTM C 33 as % of Total	**3.2816%**

4.2 Results

Results and network diagrams for each dataset are included in Appendix A along with the 65 most frequently referenced specifications by In-degree centrality. The 10 most heavily referenced specifications are ordered in Table 3 below. The 10 most referenced standards account for 32% of all the references in the network. The expanded list in Appendix A shows 83% of the network references.

Table 3. Aggregated Results for the 10 Most Referenced Documents

Designation	Description	% of total references
ACI 318	ACI Building Code for Structural Concrete	0.04618
ASTM C150/M85	Standard Specification for Portland Cement	0.04396
ACI 211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	0.03996
ASTM 33	Standard Specification for Concrete Aggregates	0.03286
ASTM C595/M240	Standard Specification for Blended Hydraulic Cements	0.03197
ACI 306	Guidance for Cold Weather Concreting	0.02842
ACI 305	Guidance for Hot Weather Concreting	0.02576
ASTM C494/M194	Standard Specification for Chemical Admixtures	0.02576
ACI 308	Standard Practice for Curing Concrete	0.02442
ACI 116	ACI Terminology	0.02267
	SUM	**0.32196**

4.3 Discussion

Defining boundaries in these networks is difficult because there is not a discrete hierarchy within the networks of specifications. In networking actors in an organization, there is typically a table of organization that provides an initial framework for understanding centrality and power in the network. The challenge in networking such organizations lies in detecting power in the relationships between actors. Centrality can be inferred by an organizational chart, but power is more difficult to define based on the ties among actors. It can be determined by the number of connections or by more dynamic factors like information flow.

Determining centrality and power within an inanimate network like this is simpler. Like an organized hierarchy, it is easy to characterize centrality by connection, but unlike a dynamic network, the static nature of the connections, where no one connection is stronger than another, connotes that power is more evenly distributed.

Can this method be used to determine if a particular standard is a powerful leverage point? Social network analysis was employed to determine its efficacy in identifying institutional barriers and leverage points within the industry, creating a framework for evaluating specific standards. Case study analysis for sustainability metrics related to the most frequently referenced standards will provide insight into whether the social networking method is valid or not (discussed in Section 7).

The network results show that other than ACI 318, ASTM C 150 “Standard Specification for Portland Cement” was most frequently referenced accounting for 4.3% of the references across all networks. ACI 211.1 “Standard Practice for Proportioning Normal, Mass, and Heavyweight Concrete” is the second most heavily referenced document related to concrete bridge construction accounting for 3.9% of the total references in the network. These data are used to inform case study in selection of these two standards to support the propositions that industry standards have actually evolved to inhibit innovation and sustainable practice.

5 ASTM C 150- Standard Specification for Portland Cement

Using network results to inform case study analysis on the impact of industry standards on sustainable practice and innovation, ASTM C 150 is evaluated here to determine if the standard itself inhibits sustainable practice and innovation.

In essence C 150 is the oldest industry standard related to concrete material and practice. ASTM C-1 Standard Specifications for Cement, established in 1904, consolidated disparate organizational and user defined specifications in an effort to streamline the contracting and construction processes and expand the market for cement products. C-1 evolved as ASTM defined and specified five different types of cement in 1941. Rather than a singular cement specification, C-1 Specification for Natural and Portland Cement ASTM developed several, making ASTM C 150 the most central cement specification. The original hypothesis of this study was that the chemical and physical requirements of C 150 play a role in inhibiting sustainable practice and innovation. But this case study has found otherwise. C 150's chemical and physical prescriptions simply establish baseline characteristics required to ensure minimum levels of uniformity, soundness, and performance of cement material. Its impacts on sustainability and innovation arise from the use of the standard in practice. It is the institutional demand for high early strength concrete and customer's unwillingness to use standards by which cement producers could produce cements with better physical and environmental performance.

High early strength in concrete is achieved by several mechanisms, two of which are directly related to Tricalcium Silicate (C_3S) to Dicalcium Silicate (C_2S) ratio (C_3S/C_2S) and fineness of cement material. The ratio between C_3S and C_2S in cement is important in determining its properties, as C_3S provides a substantial contribution to strength at early age while C_2S contributes to strength much more slowly (UK Concrete Society). Increasing C_3S concentration allows concrete to gain strength more rapidly. Alternatively, grinding cement into fine particles increases the surface area on which hydration reactions may occur. Increased fineness allows an elevated reaction rate meaning the concrete sets and gains strength more quickly with a finer cement.

In both cases, C_3S concentration and fineness, the accelerated chemical reactions generate an elevated heat of hydration, which can lead to early age shrinkage and thermal cracking. Cracking makes concrete more susceptible to chloride ion penetration and expedites corrosion, which is the major source of failure for reinforced concrete. While this type of cracking is not guaranteed to occur, and high early strength concrete can be engineered to minimize cracking, construction quality and other factors play a role in crack avoidance. High heat of hydration associated with rapid strength gain only increases the likelihood of early age cracking.

However, ASTM C 150 does not require high early strength. It specifies minimum strength to maintain adequate levels of quality and safety. Drivers for high early strength, $C_3S:C_2S$ and fineness, reside in project specifications that demand rapid construction. Producers are capable of manufacturing cement that performs well with a third less clinker by intergrinding limestone and supplementary cementitious materials (Kosmatka 2006). However, cement producers are beholden by their customers to produce cement by C 150. Cement manufacturers have actually established standards for these alternative types of blended cements (C 595 Standard Specification for Blended Hydraulic Cement and C 1157 Performance Based Specification for Hydraulic Cement).

But the market demands portland cement as specified by C 150. Engineers are unwilling to specify these types of blended cements that are less resource intensive. Until 2004, the cement industry had been toiling since 1975 to revise C 150 to include a provision permitting intergrinding up to 5% limestone to displace cement. The modification was met with tremendous opposition, particularly from state DOTs, and is now included as an optional requirement that a customer can request.

The chemical and physical requirements of ASTM C 150 do not necessarily inhibit more sustainable practice, but customer demand for rapid concrete construction using C 150 rather than alternative cementitious materials with less environmental impact pose large barriers to sustainability.

5.1 Chemical Requirements

The chemical requirements of C 150 are straight forward and exist to ensure that cement products maintain a minimum level of quality. C 150 sets very specific requirements for the chemical composition of portland cement. Table 4 illustrates the chemical requirements of Type II portland cement for general when moderate sulfate resistance or moderate heat of hydration is required. Type II cement is the most common cement used in the Unites States (Tennis 2006) and can be considered to be a standard or generic cement.

Table 4. Chemical Requirements of Type II Portland Cement in 2005

Compound	% Composition
Al_2O_3 (maximum)	6.0
Fe_2O_3 (maximum)	6.0
SO_3	3.0
MgO (maximum)	6.0
Loss on Ignition (maximum)	3.0
Insoluble Residue (maximum)	0.75
C_3A (minimum)	8.0

These requirements have remained stable over the last 70 years. The only two chemical requirements that have changed since C 150 was established in its current form, differentiating different types of cement, are those for MgO and SO_3. Therefore, the static nature of C 150's chemical requirements indicates that they are not a constraint for producers as there has been little effort to change the requirements over the years. The requirements exist to maintain a quality and soundness. However, the juxtaposition of the current chemical requirements of C 150 and the trends of actual MgO and SO_3 since the 1950s demonstrates that C 150 really does not constrain cement production.

MgO and SO_3 limits have changed marginally since the original specification was adopted, but these chemical requirements are not indicative of performance relative to sustainability metrics. Absolute MgO limits have increased by 2% (to accommodate a specific producer's mine) and absolute SO_3 limits have increased by a little more than 1% since 1904, because some cements perform better with higher SO_3 content. Actual trends in MgO and SO_3 content reflect that C 150 is flexible with respect to these compounds. Actual MgO concentrations do not even approach half of the specified limit (Figure 7). Conversely, C 150 allows SO_3 to exceed the specified limits based on other cement characteristics (Figure 8). In fact, many cements perform better (relative to strength) with SO_3 concentrations higher than the limits specified in C 150 (Paul Tennis interview).

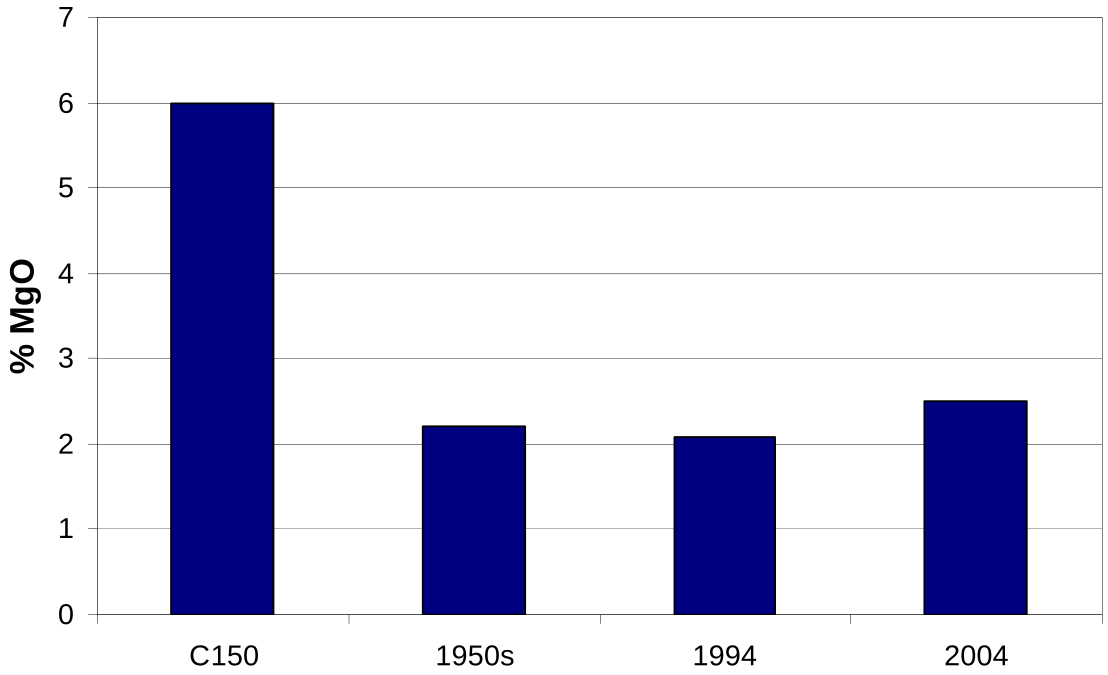

Figure 7. C 150 MgO Limit and Actual Trends

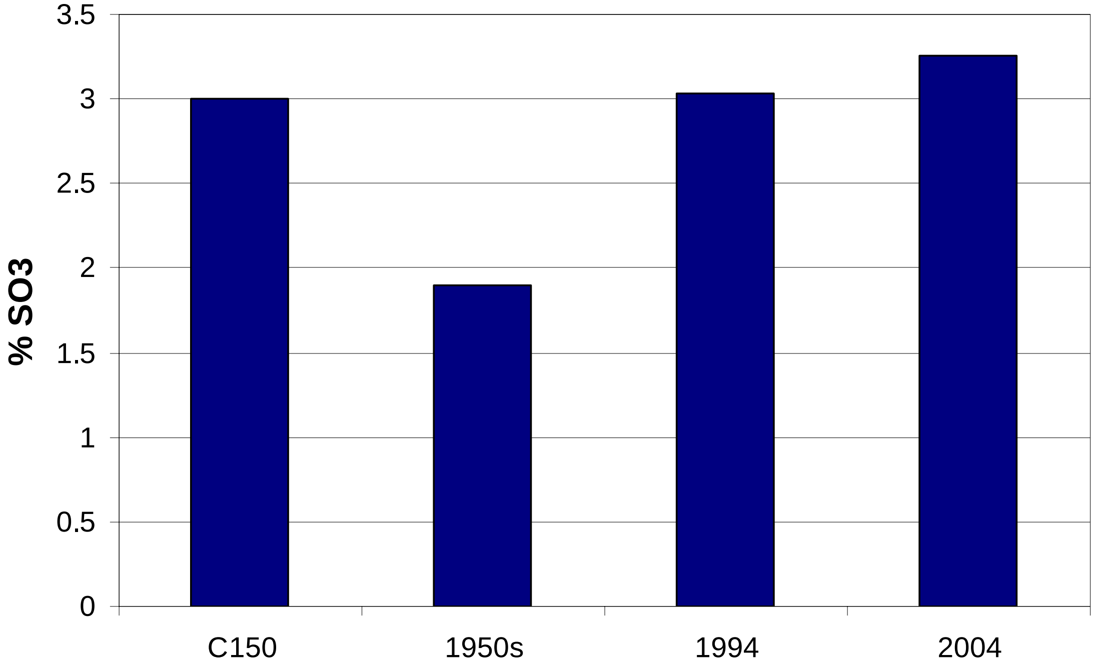

Figure 8. C 150 SO_3 Limits and Actual Trends

The major chemical factor that influences cement performance is C_3S/C_2S ratio as described earlier. C 150 does specify C_3S limits for Type IV Low Heat of Hydration cement, but not others. C_3S concentrations have increased dramatically over time with increased demand for high early strength concrete. C_3S concentrations increased by 28% between 1925 and 1950 (Gonnerman and Lerch 1954) and another 16% since 1950 to at least 56% of the $C_3S:C_2S$ ratio for all types of cement (Tennis 2006). Figure 9 demonstrates that the early age strength component of cement chemistry has increased over time.

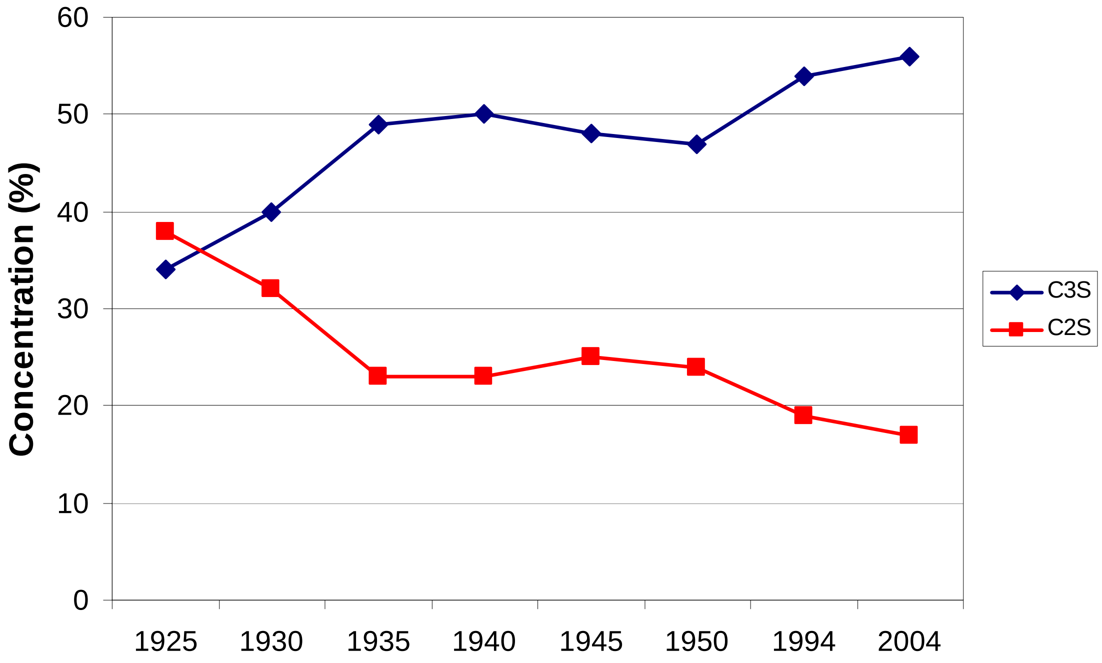

Figure 9. Actual C_3S/C_2S Ratio Over Time

Although this chemistry is not regulated by C 150, its contribution to elevated heat of hydration can lead to shrinkage and thermal cracking, which accelerate corrosion and failure of reinforced concrete.

5.2 Physical Requirements

Trends in the C_3S/C_2S ratio compounded with trends in physical characteristics, fineness and compressive strength, of cement over time are more indicative of concrete practice as it relates to sustainability. The 1941 and 2005 versions of C 150 are very similar except for the notable omission of tensile strength and inclusion of air content in the 2005 standard. The full impacts of air content other than on freeze-thaw durability are still unfolding (Shilstone 2006) and are outside scope of this study. The impacts of fineness and compressive strength are very telling of industry trends and development of more sustainable practice.

Changes in C 150 fineness requirements between 1941 and 2005 are negligible.

Table 4. ASTM C 150 Cement Fineness Requirements Over Time

	1941	2005
Type I	160	160
Type II	170	160
Type III	-	-
Type IV	180	160
Type V	180	160

The 1941 standard required a minimum fineness of 160 m^2/kg for Type I, 170 m^2/kg for Type II, no requirement for Type III, 180 m^2/kg for Type IV and 180 m^2/kg for Type V cements. The 2005 standard requires 160 m^2/kg for all types except Type III, which is high early strength cement and can be as fine as possible to generate high early strength (Table 4). However, actual trends in fineness of cements used in practice do not reflect this constant value over time. 1950 and current fineness data reflect that actual fineness has continually increased across overtime (Figure 10).

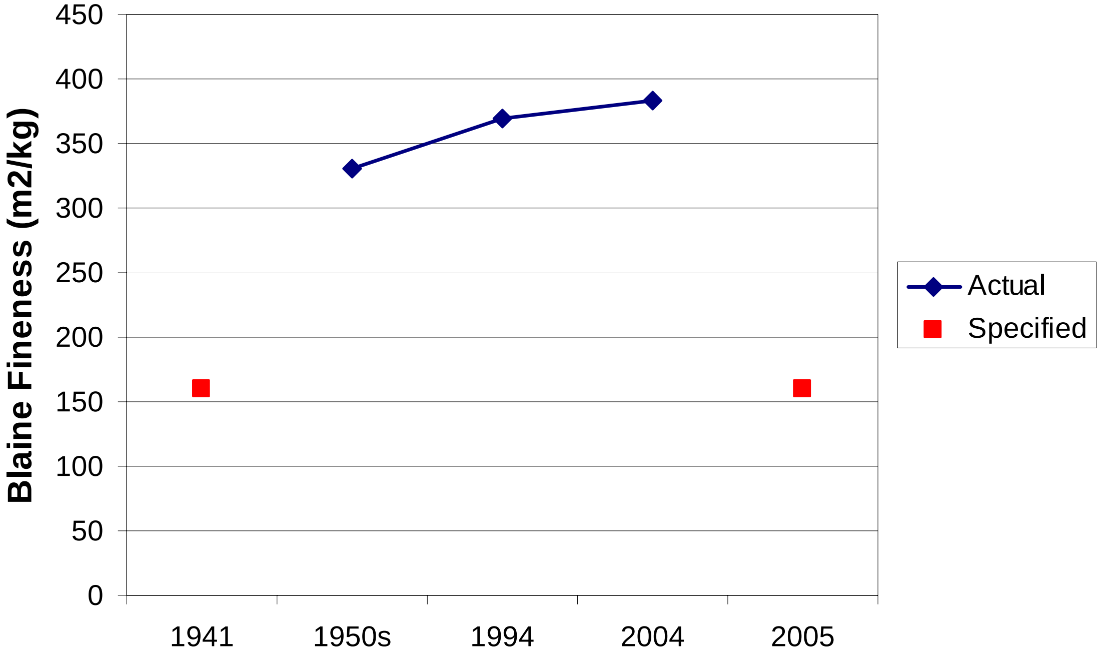

Figure 10. Blaine Fineness Trends relative to C150 Requirements Over Time

Under project and over-all industry demands for rapid concrete placement, cement fineness has continually increased and is far greater than the minimum level specified by C150. Fineness requirements were established to ensure a minimum level of strength gain, and as grinding technology has improved and demand for high early strength concrete has increased, fineness minimums in C 150 have become irrelevant; indicating that the costs of construction delay significantly outweigh the initial costs of finer cement.

Trends in C 150 requirements for early age compressive strength (Figure 11) and actual compressive strength trends (Figure 12) demonstrate that strength demanded by the market exceeds the demands of C 150. Figure 12 illustrates that actual 3-day compressive strengths in 2005 are similar to 28-day compressive strengths around 1930, demonstrating increasing demand for high early strength over time.

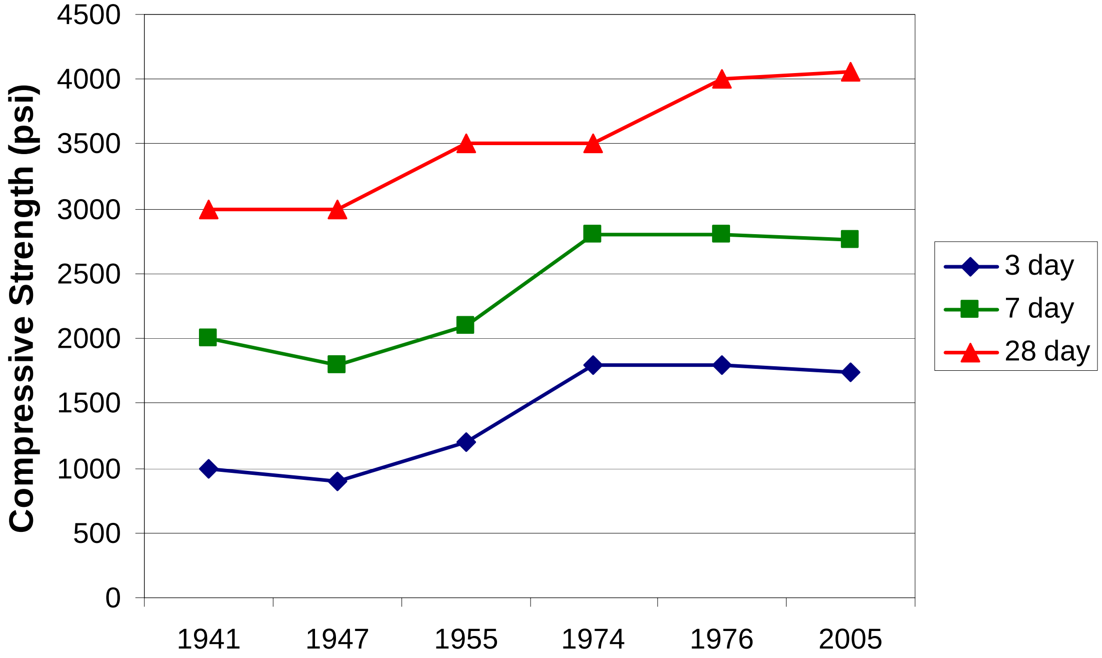

Figure 11. C 150 Compressive Strength Requirements Over Time

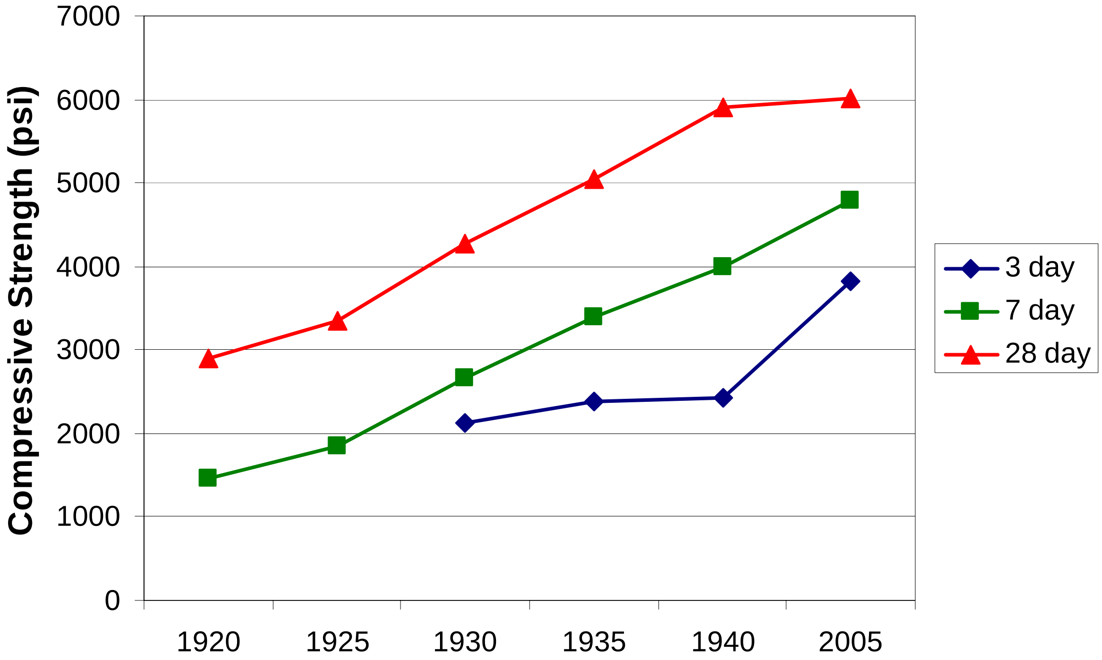

Figure 12. Actual Compressive Strength Trends Over Time

Demand for compressive strength has required increased C_3S/C_2S ratios and fineness, but these demands are not driven by ASTM C 150. Early strength is demanded by project owners and A/Es that develop the project specifications. It is the project specifications that override industry standards that require high early strength and potentially, a less durable product. Time constraints and contract incentives for rapid construction demand cement chemistry and fineness characteristics that lead to potentially less sustainable concrete (Kosmatka 2006). In fact, having observed the deleterious impacts of high early strength in construction projects, AASHTO includes a fineness maximum and is developing a C_3S maximum for its Standard Specification for Portland Cement (M85) (Kosmatka 2006). While project specifications clearly inhibit sustainable practice more so than ASTM C 150, the institutionalized use of C 150 in project specifications significantly curbs the use of alternative and more sustainable cement products discussed in Section 5.1.2.

5.3 Alternative Cement Products

Cement producers are under heavy social and regulatory pressure to reduce the CO_2 emissions associated with manufacturing portland cement. They have been pushing for many years to develop products that reduce the cement clinker content, which is accountable for much of the energy and CO_2 impacts of cement. Clinker is the product of the calcining process, which drives off CO_2 embodied in limestone, and is ground to produce cement. However, industry reluctance to use these cements in construction material specifications and their limited use in project designs are significant barriers to achieving the reduction. Industry standards for products that can yield significant CO_2

reductions in cement are rarely used in project specifications defined by the A/E (Kosmatka 2006).

ASTM C 150 now includes an optional requirement for interground limestone replacement of cement up to 5%. A customer can request that C 150 be interground with limestone, but it is not required. Intergrinding limestone reduces the CO_2 emissions associated with cement production. Displacing one pound of cement with one pound of limestone eliminates approximately one pound of CO_2. Theoretically, reducing cement content by 5% reduces CO_2 emissions by almost 5%, as energy required for grinding also emits CO_2. Customers, however, particularly state DOTs are not comfortable with the effects of intergrinding limestone on compressive strength and either do not request cement with limestone, or if they do, require elevated amounts of cement with limestone in project specifications, negating the intended CO_2 emissions reduction. In fact, 50% of state DOTs use AASHTO M85 requirements for portland cement, which does not even recognize the option to intergrind limestone. European producers, on the other hand, are able to displace up to 30% of cement clinker with interground limestone (Kosmatka 2006).

The cement industry has advocated for the acceptance of alternative cement products since the 1950s. ASTMC 595 “Standard Specification for Blended Hydraulic Cement” was passed in 1967 and ASTM 1157 “Standard Performance Specification for Hydraulic Cement” was established in 1992. C 595 pertains to blended hydraulic cements for both general and special applications, using slag or pozzolan, or both, with portland cement or portland cement clinker or slag with lime. This specification prescribes ingredients and proportions, with some performance requirements whereas

Performance Specification C 1157 is a hydraulic cement specification in which performance criteria alone govern the products and their acceptance. Cement producers maintain that C 595 and C 1157 specified products can provide similar or improved performance as C 150 products, while drastically reducing CO_2 emissions. However, C 595 was not approved for use by state DOTs until the 1990s and represents only 2% of the cement market (Tennis 2006) and C 1157 has only been approved for use by 5% of state DOTs although both products are compliant with C 150 (Kosmatka 2006).

The two largest barriers to the proliferation of these products is the structure of the market for supplementary cementitious materials and the conservatism of the engineers that specify concrete projects. The concrete industry in the United States is currently structured with ready mixed concrete producers procuring C 150 cement and blending supplementary cementitious materials at the batch plant, rather than buying cements already blended with supplementary cementitious materials by the cement producers. Batch plant blending precludes cement producers from developing products that can displace clinker, but reduces the CO_2 emissions per unit of concrete. However, intergrinding supplementary cementitious materials with cement can improve ultimate cement uniformity and concrete performance because the cemetitious material can be more closely engineered.

5.4 ASTM C 150 Conclusions

The original hypothesis for this work contended that insight into the chemical and physical requirements of C 150 would inform how the standard might be changed to develop more sustainable concrete construction. The chemical and physical requirements of C 150 simply establish baseline requirements to ensure material consistency and quality. C 150 itself does not specifically inhibit more sustainable concrete practice, even though requirements for intergrinding limestone could be increased or even made mandatory. It is the way that ASTM C 150 is used in practice by architects and engineers that inhibits more sustainable concrete construction. The conservative culture which has evolved from an industry heavily reliant on standardization manifests itself in the A/E's unwillingness to use alternative products that reduce the amount of clinker required to produce a unit of cement. So while standards have played a role in locking in unsustainable practice, ASTM C 150 itself does not inhibit more sustainable concrete construction.

6 ACI 211.1- Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

This guidance document is the industry-accepted practice for proportioning concrete. It contains the theory and procedures used to design concrete mixes. However, a major point of contention in the ACI 211.1 subcommittee has been related to mix design theory. The document has historically prescribed a "Gap" method of aggregate gradation; agents for change in the document are pushing for including methods of "Optimized" aggregate gradation. Proponents of optimized aggregate gradation believe this method produces a higher quality, more durable, and economized concrete than gap graded concrete. Several existing studies have documented these benefits of optimized gradation. The objective of this section is to evaluate the benefits of optimized aggregate gradation with respect to sustainability indicators: energy intensity, carbon dioxide emissions, and water intensity.

6.1 Concrete Mix Proportioning

Abolmaali, Jerath, and Watkins, "Development of a Systematic Mix Design Procedure for Construction of Durable Concrete Pavement Using Dense Graded Aggregates," describe the evolution of gap graded proportioning as follows:

> The development of concrete, using gap-graded aggregates, began in the 1960's and 1970's to facilitate the construction of buildings. In building construction, fast removal of formwork required the development of high-early strength concrete. This economic environment encouraged material suppliers to modify their product specifications to meet the demands of the building industry. With this paradigm shift in grading specifications, civil projects began to suffer from quality issues such as lower ultimate strength and decreased durability.

> The First Edition (approx. 1925) of Portland Cement Association's *Design and Control of Concrete Mixtures* recommended that only 65% of the fine aggregates be allowed to pass the #8 sieve. The 1923 Standard Specification for Concrete Aggregates, ASTM C 33-23, also promoted the use of coarse fine aggregate. Currently, the Standard Specification for Concrete Aggregates ASTM C 33-00 allows 100% of the material to pass the #8 sieve. This specification, along with the standard coarse aggregate designations, entitles the material supplier to remove nearly all particles passing the 3/8" and retained on the #8 sieves. This has led to our present day gap-graded mixes.

ASTM C 33 has since been updated to allow for combined aggregate gradation, a method which maintains intermediate aggregates on the #8 sieve. Having followed ASTM C 33 for many years, the typical mixes remain gap graded with only coarse and fine aggregates. Intermediate aggregate sizes fall out of the sieving procedure, demonstrated by Figure 13. This gap grading method can be identified by gradation charts that show distinct peaks at larger and smaller aggregate sizes rather than a "smooth" gradation throughout sieve sizes.

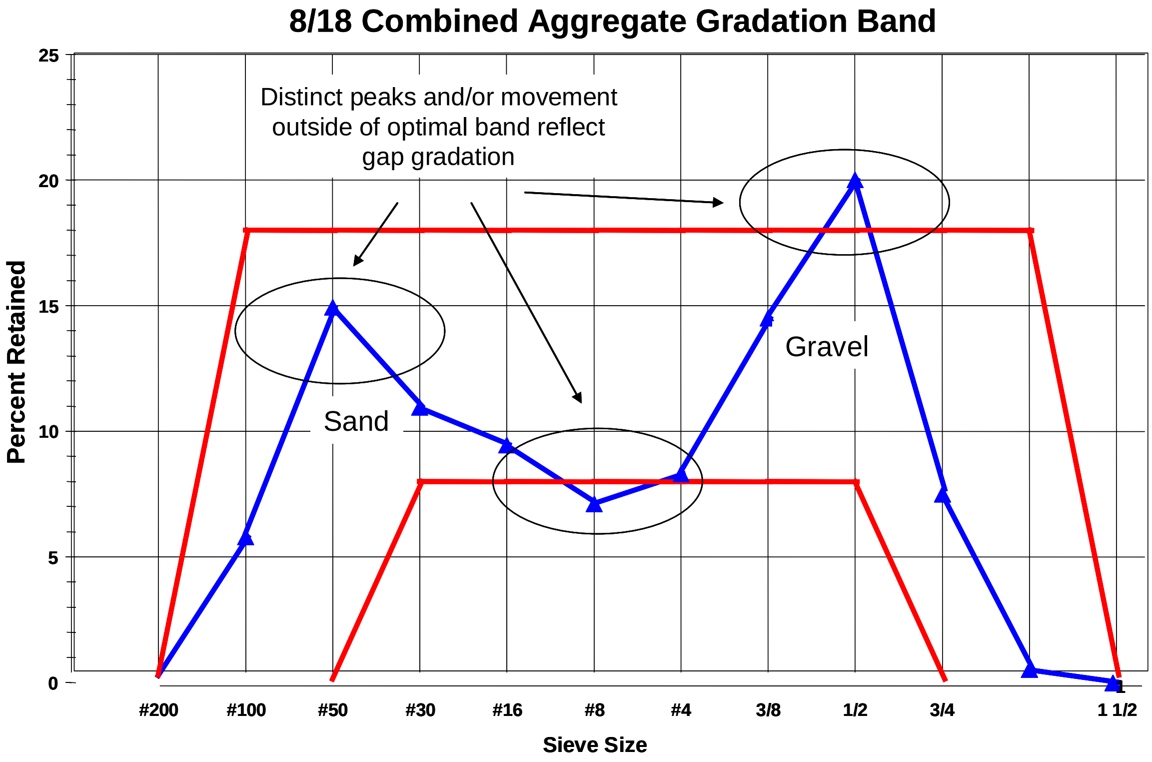

Figure 13. Aggregate Gradation Curve Reflecting Gap Gradation

Figure provided by Michigan Department of Transportation

Alternatively, methods of optimized gradation included in recent revisions to ACI 211.1 sought to reduce the gap in aggregate sizes reflected in Figure 13, and keep the range of aggregate sizes within the boundaries of the optimal 8/18 aggregate gradation band represented by the red lines in Figure 13 presented conceptually in Figures 14 and 15. Where gap gradation yields proportions of coarse and fine aggregates, Figure 14; Figure 15 illustrates a smoother gradation curve, which maintains proportions of intermediate aggregates within the mix design.

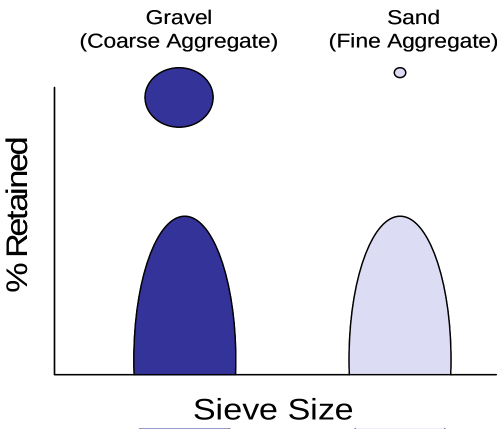

Figure 14. Conceptual Representation of Gap Gradation

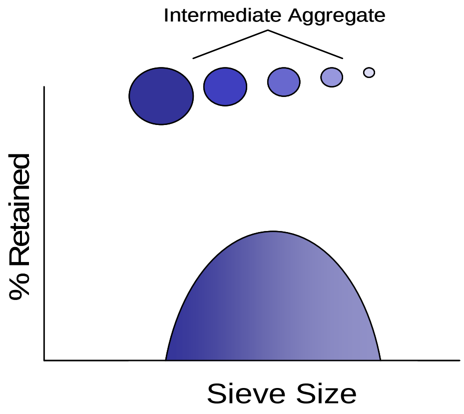

Figure 15. Conceptual Representation of Optimized Gradation

The sustainability and durability benefits of this type of mix optimization hinge on the idea that an optimized gradation reduces the requirement for cement paste. The intermediate aggregate reduces cement paste simply by displacing a greater portion of cement paste required in the mix. Therefore, aggregate optimization economizes the mix by displacing concrete's most expensive constituent, cement. Well-graded concrete will also yield improved long-term strength due to tighter particle packing (Figure 15). Replacing a large volume of paste with aggregate will ultimately yield a stronger product.

Rebar corrosion in reinforced concrete is the primary mechanism for bridge deck failures (Sheissl 1998). Over the life of the concrete, chloride ions diffuse through the matrix and the rebar eventually begins to corrode and expand, cracking the concrete from the inside-out. The moment that the steel rebar and chloride ions begin exchanging electrons is called depassivation. Within this study, the concrete is considered to have failed upon depssivation because the corrosion process is nearly impossible to reverse. Even though the concrete will be functional for longer, service life estimations in this study are generally equivalent to “time until depassivation.”

Well-graded concrete mixes are thought to improve the time until depassivation in two ways. First, cement paste is the most porous part of the matrix. Reducing the paste volume and increasing the amount of aggregate physically blocks the movement of water, and chloride ions, through the matrix (Yang and Cho, 2003). Second, reducing the amount of cement in the mix can reduce the likelihood of early age shrinkage and thermal cracking caused by high heat of hydration. Concrete with high cement content generates higher heats of hydration and is more subject to early age cracking. Early age cracking creates large conduits for chloride ions to penetrate the concrete and begin depassivation and expedites corrosion and concrete failure. Likewise, concrete that is resistant to chloride ion diffusion is considered to be more durable.

In practice, gap graded mixes are also subject to aggregate segregation during vibration. As concrete is overly compacted using vibration, the aggregates have a greater tendency to segregate or distribute unevenly, creating inconsistent strength and durability. Gap gradation techniques were standardized before vibration became common practice and the standards have not changed to reflect the innovation (Shilstone 2006). Optimized gradation improves aggregate distribution during vibration, guarding against segregation.

So, while aggregate optimization may require more time to gain strength, it economizes the mix, improves long-term strength, and can extend service life.

Figure 16 illustrates how an optimized gradation that includes intermediate aggregate sizes displaces cement paste volume in the matrix.

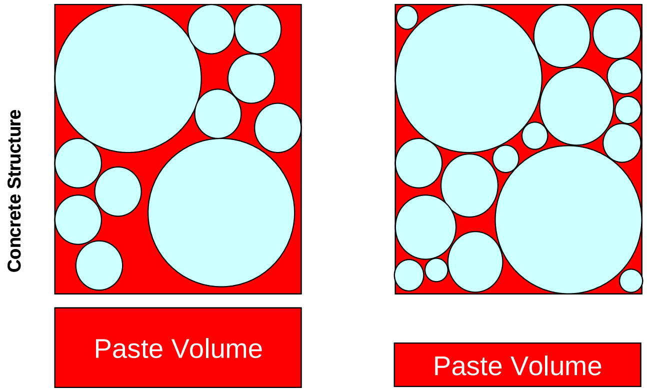

Figure 16. Conceptualization of Cement Paste Displacement

While the conceptual Figure 15 reflects the desired combined aggregate gradation curve for an optimized aggregate gradation, realistically, the contractor can strive simply to make sure that all points on the gradation curve fall within the 8/18 band as shown in Figure 17. Not only do all points fall within the optimized gradation band, a third peak in the intermediate range on the #4 sieve reflects additional intermediate aggregate.

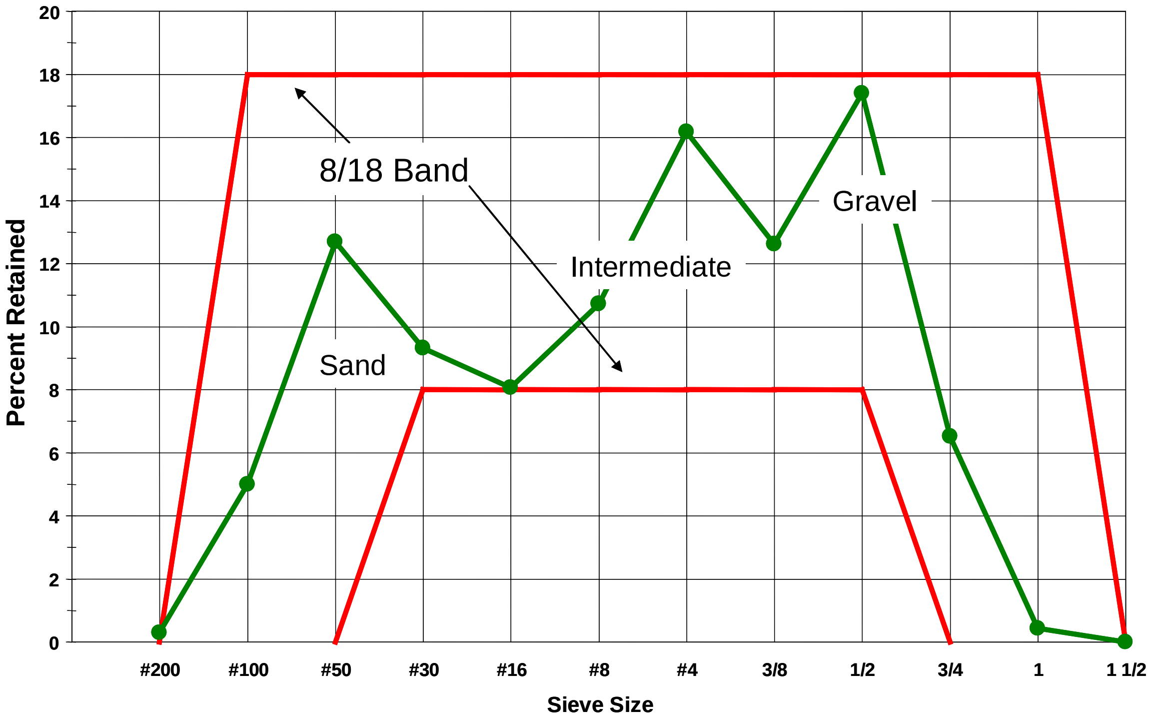

Figure 17. Practical Optimized Aggregate Gradation

Figure provided by Michigan Department of Transportation

6.2 Institutional Barriers

The revision to include optimized gradation practices in ACI 211 has met resistance for several reasons. Primarily, this is a movement to change mix design theory and represents a drastic departure from the status quo. As described earlier, the concrete industry is very conservative and it is very difficult to change a method that has been reinforced by a standard for many years. Significant capital investments are made in the methods, processes, and technologies supported by the standards. In this case, ready mixed concrete producers have been resistant to the change because their operations have evolved to create gap graded mixes. Coarse and fine aggregates are stored in dedicated bins and silos; meaning that producers only have two bins, one for coarse aggregate and one for sand. Requiring intermediate aggregate in the mixed concrete design guidance would require ready mixed plants to build additional bins and silos to hold the intermediate sized stone. Therefore ready mixed concrete producers have been resistant to the change, due to the possibility of required additional capital investment.

Gap grading evolved as high early strength became an important metric in concrete performance. Under continually increasing economic pressure to place concrete rapidly, gap graded mixes allowed concrete to achieve strength requirements sooner using a mix with high workability. The Second Edition of the Design and Control of Concrete Mixtures articulates the “Water-Cement Ratio Strength Law:”

> For given materials and conditions of manipulation, the strength of concrete is determined solely by the ratio of the volume of mixing water to the volume of cement so long as the mixture is plastic and workable. Designing a concrete mix for a given strength, therefore, consists in selecting the water-cement ratio corresponding to that strength and finding the most suitable combination of aggregates which will give the desired workability when mixed with the cement and water in this ratio.

This statement, based on Abrams’ research, effectively qualified strength as the focal point in evaluating concrete performance. This dilemma been compounded by the fact that the ASTM concrete and cement compressive strength tests are very simple and definitive test that can be executed quickly and cheaply. Consequently, project specifications have been written to require only minimum compressive strength, (including maximum w/c ratio, cementitious content), slump/workability, and air-entrainment. Workable concrete requires less labor to finish and sets and gains strength very quickly, due to higher cement content and small particle sizes. By contrast, the ancient Romans used very coarse, unworkable, concrete that required labor intensive tamping and quality control in placement, but has lasted for millennia.

It is important to recognize that after Abrams established the relationship between water to cement ratio and strength, compressive strength became the focal point of mix design, and engineers began prescribing minimum strength and cement requirements in project specifications. To achieve these minimum strengths sooner, PCA and ACI then prescribed gap grading techniques in guidance for proportioning. Over time concrete practice has become optimized for high early strength and industry standards, guidance documents, and project specifications have locked-in high early strength as the primary measure of performance. Similar to an agricultural system optimized for productivity rather than long-term sustainability, concrete optimized for high early strength at the cost of durability has elevated environmental impacts. Concrete optimized for durability can improve long-term physical and environmental performance.

The value of optimized proportions has begun to emerge over the last decade or two; largely embodied in the NRMCA's performance-based specification initiative, the quest for High Performance Concrete (HPC), and the controversy over optimized aggregate gradation. The Shilstone Method is a mix design procedure based on optimized aggregate gradation being used by several state Departments of Transportation, including Michigan and North Dakota. The Michigan DOT specifies the use of the Shilstone Method to include intermediate aggregate sizes in federal highway projects and most state projects (Staton 2006). Studies demonstrating the durability benefits of paste reduction and decreased permeability are beginning to disseminate. Reducing cement paste economizes the mix and intuitively reduces the environmental impacts associated with cement consumption. The environmental impacts of well-graded mixes illustrate the trade-offs between sacrificing rapid strength gain by decreasing cement and enhancing durability by increasing aggregate content.

Whether mix optimization actually produces more durable concrete with reduced cement content remains disputed. Conventional practice assumes that increased cement content produces stronger and therefore, more durable concrete. The analysis carried out in this thesis evaluates the perceived benefits of mix optimization relative to durability and three sustainability indicators: primary energy intensity, carbon dioxide emissions, and water intensity. The objective is not to evaluate or favor any one particular technology, innovation, or optimization technique, but to evaluate the environmental benefits of mix optimization in general. Two mix optimization techniques are evaluated for environmental benefits: aggregate optimization and performance based specification.

6.3 Methodology

Mix Designs

Thirty-one mix designs implementing different types of mix optimization techniques were gathered from existing studies to evaluate the sustainability benefits of mix optimization**.** Twenty-eight of the mix designs studied feature optimized aggregate gradation using the Shilstone Method of aggregate gradation, provided by a University of North Dakota-Grand Forks (UND) study, commissioned by the North Dakota Department of Transportation, "Development of a Systematic Mix Design Procedure for Construction of Durable Concrete Pavement Using Dense-Graded Aggregates (Abolmaali et. al 2004)." The final three mix designs reflect mix optimization achieved through Performance Based Specifications extracted from a NRMCA study of

Performance Based Specifications. UND and NRMCA mix designs can be found in Appendix B.

Model

The method developed to test the benefits of mix optimization is a two-step process to determine the environmental impact of the concrete mix relative to primary energy, carbon dioxide emissions, and water consumption and then normalize environmental impact over the projected service life estimates to estimate “material impact per year” of service life.

Initially, each concrete specimen or mix design was evaluated with respect to the sustainability indicators using a “material intensity” calculator developed at the University of Michigan (Kendall 2006). Each component of the mix design was input into the calculator in terms of kilograms of mix component per liter of concrete. The calculator reports megajoules of energy consumed, kilograms of water consumed and grams of carbon dioxide emitted per liter of concrete. All inputs and emissions consider upstream energy, water consumption and CO_2 emissions.

The second modeling step employed LIFE 365™, an industry developed assessment tool to determine the service life of concrete mixes. Holding all other inputs equal, service life projections were based on chloride ion diffusion coefficients. Durability data from the UND study specimens were gathered in terms of “charge passed” in coulombs determined by ASTM 1202 Test Method for Rapid Ion Chloride Permeability. ASTM C 1202 tests the conductivity of a concrete specimen exposed to chloride ions to get an estimation of how fast chloride ions can diffuse through concrete. LIFE 365™ required a conversion of charge passed (coulombs) and diffusion coefficient

(mm^2/year). To do so, a relationship between charge passed and diffusion coefficient (Equation 1) developed by Zemajtis (1998) was used to calculate the input values for LIFE 365™:

$$(\text{Permly} - 400)/12.76 = D_c \quad \text{(Equation 1)}$$

where "Permly" is electrical charge passed in coulombs and diffusion coefficient is measured in millimeter per year.

Diffusion coefficients for each mix design were input into LIFE 365™, to calculate time to corrosion based on chloride diffusion through Fick's second law of diffusion (Bentz and Thomas 2001). The time to corrosion was then divided into environmental impact results for each fresh mix to determine "material impact per year" over the projected service life of the concrete.

Uncertainty

It is important, at least qualitatively, to recognize the level of uncertainty that exists in the model. Uncertainty exists at each step of the analysis: life-cycle inventory, laboratory concrete preparation, calculation of diffusion coefficient, and the assumptions of LIFE 365™ in predicting service life.

The quality of data used in the life-cycle inventory contains uncertainty due to data availability. Assumptions using surrogates are made to make environmental impact estimates. A major source of uncertainty is also laboratory error. UND investigators cite laboratory error several times to explain inconsistent results. Another source of uncertainty is the development of the relationship between "charge passed" and "diffusion coefficient" is likely to have a known level of uncertainty in associating these two measures of ion diffusion. Finally, the assumptions made by LIFE 365™ are a major source of uncertainty. LIFE 365™ assumes that no early age cracking occurs, which can happen at a result of excessive heat of hydration, shrinkage, or inadvertent overload.

North Dakota Department of Transportation (NDDOT) Optimization Study

UND investigators evaluated concrete performance for conventionally gap graded, dense graded, and optimally graded mix designs[2] for four different aggregate sources at three levels of air entrainment. Gap graded mixes were produced using North Dakota Department of Transportation (NDDOT) Standard Specifications for Road and Bridge Construction. Dense graded mixes were produced using the Shilstone *seeMix* design tool, which produce gradation curves that can be practically achieved in the field. The set of mix designs termed "optimally graded" was graded by hand to reflect a smooth "theoretical" gradation curve that is recognized to be impractical in field construction. Additional details on mix design methodology can be found in Abolmaali, Jerath, and Watkins pages 16-20.

UND reported electrical charge passed results for four different depths within the specimen: 0-2 inches, 2-4 inches, 4-6 inches, and 6-8 inches. Measurements from 0-2 inch depth were used in this work to be consistent with LIFE 365™ models, which were set with a rebar depth of 2 inches from the concrete surface. ASTM C 1202 reports

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[2] Note on terminology: The UND study refers to what has thus far been termed "well-graded" or "optimized" aggregate gradation as "dense-graded" concrete. It also defines a third type of gradation as "optimally-graded," which differs from "dense-gradation" in that the aggregate has been graded by hand in order to achieve the theoretical "haystack-shaped" gradation curve. This type of gradation is completely impractical in the field. The study qualifies its "dense" gradation as being practical in field applications.

chloride ion concentration at a specific location in terms of “charge passed” in coulombs, the relationship in Equation 1 was applied to each measurement to derive a “diffusion coefficient.”

In evaluating UND results, emphasis is placed on the mix designs with 6% air entrainment because these more accurately reflect typical project air entrainment requirements in northern climates with salt exposure. This study is narrowly focused on corrosion as the primary deterioration mechanism and permeability as an indicator of corrosion potential.

Rolag Aggregate Source

Table 5 shows the results of the UND permeability study, the conversion to diffusion coefficient, and time until depassivation/years until corrosion from LIFE 365 for mixes designed with Rolag aggregate. Service life estimations were then divided into environmental impact results of the fresh mix to find “annualized material impact,” which illustrates the system’s environmental impact over its life-time.

Table 5. Service Life Estimations for Rolag Aggregate Source (6% Air)

Mix	Charge (Coulombs)	Diffusion Coefficient mm^2/year	m^2/s	Years to Corrosion
RO-GG-6%	2614	173.5	5.50E-12	33.1
RO-DG-6%	1765	107.0	3.39E-12	54.6
RO-OG-6%	1755	106.2	3.37E-12	54.9

Figure 18 shows energy intensity results reflecting a reduction in energy per liter of material and annualized energy per liter, using the service life estimations from Table 5, of concrete for all dense graded mix designs. The dense graded fresh mix with 6% air, consumes 18% less primary energy per liter of material than its gap graded counterpart. The dense graded mix also consumes 50% less primary energy per liter year than the gap graded mix over the projected service lives of the two materials. The optimally graded mix outperformed the dense graded mix, reducing initial and annualized primary energy consumption per liter by 8.7% and 9.2%, respectively (Figure 18). Carbon dioxide emissions results usually follow primary energy as CO_2 emissions are closely correlated with energy consumption. However, the calcination process releases additional CO_2 from the limestone. Therefore, CO_2 emissions remain proportional with energy consumption, but are much higher than one would expect with respect to other industrial processes(Figure19).

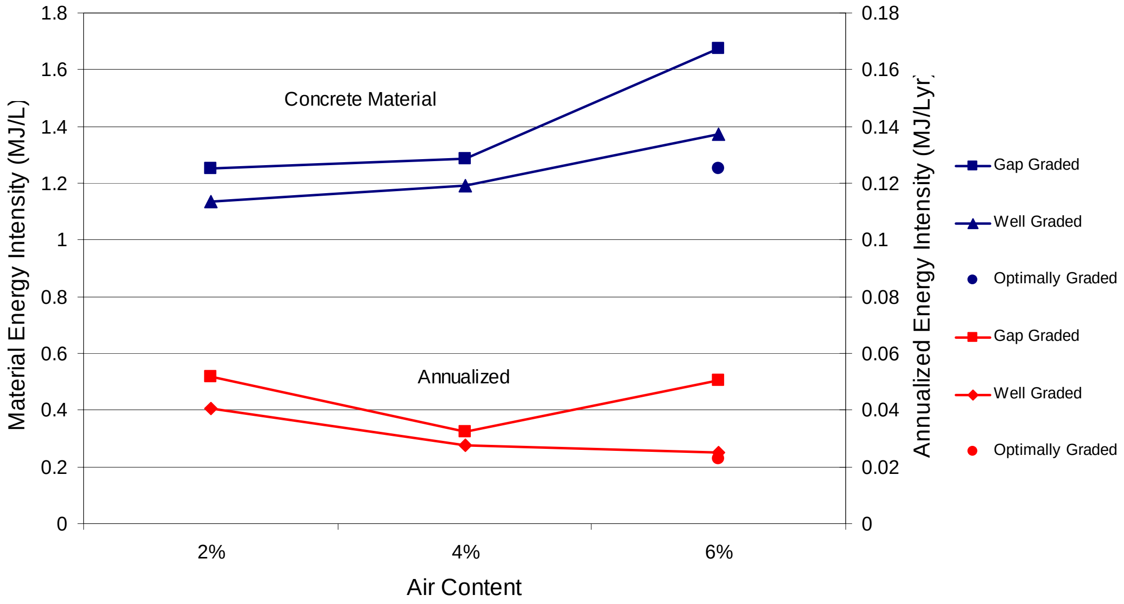


Figure 18. Initial and Annualized Energy Intensity-Rolag

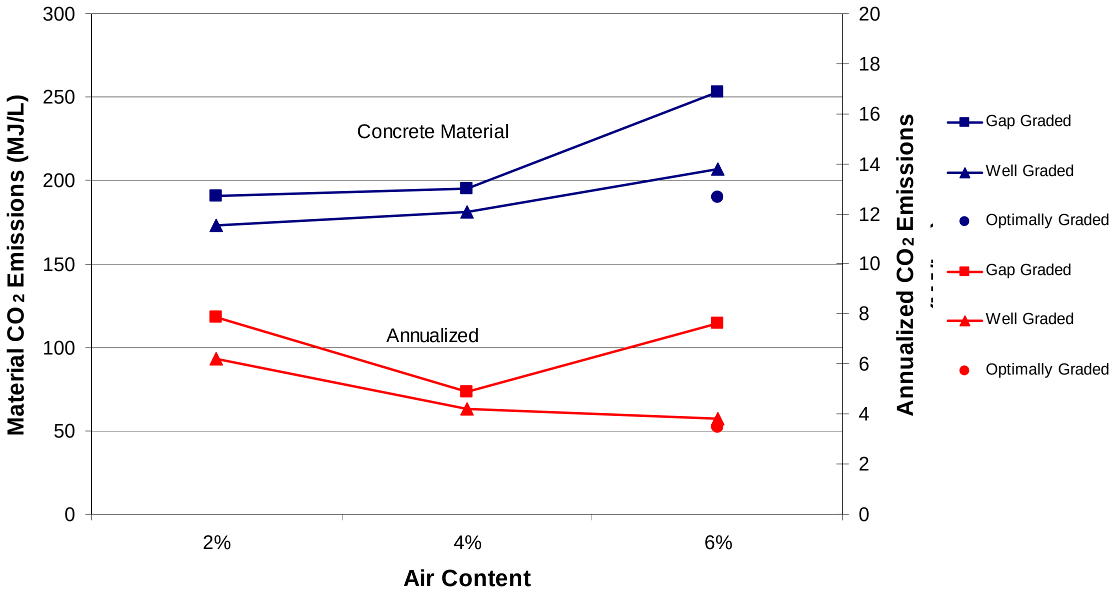


Figure 19. Initial and Annualized CO_2 Emissions- Rolag

Water consumption results for the Rolag aggregate source followed the same trend. Water intensity decreased for dense and optimally graded mixes for the fresh mix and over their projected service lives. The dense graded mix with 6% air required 11% and 46% less water than its gap graded counterpart both in the fresh mix and annualized, respectively (Figure 20).

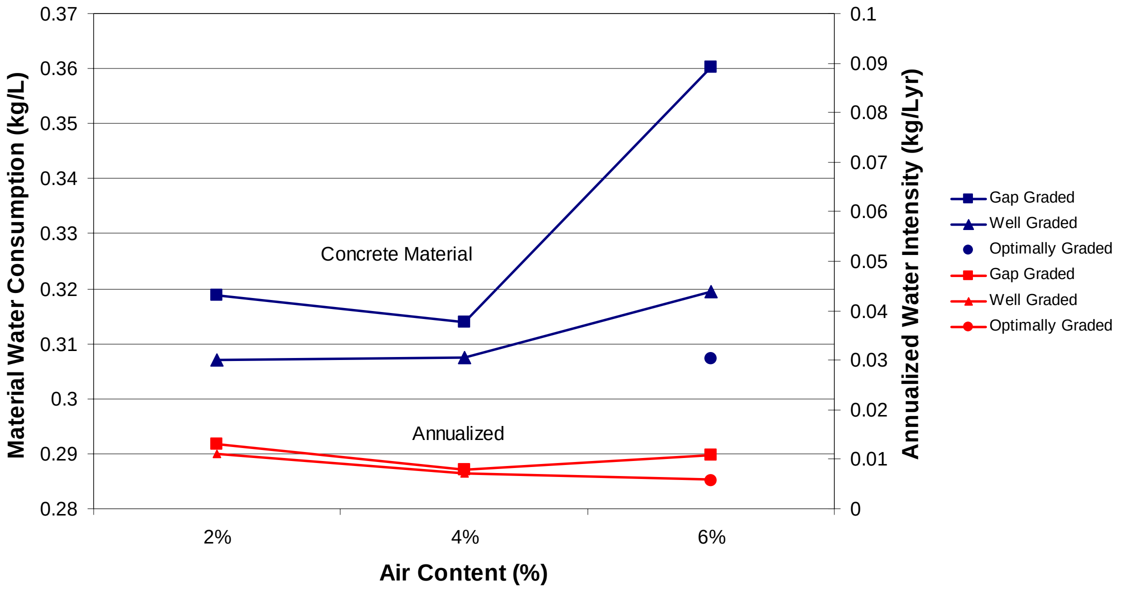


Figure 20. Initial and Annualized Water Intensity- Rolag

Riverdale Aggregate Source

Table 6 shows the results of the UND permeability study, the conversion to diffusion coefficient, and time until depassivation/years until corrosion from LIFE 365 for mixes designed with Riverdale aggregate. Service life estimations were then divided into material impact results of the fresh mix to find "annualized material impact," which illustrates the system's environmental impact over its life-time.

Table 6. Service Life Estimations for Riverdale Aggregate Source (6% Air)

Mix	Charge	Diffusion Coefficient mm^2/year	m^2/s	Years to Corrosion
RI-GG-6%	2072	131.0	4.16E-12	46.1
RI-DG-6%	1766	107.1	3.39E-12	54.6
RI-OG-6%	2935	198.7	6.30E-12	28.6

Figure 21 shows the energy intensity results for the Riverdale aggregate source. At 6% air entrainment the dense graded mix reduced primary energy consumption by 20.7% per liter of material and by 33% annualized over the specimen's projected service life. The optimally graded mix did not follow the expected trend, negligibly reducing the energy requirement of the mix per liter, but primary energy consumption was 90% greater over the projected service life than that of the dense graded mix. Carbon dioxide results were again proportionally higher than primary energy consumption reflecting calcination; the dense graded mix with 6% air outperformed all other mixes (Figure 22).

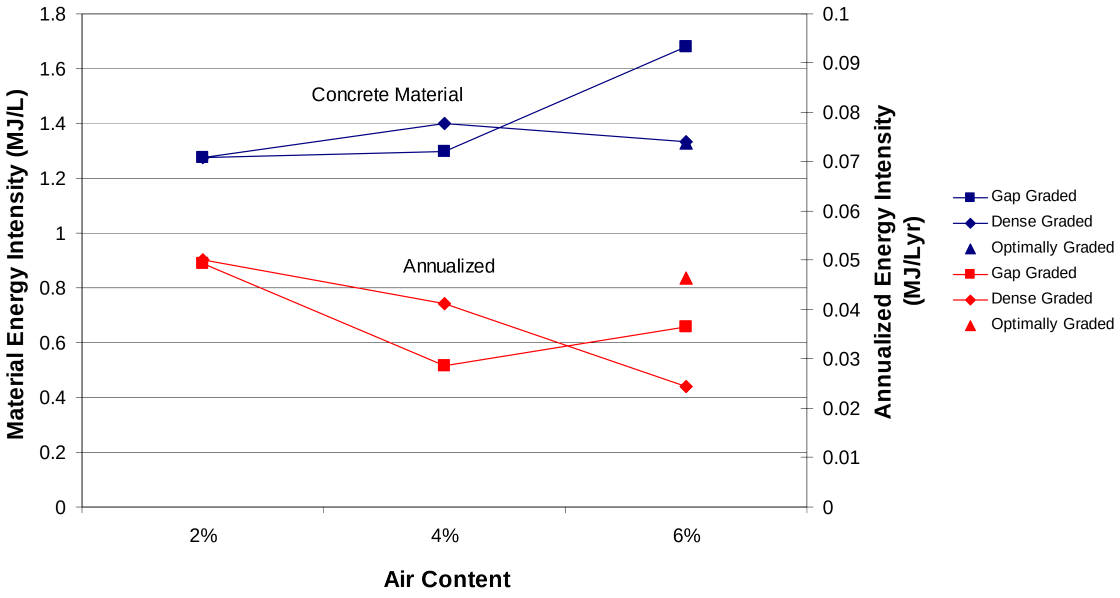


Figure 21. Initial and Annualized Energy Intensity- Riverdale

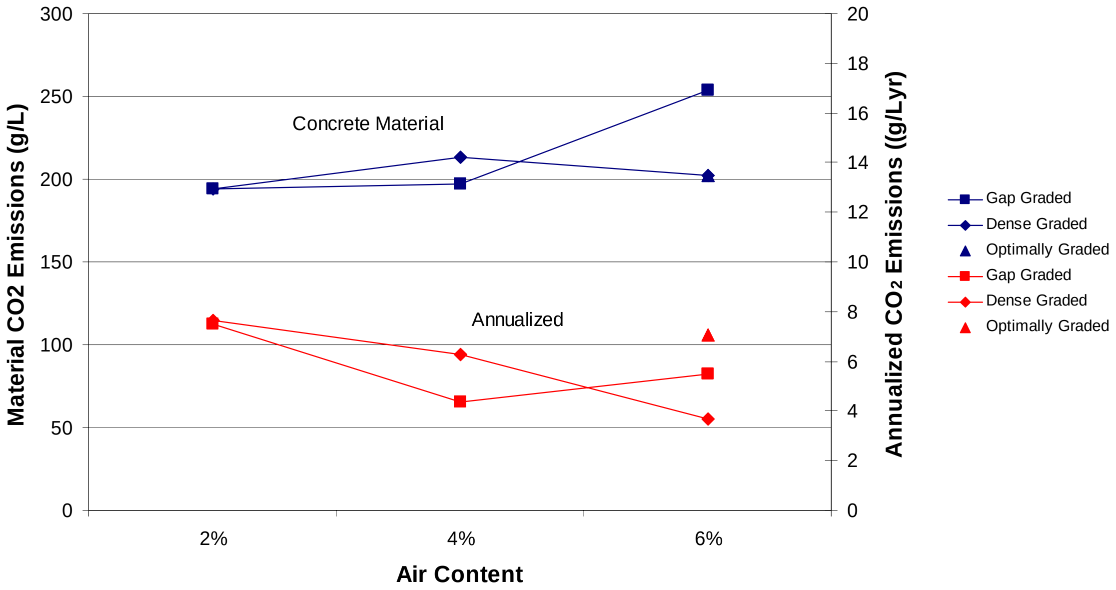


Figure 22. Initial and Annualized CO_2 Emissions- Riverdale

Water consumption followed a similar pattern where the dense mix reduced consumption both per liter of material and over the projected service life by 13.8% and 27.2%, respectively (Figure 23). Results for the optimized mix with respect to the dense graded mix were also similarly inconsistent with expectations.

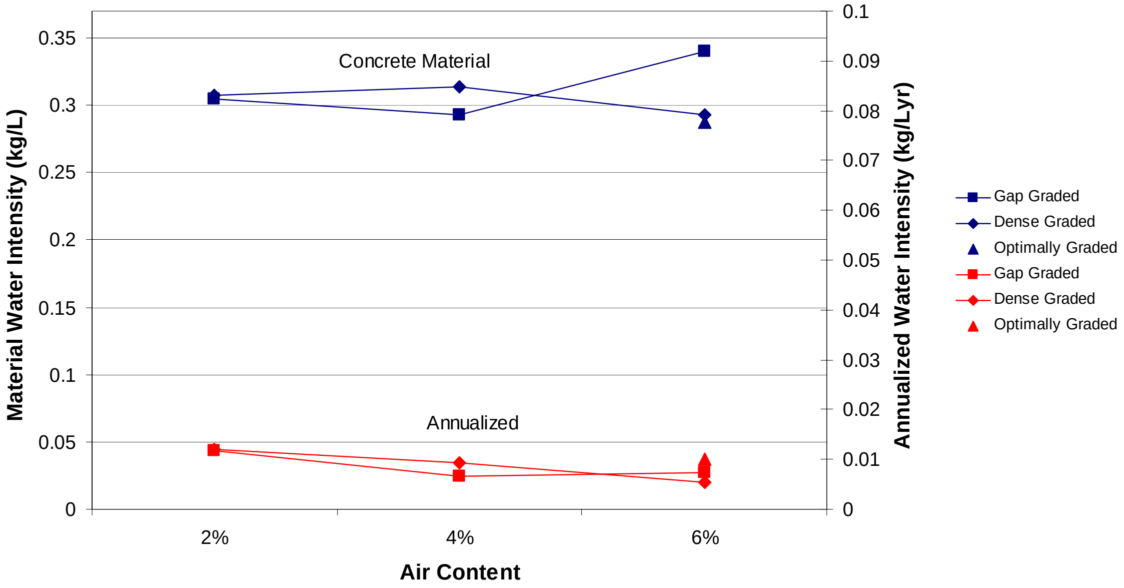


Figure 23. Initial and Annualized Water Intensity- Riverdale

There are interesting results with respect to the mixes with 2% and 4% air entrainment. The gap graded mixes perform better with low air content and then do not perform as well at 6%. As stated earlier, this evaluation focuses on the mixes with 6% air entrainment in accordance PCA "Design and Control of Concrete Mixtures" guidance for construction in northern climates.

Klocke Aggregate Source

Table 7 shows the results of the UND permeability study, the conversion to diffusion coefficient, and time until depassivation/years until corrosion from LIFE 365 for mixes designed with Klocke aggregate. Again, service life estimations were used to find "annualized material impact," which illustrates the system's environmental impact over its life-time.

Table 7. Service Life Estimations for Klocke Aggregate Source (6% Air)

Mix	Charge	Diffusion Coefficient mm^2/year	m^2/s	Years to Corrosion
KL-GG-6%	2245	144.6	4.58E-12	40.1
KL-DG-6%	1379	76.7	2.43E-12	76.5
KL-OG-6%	1594	93.6	2.97E-12	62.2

Figure 24 represents primary energy consumption of the mixes designed from the Klocke aggregate source. The gap, dense, and optimally graded mix designs for each level of air entrainment performed similarly. The improvement in energy intensity demonstrated by the fresh dense graded mix at 6% was less than one percent. On an annual basis over the service life of the specimen, however, the dense graded specimen was projected to consume 48% less energy than the gap graded specimen. The optimally graded specimen, again, behaved erratically, showing a minor improvement in material impact and a 20.3% increase in annual energy intensity relative to the dense graded specimen. Again, carbon dioxide emissions were proportional to energy intensity reflecting elevated CO_2 emissions from calcination (Figure 25).

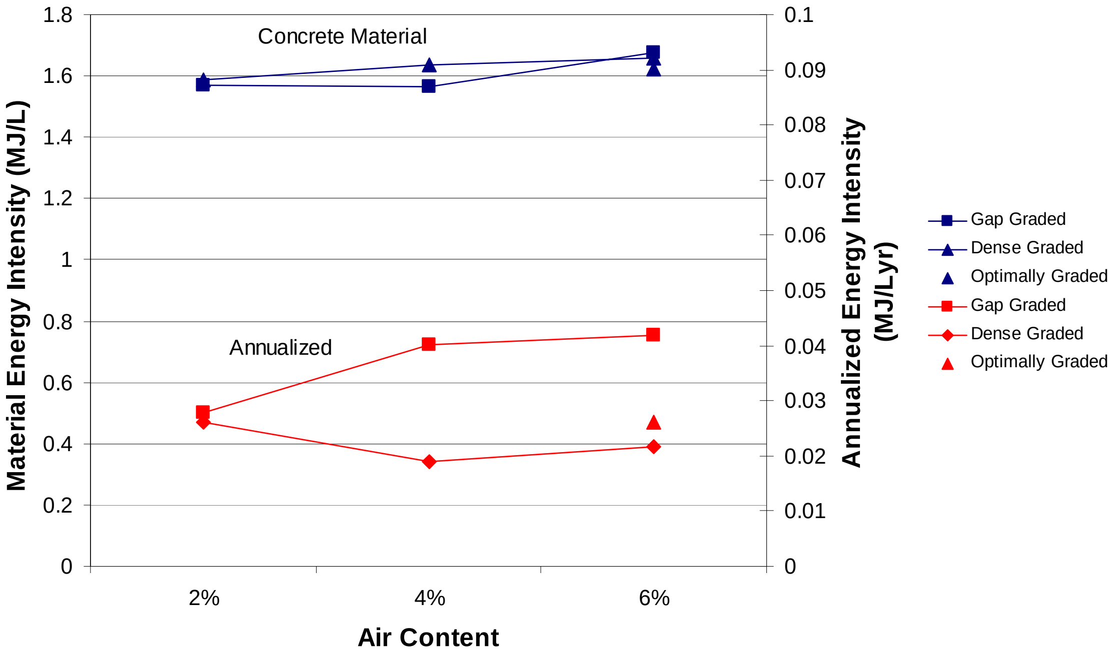


Figure 24. Initial and Annualized Energy Intensity- Klocke

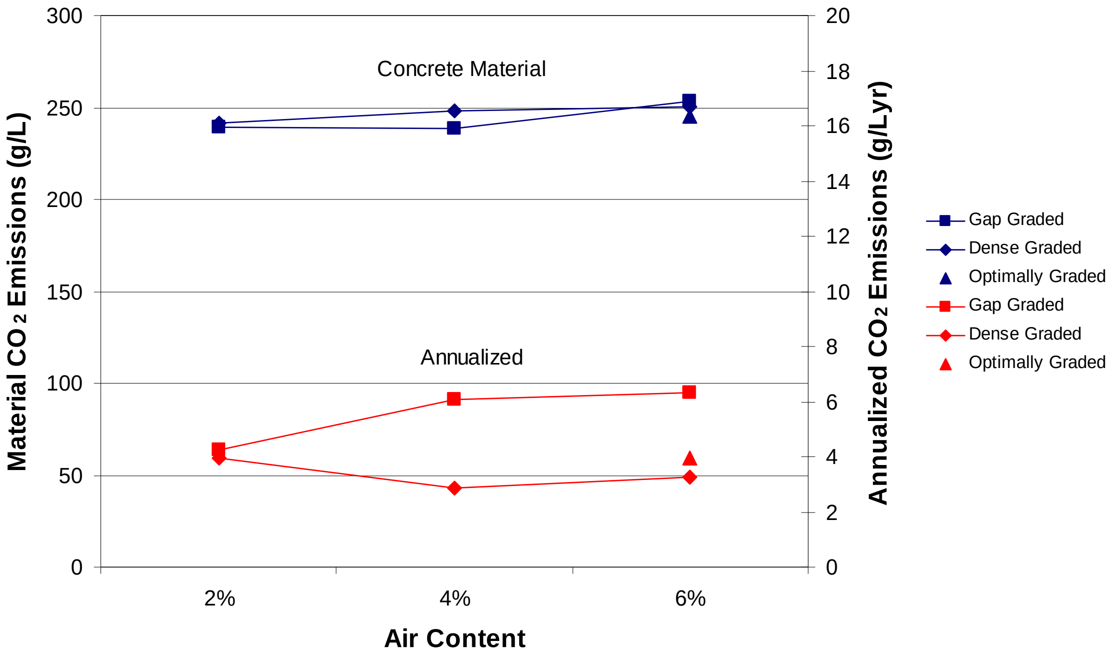


Figure 25. Initial and Annualized CO_2 Emissions- Klocke

Water consumption is also reduced for dense graded aggregates, however, actual differences were minimal. The fresh dense graded specimen was two percent less intense than the gap graded mix and the optimally graded mix showed less than a two percent improvement over the dense graded mix. The annualized results were similar except that the optimally graded mix reflected a 20% increase in water intensity than the dense graded mix (Figure 26).

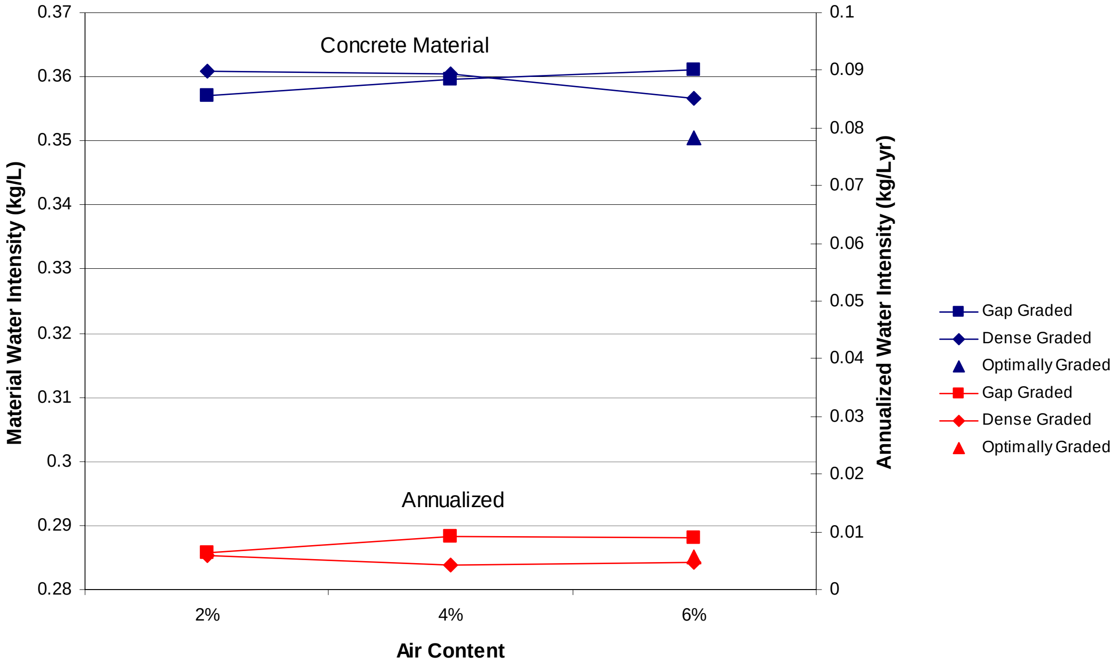


Figure 26. Initial and Annualized Water Intensity- Klocke

Glendive Aggregate Source

Table 8 shows the results of the UND permeability study, the conversion to diffusion coefficient, and time until depassivation/years to corrosion from LIFE 365.

Table 8. Service Life Estimations for Glendive Aggregate Source (6% Air)

Mix	Charge	Diffusion Coefficient mm^2/year	m^2/s	Years to Corrosion
GL-GG-6%	2233	143.7	4.56E-12	40.1
GL-DG-6%	2959	200.5	6.36E-12	28.3
GL-OG-6%	4269	303.2	9.61E-12	18.3

Figure 27 shows that the material impact calculations of the Glendive Aggregate source material with 6% air entrainment follows the expected trend that dense and optimally graded specimens require less primary energy than the gap graded mix. The fresh dense graded mix requires 9.3% less energy per liter of material than the gap graded mix and the optimally graded mix requires 8.7% less energy than the dense graded mix. The annualized projection, on the other hand, reflect an opposite trend in that the gap graded mix uses 28.4% less energy per liter per year than the dense graded mix, which requires 41.1% more energy than the optimally graded mix. Again, carbon dioxide emissions proportionally follow the results of the energy output (Figure 28).

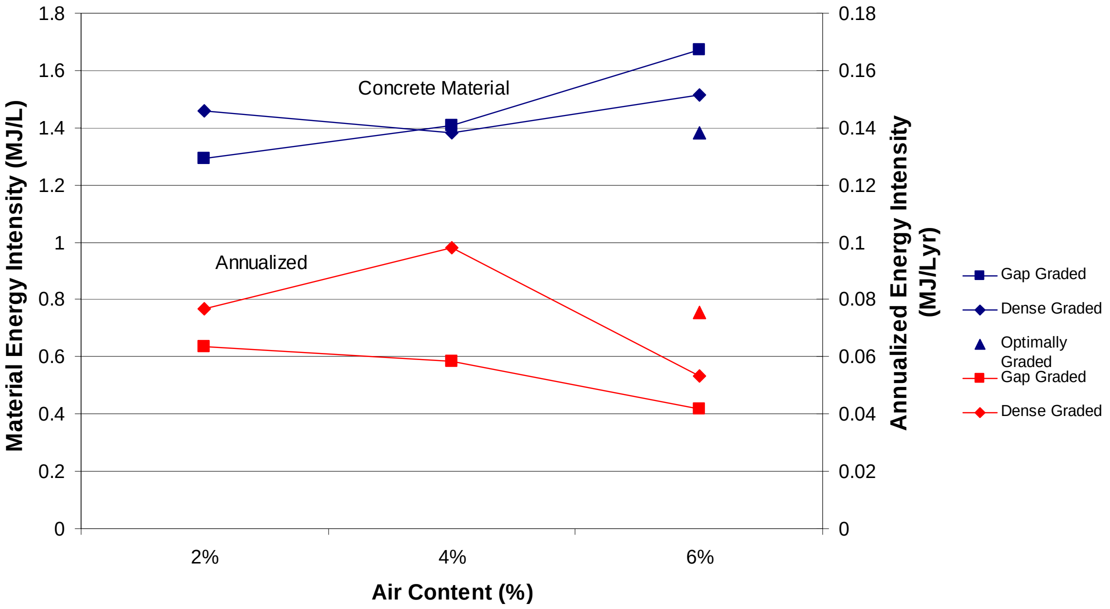


Figure 27. Initial and Annualized Energy Intensity- Glendive

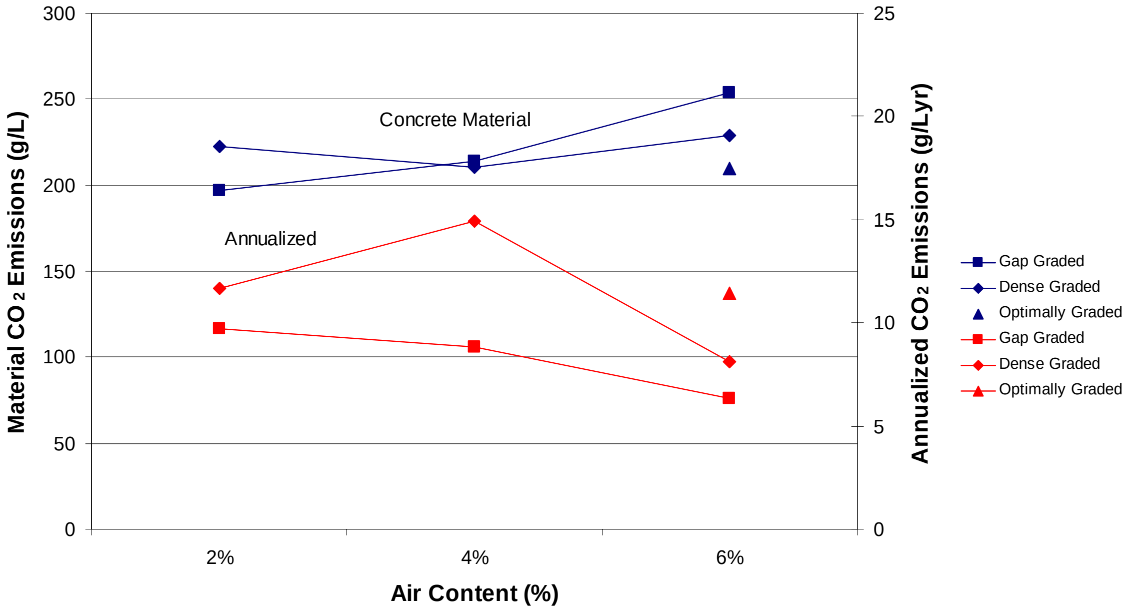


Figure 28. Initial and Annualized Carbon Dioxide Emissions- Glendive

Water intensity trends also follow energy and carbon dioxide emissions trends for the Glendive source. The dense graded fresh mixes require 7.28% less water than the gap graded mix and the optimally graded mix requires 4.8% less water than the dense graded mix. The annual projections for the dense graded mix show a 31.4% increased water requirement compared with the gap graded mix and the optimally graded requires 47.3% more water than the dense graded mix per liter of concrete (Figure 29).

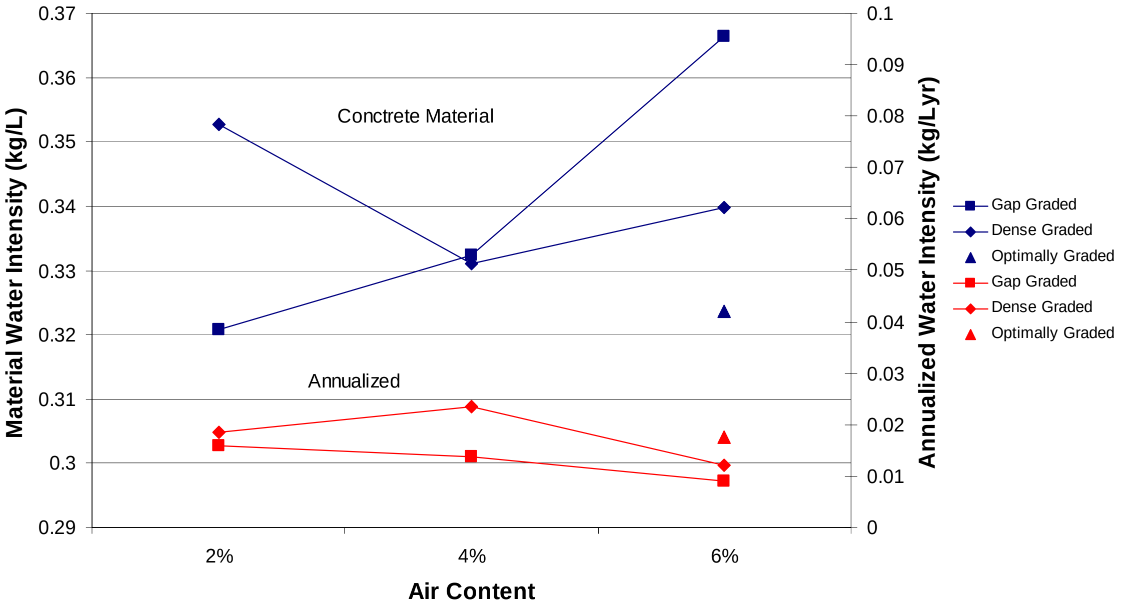


Figure 29. Initial and Annualized Water Intensity- Glendive

In all cases the mix designs with 2% and 4% air entrainment reflect inconsistencies with the hypothesis that dense and optimally graded mixes will out perform gap graded mixes, but the affects of air entrainment fall outside the scope of this study since this study focuses on bridges in cold climates with required high cement or air entrainment (Kosmatka and Panarese 1988). Such inconsistencies related to air entrainment provide additional avenues for further research.

Cement Paste Requirement

Figure 28 shows declining paste volume for dense and optimally graded mix designs except for the Klocke aggregate source reflecting that optimized gradation does, indeed, reduce required cement volume. Displacing cement is an essential measure for more sustainable concrete as results indicate that energy intensity, CO_2 emissions, and water intensity decrease with cement reduction. Environmental impacts of the dense graded Klocke specimens are marginally less than those of its gap graded counterpart with 6% air entrainment.

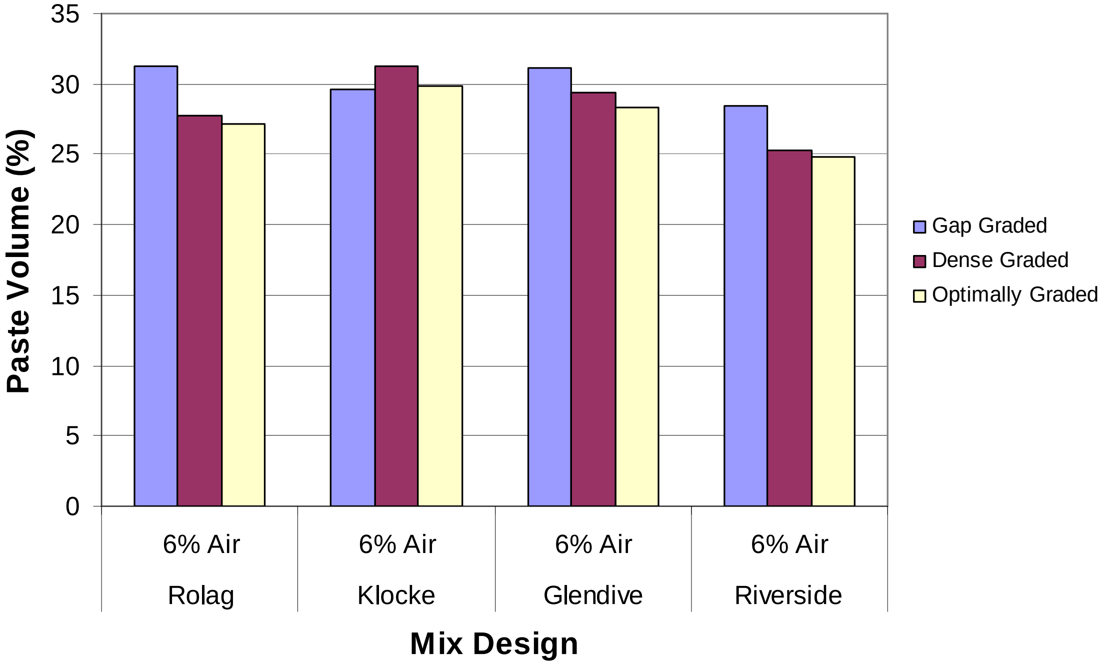


Figure 28. Paste Content Comparison- Mix Designs with 6% Air Entrainment

Figure 29 demonstrates that while trends in paste requirement are inconsistent for various levels of air entrainment, but cement requirements absolutely increase with increasing levels of air entrainment. These affects of air entrainment on cement requirement are interesting, but outside the scope of this study.

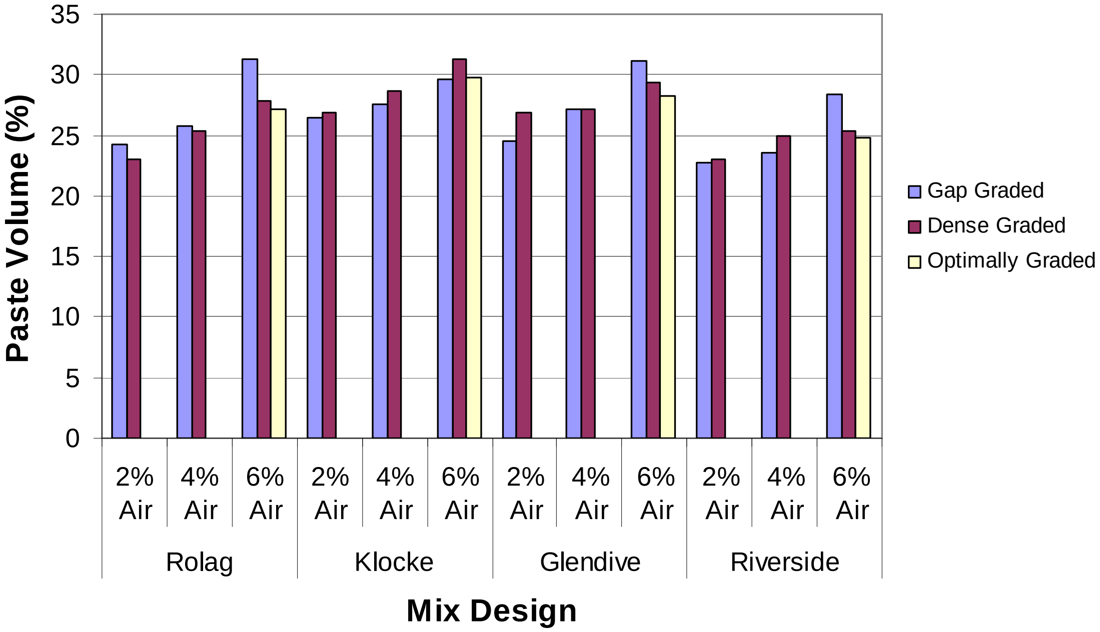


Figure 29. Paste Content- All Mix Designs

NRMCA Performance Based Mix Designs

The National Ready Mixed Concrete Association (NRMCA) mix design BR-1 represents a typical prescriptive HPC bridge deck specification used by a state Department of Transportation (Appendix C) and BR-2 and BR-3 represent mixes designed for the same application based on a model performance based specification fashioned by the NRMCA (Lobo and Obla 2005) (Appendix C).

Material impact results show that performance based fresh mix designs BR-2 and BR-3 reduce energy intensity by 23% and 12% (Figure 30); CO_2 emissions by 24% and 40% (Figure 31); and water intensity by 59% and 57% (Figure 32), respectively.

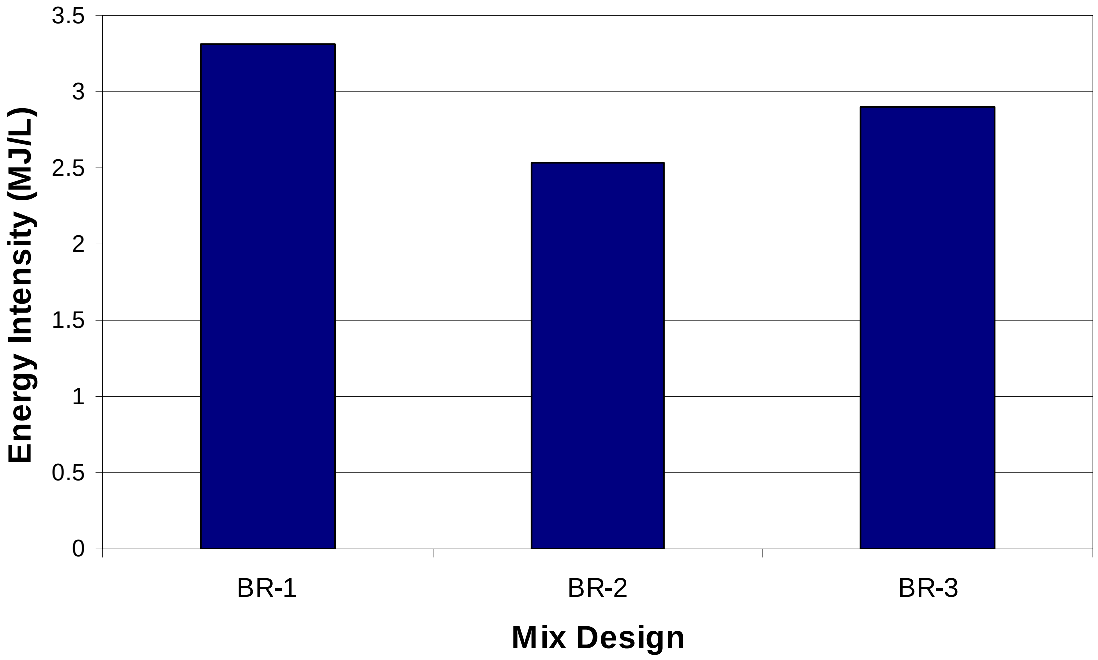


Figure 30. Initial Energy Intensity- NRMCA Mixes

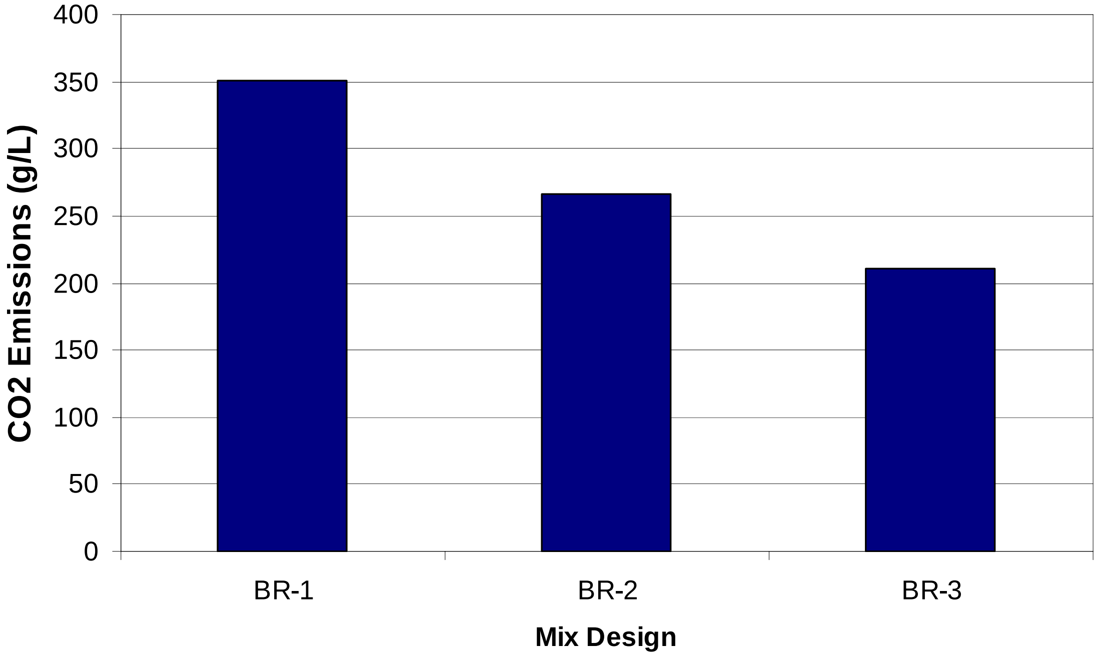


Figure 31. Initial CO_2 Emissions- NRMCA Mixes

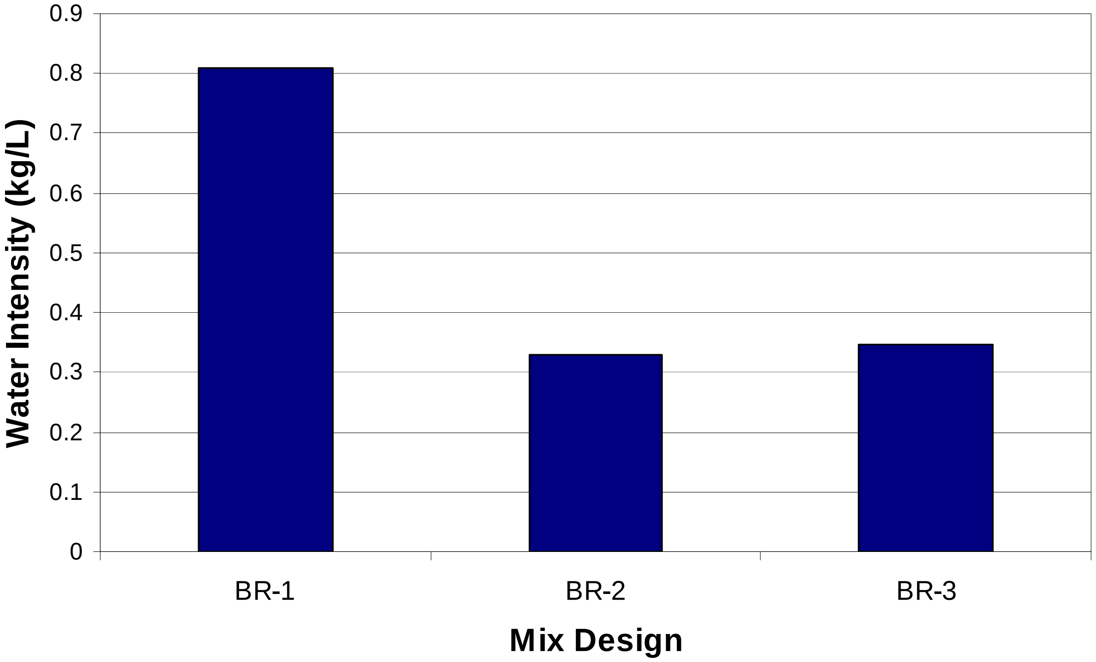


Figure 32. Initial Water Intensity- NRMCA Mixes

Figure 33 demonstrates that performance specifications BR-2 and BR-3 reduce annualized primary energy consumption by 41.8% and 48.6%, respectively. Figure 34 relates subsequent improvements in carbon dioxide emissions. CO_2 emissions reduction for BR-2 proportionally follows energy intensity improvements at 42.3% relative to BR-1. CO_2 emissions reduction for BR-3 relative to BR-1, however, were much higher than energy reduction at 64.7% (Figure 34).

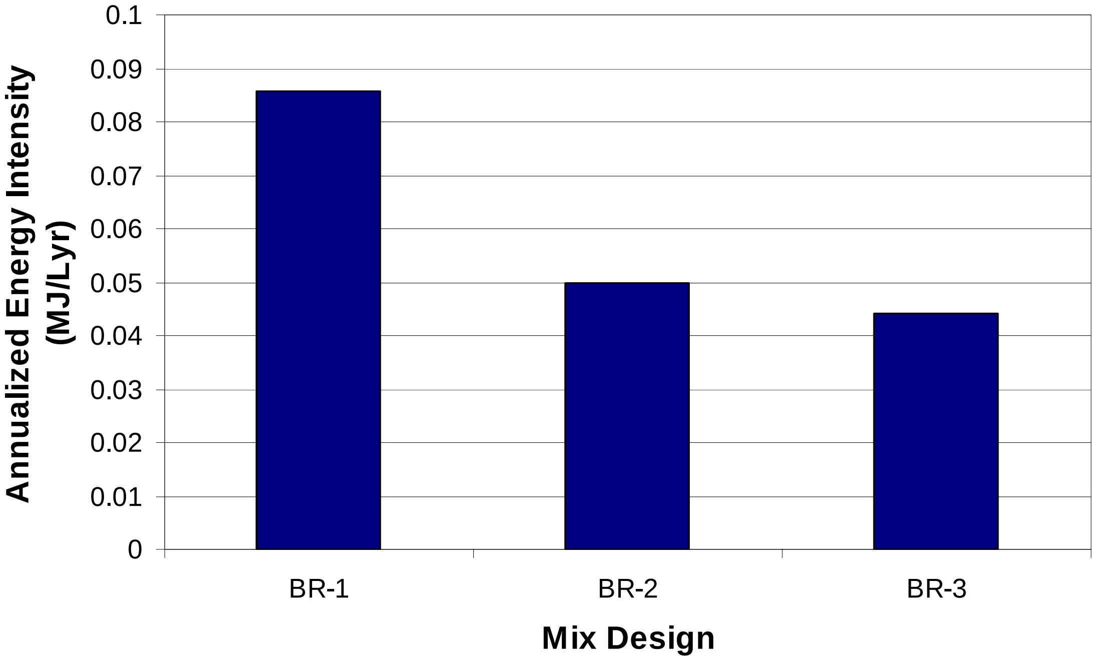


Figure 33. Annualized Energy Intensity- NRMCA Mixes

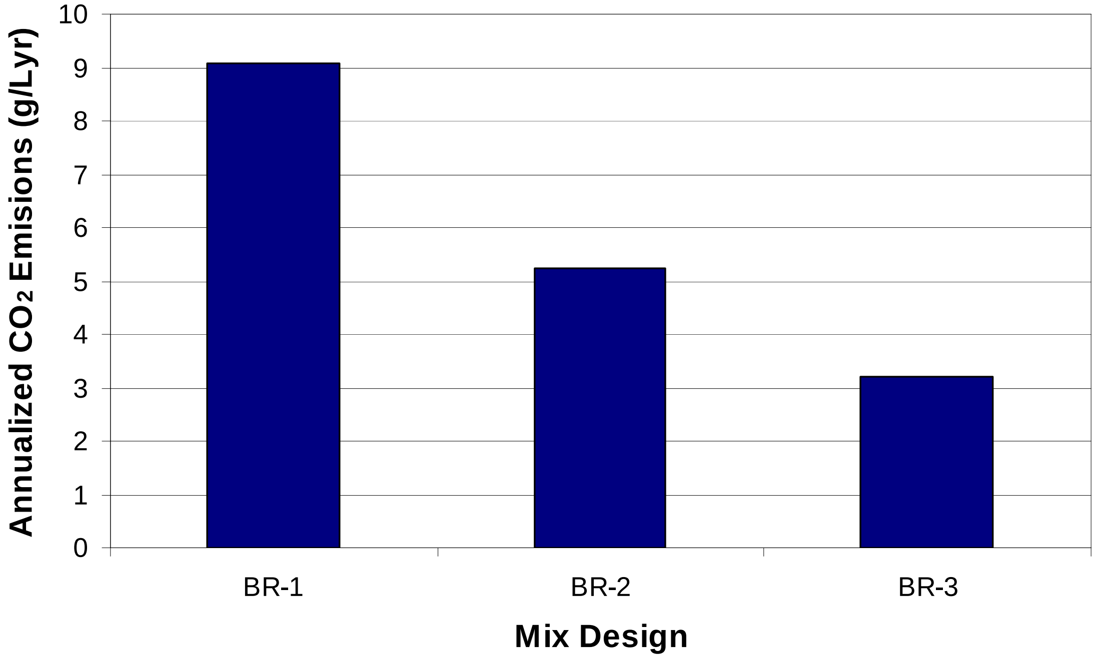


Figure 34. Annualized CO_2 Emissions- NRMCA

Mix designs BR-2 and BR-3 exhibit reduced annualized water intensity by 68.9% and 74.9% relative to BR-1, respectively.

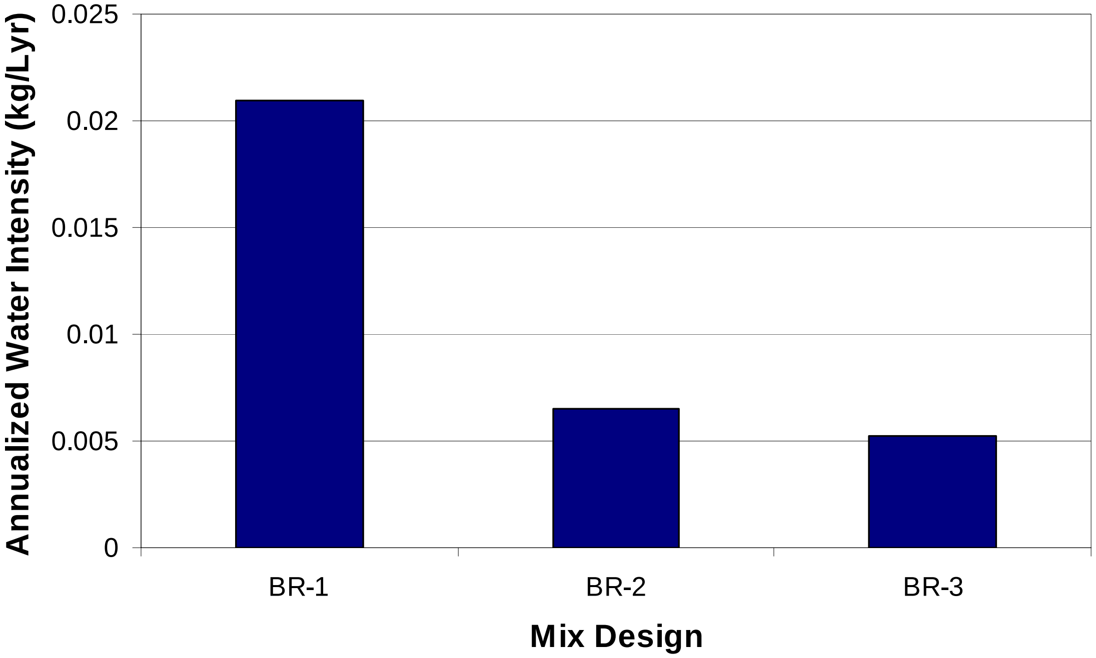


Figure 35. Annualized Water Intensity- NRMCA

6.4 Discussion

Initial Material Impacts- Fresh Mix

Material impact results from material with 6% air entrainment categorically reflect the benefits expected from mix optimization and from cement paste reduction including improved energy intensity, CO_2 emissions, and water intensity (Table 9) in addition to durability.

Table 9. Impact Reduction in Dense Relative to Gap Graded Mixes (6% Air)

Impact	Rolag	Riverdale	Klocke	Glendive
Energy Intensity	18%	21%	1%	9%
CO_2 Emissions	18%	20%	1%	10%
Water Intensity	11%	14%	1%	7%

Each optimized specimen, dense and optimally graded, improved environmental performance for all three indicators. Dense and optimally graded mixes from each aggregate source demonstrated reduced primary energy intensity and subsequent CO_2 emissions reductions relative to the gap graded designs. Dense graded Rolag and Riverdale mixes require 18% and 20% less primary energy per liter of concrete than their gap graded counterparts (Figures 18 and 21). The Klocke and Glendive sources demonstrated energy intensity and CO_2 emissions reductions of just below 10%. Water intensity was also reduced between 2% and 14% in all cases of dense and optimally graded mix designs. However, the results are not extremely significant until service life is included.

Table 10 illustrates the environmental benefits of performance based specifications. NRMCA results reflect similar trends where BR-2 reduces energy intensity by 23.4% and CO_2 emissions by 24% with respect to BR-1. Mix BR-2 was designed with less cementitious material, reducing cement content by 124 lbs. and slightly increasing fly ash content.

Table 10. Impact Reduction in Performance Based Mixes

Impact	BR-1	BR-2	BR-3
Energy Intensity	-	23%	13%
CO_2 Emissions	-	24%	40%
Water Intensity	-	59%	57%

Results for BR-3 were interesting. BR-3 cementitious material was composed of 50% cement and 50% GGBFS. However, this mix design only reduced energy consumption by 12.5% (Figure 30); half of the energy reduction for BR-1. One would expect BR-3 energy performance to be better than BR-1 and BR-2, particularly because of its very low cement content. BR-3 CO_2 emissions followed the expected trend with a

40% reduction over BR-1, but 16% greater than BR-2 (Figure 31). The inconsistency in the energy consumption and CO_2 emissions for BR-3 is strange, but can be explained by the primary energy consumed by grinding GGBFS. The amount of CO_2 displaced through cement reduction outweighs the CO_2 emitted by the GGBFS grinding process, but the energy consumed in grinding slag is closer to that of grinding clinker. So energy reduction is not consistent with CO_2 emissions because even though 50% of cement is displaced, grinding GGBFS requires primary energy of electricity of grinding. But the CO_2 emissions associated with grinding are much less than those produced in the calcining process.

It is important to note that while the absolute benefits of optimization are clear in these cases, energy reduction is occurring on the order of tenths of megajoules per liter of concrete. CO_2 emission improvements occur on the order of tens of grams per liter of concrete and water reductions are in hundredths of kilograms per liter of concrete. This study does not address the marginal benefits of these improvements; the capital and operational benefits and costs of optimization related to working with intermediate aggregate and perhaps less workable mixes. However, when extrapolated to a large job, the absolute environmental benefits of optimization are substantial. For example, the results from the Rolag aggregate source indicate that the dense graded mix would reduce initial material energy consumption by 300,000 MJ in a job requiring 1000 m^3 when compared to using a gap graded mix. That is equivalent to about 50 barrels of oil. This projection will improve after incorporating the durability benefits of mix optimization, and considering that there are 12 billion m^3 of concrete placed in the world each year, this number is not insignificant (Lepech 2007).

Annualized Material Impacts

Annualized results also demonstrate the environmental benefits of mix optimization, but with more variability than fresh material impact projections. Incorporating service life projections based on LIFE 365 introduces a higher level of uncertainty. The material impact results were very discrete because calculations are based on known datasets and the major uncertainty comes from the quality of the data input into the model. Service life projections are subject to laboratory error and material variability in deriving permeability results and then error associated with the assumptions made within LIFE 365™ itself.

LIFE 365™ does not account for potential early age cracking even though early age cracking is a reality of concrete construction. While early age cracking is not guaranteed to occur, contractors must be careful about proportioning and placement, particularly with high early strength concrete. Mehta has 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 (Mehta 2001).

This study, however, is not focused on optimization for strength. Aggregate optimization is focused on durability. Even though LIFE 365™ assumes no early age cracking, it is a relevant tool for estimating service life in this project because the North Dakota specimens were not designed for high early strength. They have w/c ratio much higher than 0.35 and incorporate 30% fly ash, which decreases rate and heat of hydration. According to a University of Wisconsin study (Cramer 1995) concrete designed with a

Shilstone mix design is equally susceptible to early age shrinkage cracking, supporting the LIFE 365 assumption of no early age cracking..

Along these lines, results demonstrate annualized material impact benefits from optimized mix designs (Table 11).

Table 11. Annualized Impact Reduction of Dense relative to Gap Graded Mixes (6% air)

Impact	Rolag	Riverdale	Klocke	Glendive
Energy Intensity	50%	33%	48%	-28%
CO_2 Emissions	50%	33%	48%	-28%
Water Intensity	46%	27%	48%	-31%

In most cases, greater projected service life drastically improves the benefits of well-graded aggregate relative to gap gradations. 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 (Tables 5, 6, and 7). Optimally graded mixes showed some variability in results reflecting higher ion transport than the dense graded Riverdale and Klocke mixes and even the gap graded Riverdale mix. UND attributes these irregularities to potential problems with mix consolidation in the optimally graded laboratory specimens. This is significant in that one of the major concerns about optimal aggregate gradation is concrete workability. If problems with consolidation affect performance, these mixes may not be viable.

Otherwise, dense graded mixes with 6% air entrainment for Rolag, Riverdale, and Klock improve energy performance per annualized liter by 50%, 33%, and 48%, respectively. These results are a function of both paste reduction and service life improvements. Observing Figure 28 and Table 5 for Rolag paste content and service life projection, it is clear that these two factors dictate annualized environmental benefits. This makes sense because the two components of the model are material impact and durability. The dense graded Klocke mix only shows 33% energy reduction per liter-year relative to its gap graded counterpart, because it required more paste by volume. Klocke was the only aggregate source that required higher cement content for dense graded mixes. Recall that the differences in initial material impact of the Klocke fresh mix were negligible (Table 9). Therefore, the 33% reduction in energy intensity per year should be attributed to its long service life projection.

Results for the Glendive aggregate source produced the greatest departures from expected results. While the material impact per liter of material with 6% air entrainment clearly demonstrated benefits of mix optimization, service life projections reversed this trend on an annualized basis. The gap graded mix demonstrated significantly longer service life than the dense and optimally graded, in that order (Table 8). UND suggested that this inconsistency was possibly due to laboratory error in creating the specimens or running the ASTM Rapid Chloride Ion Permeability Test.

Interestingly, the curves for water intensity reflected similar trends to those for energy and CO_2. The material intensity calculator does not account for life-cycle energy consumption related to water extraction, processing, and handling. However, trends in water reduction in dense graded mixes with 6% air entrainment should mirror that of cement reduction because aggregate is indeed replacing cement paste, which is inclusive of water. Therefore, the displacement of water will mirror the reduction of energy intensity because cement accounts for most of the energy requirement associated with the concrete mix. The displacement may not be proportional to cement reduction because the changes in the mix may require a higher w/c ratio, which might call for a greater reduction in cement than water.

Durability is clearly the most significant factor in environmental performance. Environmental performance drastically increased for specimens with the longest service life. The outlying cases that did not support mix optimization, the Klocke paste content results and the Glendive annualized results, also solidify that long-term durability can overcome high initial material impact. Even though the dense graded Klocke mixture with 6% air entrainment required more cement paste then its gap graded counterpart, it outperformed the gap graded mix in each environmental category because of its superior service life. Similarly, the initial material impact results from Glendive favored dense and optimally graded mix designs, but annualized results with short service life favored gap gradation because of permeability and service life performance.

NRMCA results for performance based standards also dramatically improved environmental performance over time. The performance based mix designs BR-2 and BR-3 demonstrated lower diffusion coefficients, which improved their durability and consequent annualized material impact. The two performance based standard mix designs had very low diffusion coefficients. BR-3 performed the best because of its high GGBFS content, which yields a very dense concrete, minimizing chloride ion ingress.

6.5 ACI 211.1 Conclusions

While there are several inconsistencies in results from the Glendive source, the two optimally graded mixes and the Klocke cement paste content, over-all environmental benefits of optimizing for are demonstrated. In three of the four UND cases, optimized mix designs had longer projected service lives, which are the most significant factor in determining environmental performance. Extending service life can make up for high initial material impact.

This analysis focuses myopically on chloride induced reinforced concrete deterioration without accounting for other performance factors, most importantly the affects of air voids and w/c ratio. Additional research should expand to evaluate these other factors including workability. The inconsistencies in the optimally graded mixes also should be explored. These results indicate that perhaps the “haystack” gradation curve reduces workability to the point that consolidation is a problem.

7 Thesis Conclusions

This study has proposed that by using consensus industry standards in 1904 to develop the market for U.S. cement in the short-term, industry standards have led to "sub-optimal" mix designs. Producers surrendered ultimate control of their product to the market and their product is now dictated by the industry members represented on standards writing committees. The 1904 standard also institutionalized the scientific reduction of cement and concrete in the United States, developing a technocratic culture that reduced and standardized concrete for its component parts rather than the whole. Furthermore, prescriptive standards for the components of concrete have institutionalized sub-optimal concrete construction.

However, the question of "What is optimal?" is always subject to the intention of optimization. Results support the claim that standards have played a large part in creating less durable concrete, because contemporary concrete has been optimized for rapid construction at the cost of log-term durability. To compound this problem, standardization has created a conservative culture of architects and engineers that rely heavily on industry standards to mitigate legal liabilities related to design failure. Therefore, by creating a commodity product and a conservative, technocratic culture, industry standards have institutionalized concrete construction optimized for high early strength and prove to be strong barriers to innovation for sustainability.

Case study analyses of ASTM C 150 "Standard Specification for Portland Cement" and ACI 211.1 "Standard Practice for Proportioning Normal, Heavyweight, and Mass Concrete" supports this proposition. The C 150 case demonstrated that by establishing industry standards, cement producers surrendered control of the products they provide and the conservative culture that they foster makes it difficult to innovate with new products. Cement producers established C-1 in 1904 to develop the market for domestic cement. Unfortunately, this standard locked-in procurement behavior by which customers rarely buy cements other than those conforming with C 150. Even though knowledge and technology have evolved such that cement companies can provide more optimal products, C-1 established a culture that resists change from products with which it has grown accustomed. For perspective, changing C 150 to incorporate intergrinding 5% limestone took 25 years.

While the C 150 case study made it clear that industry standards have played a significant role in developing and reinforcing conservative behavior, resistant to innovation for sustainability, it is the project specifications that explicitly inhibit sustainable concrete construction. Project specifications can override industry standards on an individual project basis at the discretion of the A/E. While it is possible to develop standards that incorporate more sustainable practice, the standards which the A/E uses in each project is up to professional discretion. Industry standards are a strong leverage point for raising awareness for innovation and sustainability, but ultimately the project specifications must incorporate innovative standards for sustainable concrete construction.

Study of ACI 211.1 demonstrated how even a guidance document has institutionalized mix proportioning optimized for high early strength at the cost of durability and, again, how difficult it is to change the status quo. Comparison of gap graded mixes prescribed by ACI 211.1 and optimally graded mixes using the Shilstone Method show that optimal proportioning can drastically reduce cement requirements, improving environmental performance and durability. While ACI 211.1 is not a legal document, it is well established as the accepted method by which concrete is proportioned. Revising 211.1 to include alternate gradation methods has also been an arduous process that took 15-20 years. Institutionalizing optimal gradation in practice will be an even more monumental task. Ready-mixed concrete producers that have always proportioned gap graded concrete are not comfortable with optimized gradation, compounded by the lack of infrastructure to support demand for well-graded aggregates. The transition to more sustainable proportioning will be lengthy, as the status quo has been long supported by ACI 211.1.

Social Network Analysis

Social networking was effective in identifying the most central standards related to concrete bridges. The standards identified provided excellent cases for understanding the central problems related to culture and innovation in general. The cases studied also illustrated barriers to more sustainable concrete construction. But there is not clear causation between network centrality and the degree to which the standards inhibit sustainability in order to identify leverage points for innovation for sustainable practice. Throughout the networks, the oldest standards were generally the most heavily referenced. Not coincidentally, those oldest standards and most heavily referenced standards are the core components and practices related to concrete: cement, proportioning, and admixtures.

There was little attempt to study social networking in terms of causality. It is difficult to surmise from this study if network centrality confers any degree of influence of particular standards. To determine the validity of social networking for concrete industry standards, follow-on work should proceed with additional case studies of the standards generated from this study. Perhaps a greater sample size will provide insight into this question of centrality and causation with respect to barriers to innovation and sustainability. Additionally, sensitivity analysis of network boundaries should be tested to verify these results for network centrality.

Additional Research

Follow-on research should continue with case studies of the most heavily referenced standards in this network to expand the sample size in testing the study propositions. This study's conclusions are only based on case studies of two standards. Additional cases should be studied to support or refute these conclusions. Additional study of the manner in which ASTM C 33 Standard Specification for Concrete Aggregates, which was the third most heavily referenced standard, was changed to accommodate gap gradation and the how it was recently changed to accommodate combined aggregate gradation would provide additional insight into the details of how the standardization process impacts innovation. Furthermore, studying ACI 305 Hot Weather Concreting and ACI 306 Cold Weather Concreting may provide additional insight into the efficacy of social networking for this application because both of these documents appeared unexpectedly as two of the ten most referenced documents related to concrete bridge construction.

Additional work should evaluate the environmental impacts of prescriptive specifications for other attributes. This study focused mainly on the repercussions of specifying for compressive strength and w/c ratio. Case studies should be built for prescriptions for air content and workability. Both of these attributes are related to strength and w/c ratio, but they should be folded into the analysis in depth. Air entrainment emerged in the 1950s to improve freeze-thaw durability. The University of North Dakota-Grand Forks report indicates that air content and cement content are positively correlated. Increasing air content requires more cement. The ramifications of this relationship should be studied in the historical context of the development of concrete.

This study found that project specifications inhibit innovation more so than industry standards. Further work should focus on a specific set of contract documents related to concrete bridge construction to identify specific requirements that inhibit sustainable practice. For example, in a typical set of Michigan contract documents, MDOT attempts to minimize traffic delays due to construction, which can lead to hasty concrete construction and less durable concrete. Perhaps life-cycle assessment including the costs of rapid construction, congestion, and durability should be evaluated in the context of project specifications. Life-cycle analysis may inform other opportunities to reform contract documents for more sustainable practice (Keoleian et al. 2005).

8 Appendices

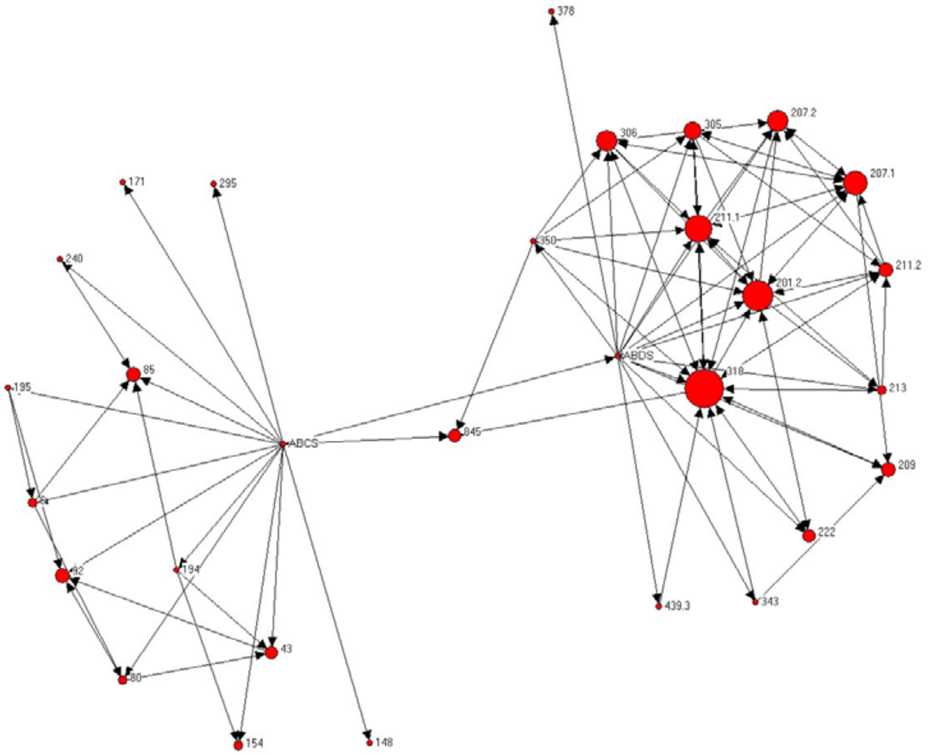
Appendix A- Network Results

65 Most Heavily Referenced Standards

Designation	Description	% of total references
ACI 318	ACI Building Code for Structural Concrete	0.04618
ASTM C150/M85	Standard Specification on Portland Cement	0.04396
ACI 211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	0.03996
ASTM 33	Standard Specification for Concrete Aggregates	0.03286
ASTM C595/M240	Standard Specification for Blended Hydraulic Cements	0.03197
ACI 306	Cold Weather Concreting	0.02842
ACI 305	Hot Weather Concreting	0.02576
ASTM C494/M194	Standard Specification forChemical Admixtures	0.02576
ACI 308	Standard. Practice for Curing Concrete	0.02442
ACI 116	ACI Terminology	0.02267
ASTM C260/M154	Standard Specification for Air Entraining Admixtures	0.02220
ASTM C618/M295	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	0.02087
ACI 301	Specifications for Structural Concrete	0.02043
ACI 304	Guide for Measuring, Mixing, Transporting, and Placing	0.01998
ASTM C125	C09 Terminology	0.01776
ACI 212.3	Chemical Admixtures for Concrete	0.01687
ACI 211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	0.01643
ASTM C330/M195	Light Weight Aggregates for Structural Concrete	0.01643
ASTM C1157	Performance Specification for Hydraulic Cement	0.01599
ACI 207.1	Mass Concrete	0.01421
ASTM C219	C01 Terminology	0.01421
ACI 302.1	Guide for Concrete Slab and Flooring	0.01332
ACI 223	Std. Practice for Use of Shrinkage Compensating Concrete	0.01288
ACI 347	Guide to Formwork	0.01288
ACI 465	Processing Additions for Use in the Manufacture of Hydraulic Cement	0.01288
ACI 309	Guide to Consolidation of Concrete	0.01243
ACI 117	Std. Specs for Tolerances and Concrete Construction Materials	0.01199
ASTM C989/M302	GGBFS	0.01199
ACI 207.2	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete	0.01110
ASTM C226	Standard Specification Air Entraining Additions for Use in the Manufacture of Air Entraining Hydraulic Cement	0.01110
ACI 214	Recommended Practice of Evaluation of Strenth Test Results	0.01021
ACI 224	Control of Cracking in Concrete Structures	0.00977
ASTM C845	Standard Specification for Expansive Hydraulic Cement	0.00977
ASTM C309/M148	Standard Specification for Liquid-Membrane Forming Compounds for Curing Concrete	0.00977
ASTM C1017	Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete	0.00799
ASTM C1240/M307	Silica Fume in Cementitious Mixtures	0.00799
ACI 233	Ground Granulated Blast Furnace Slag	0.00755
ACI 311.1	Manual for Concrete Inspection	0.00755
ASTM C51	Terminology Relating to Lima and Limestone	0.00711
ASTM E92	Wire Seives	0.00666
ACI 232.2	ACI Fly Ash	0.00666
ACI 504	Guide to Sealing Joints and Concrete Structures	0.00666
ASTM C685/M241	Concrete Made by Continuous Mixing and Volumetric Batching	0.00666
ACI 222	Corrosion of Metals in Concrete	0.00622
ACI 505	Non-reinforced Concrete Irrigation Pipe and Rubber Gasket Joints	0.00622
ACI 209	Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures	0.00577
ACI 311.4	Guide for Concrete Inspection	0.00577
ASTM C171/M171	Sheet Materials for Curing Concrete (ASTM)	0.00533
ASTM C94	Specification for Ready Mixed Concrete	0.00533
ACI 221	Guide for Use of Normal Weight and Heavy Weight Aggregates in Concrete	0.00533
ASTM C688	Functional Additions for Use in Hydraulic Cement	0.00533
M 43	Sizes of Aggegate for Road and Bridge Construction	0.00489
ACI 213	Guide to Structural Light Weight Aggregate	0.00489
ACI 313	Concrete Silos	0.00444
ACI 506.2	Specification for Shotcrete	0.00444
ACI 515.1	Guide to Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems	0.00444
M6	Fine Aggregate for Portland Cement Concrete	0.00400
ACI 225	Guide to Selection and Use of Hydraulic Cement	0.00400
ASTM C511/M201	Mixing Rooms and Moist Cabinets, Moist Rooms, and Water Storage Tanks used in the Testing of Hydraulic Cements and Concretes	0.00400
ACI 517.2	Accelerated Curing of Concrete	0.00400
ASTM C821	Lime for Use with Pozzolans	0.00400
ACI 303	Guide to Cast in Place Architectural Concrete	0.00355
ACI 350	Environmental Engineering Concrete Structures	0.00355
ACI 503	Use of Epoxy Compounds with Concrete	0.00355
ACI 544.1	SOA Report on FRC	0.00355

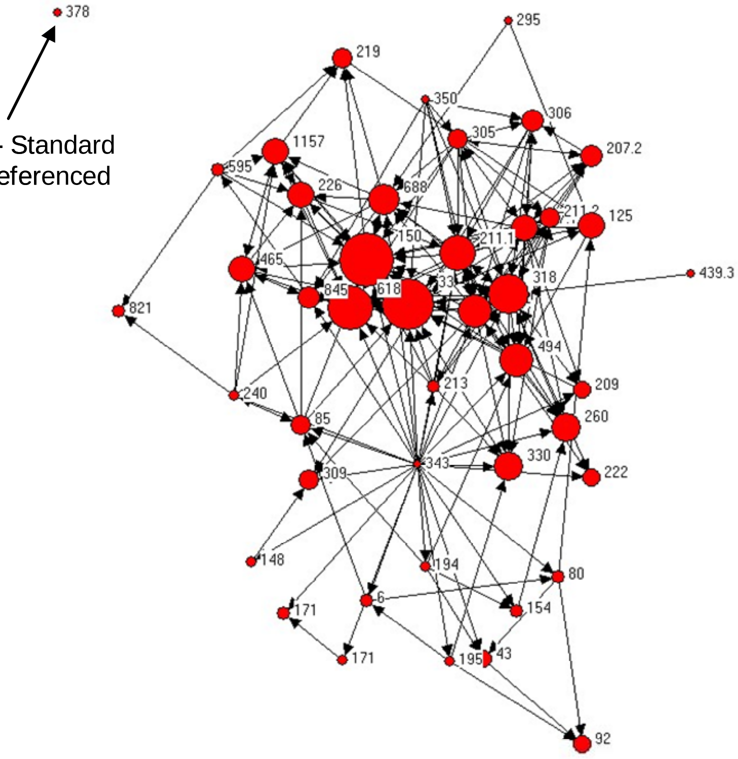
AASHTO LRFD Standard Specifications- 1^{st} Degree

Designation	Description	#	% of Total
ACI 318	Building Code	12	12.3711%
ACI 201.2	Guide to Durable Concrete	9	9.2784%
ACI 211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	8	8.2474%
ACI 207.1	Mass Concrete	7	7.2165%
ACI 207.2	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete	6	6.1856%
ACI 306	Cold Weather Concreting	6	6.1856%
ACI305	Hot Weather Concreting	5	5.1546%
ASTM 150/M 85	Portland Cement	4	4.1237%
ASTM E 92	Wire Seive	4	4.1237%
ACI 209	Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures	4	4.1237%
ACI 211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	4	4.1237%
AASHTO M43	Size of Aggregate for Road and Bridge Construction	3	3.0928%
ACI 222	Corrosion of Metals in Concrete	3	3.0928%
ASTM 845	Standard Specification for Expansive Hydraulic Cement	3	3.0928%
AASHTO M6	Fine Aggregate for Portland Cement Concrete	2	2.0619%
AASHTO M80	Course Aggregate for Portland Cement Concrete	2	2.0619%
AASHTO M154	Air Entraining Admixtures	2	2.0619%
ACI 213	Guide to Structural Light Weight Aggregate	2	2.0619%
ASTM 309/M148	Liquid Membrane Forming Compounds for Curing Concrete	1	1.0309%
ASTM 171/M171	Sheet Materials for Curing Concrete (AASHTO)	1	1.0309%
ASTM 494/M194	Chemical Admixtures	1	1.0309%
ASTM 330/M195	Light Weight Aggregates for Structural Concrete	1	1.0309%
ASTM 595/M240	Blended Hydraulic Cement	1	1.0309%
ASTM 618/M295	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	1	1.0309%
ACI 343	Analysis and Design of Reinforced Concrete Bridge Structures	1	1.0309%
ACI 350	Environmental Engineering Concrete Structures	1	1.0309%
ACI 439.3	Mechanical Connections of Reinforcing Bars	1	1.0309%
ABCS	AASHTO Bridge Construction Specifications	1	1.0309%
ABDS	AASHTO Bridge Design Specifications	1	1.0309%
	Sum	**97**	100.00%



AASHTO LRFD Standard Specifications- 2nd Degree

Designation	Description	#	% of Total
150/85	Portland Cement	20	9.9502%
33	Concrete Aggregates	15	7.4627%
595/240	Blended Hydraulic Cements	14	6.9652%
318	ACI Building Code	11	5.4726%
211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	10	4.9751%
201.2	Guide to Durable Concrete	9	4.4776%
494/194	Chemical Admixtures	9	4.4776%
618/295	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	8	3.9801%
260/154	Air Entraining Admixtures	9	4.4776%
330/195	Light Weight Aggregates for Structural Concrete	8	3.9801%
207.1	Mass Concrete	6	2.9851%
125	C09 Terminology	6	2.9851%
226	Air Entraining Additions for Use in the Manufacture of Air Entraining Hydraulic Cement	6	2.9851%
465	Processing Additions for Use in the Manufacture of Hydraulic Cement	6	2.9851%
1157	Performance Specification for Hydraulic Cement	6	2.9851%
207.2	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete	5	2.4876%
306	Cold Weather Concreting	5	2.4876%
845	Expansive Hydraulic Cement	5	2.4876%
211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	4	1.9900%
305	Hot Weather Concreting	4	1.9900%
219	C01 Terminology	4	1.9900%
309	Guide to Consolidation of Concrete	4	1.9900%
209	Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures	3	1.4925%
222	Corrosion of Metals in Concrete	3	1.4925%
43	Sizes of Aggegate for Road and Bridge Construction	3	1.4925%
92	Wire Seive	3	1.4925%
213	Guide for Structural Lightweight Aggregate Concrete	2	0.9950%
6	Fine Aggregate for Portland Cement	2	0.9950%
80	Coarse Aggregate for Portland Cement Concrete	2	0.9950%
171/171	Sheet Materials for Curing Concrete (ASTM)	3	1.4925%
688	Functional Additions for Use in Hydraulic Cement	2	0.9950%
821	Lime for Use with Pozzolans	2	0.9950%
148	Liquid-Membrane Forming Compounds for Curing Concrete	1	0.4975%
343	Guide for Concrete Highway and Bridgedeck Construction	0	0.0000%
350	Environmental Engineering Concrete Structures	0	0.0000%
378		0	0.0000%
449		0	0.0000%
	Sum	**200**	99.5025%



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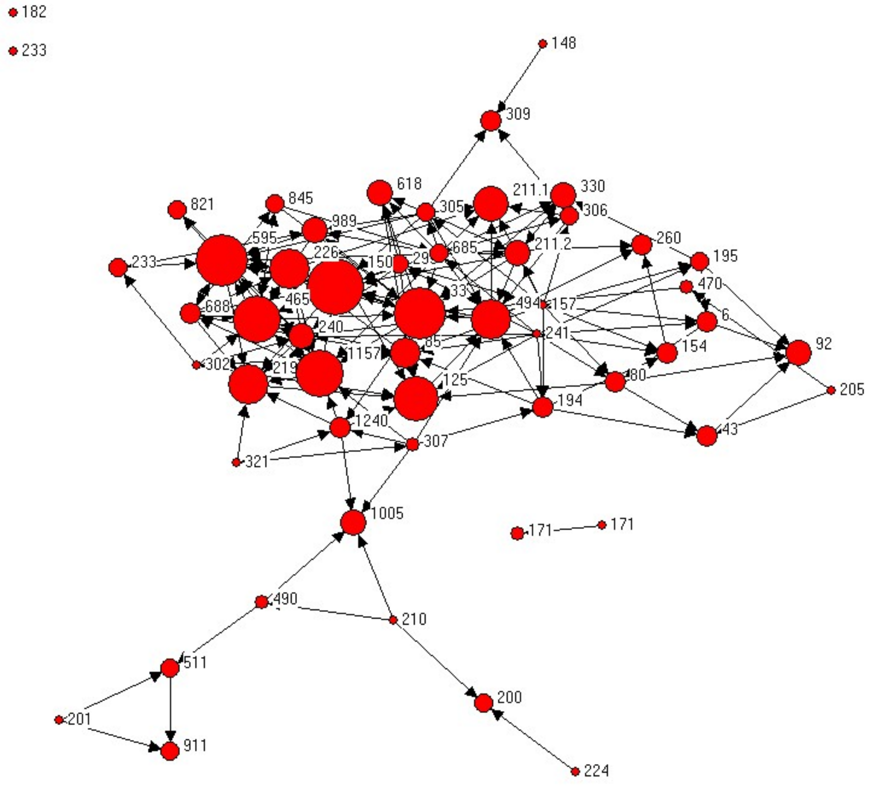
is not referenced

AASHTO Material Specifications- 1st Degree

Designation	Description	#	% of Total
150/85	Portland Cement	16	9.4118%
595/240	Blended Hydraulic Cements	14	8.2353%
494/194	Chemical Admixtures	10	5.8824%
33	Concrete Aggregates	10	5.8824%
465	Processing Additions for Use in the Manufacture of Hydraulic Cement	9	5.2941%
1157	Performance Specification for Hydraulic Cement	9	5.2941%
125	C09 Terminology	8	4.7059%
226	Air Entraining Additions for Use in the Manufacture of Air Entraining Hydraulic Cement	7	4.1176%
219	C01 Terminology	7	4.1176%
618/295	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	6	3.5294%
330/195	Light Weight Aggregates for Structural Concrete	6	3.5294%
260/154	Air Entraining Admixtures	6	3.5294%
211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	6	3.5294%
1240/307	Silica Fume in Cementitious Mixtures (ASTM)	4	2.3529%
1005	Reference Masses and Devices for Determining Mass and Volume for Use in Physical Testing of Hydraulic Ceme	4	2.3529%
989	GGBFS	4	2.3529%
211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	4	2.3529%
92	Wire Seives	4	2.3529%
309/148	Standard Specification for Liquid Forming Compounds for Curing Concrete	3	1.7647%
688	Functional Additions for Use in Hydraulic Cement	3	1.7647%
80	Coarse Aggregate for Portland Cement Concrete	3	1.7647%
43	Sizes of Aggegate for Road and Bridge Construction	3	1.7647%
6	Fine Aggregate for Portland Cement	3	1.7647%
685/241	Concrete Made by Volumetric Batching and Contiuous Mixing	2	1.1765%
511/201	Mixing Rooms and Moist Cabinets, Moist Rooms, and Water Storage Tanks used in the Testing of Hydraulic Cen	2	1.1765%
911	Quicklime, Hydrated Lime and Limestone for Chemical Uses	2	1.1765%
845	Expansive Hydraulic Cement	2	1.1765%
821	Lime for Use with Pozzolans	2	1.1765%
306	Cold Weather Concreting	2	1.1765%
305	Hot Weather Concreting	2	1.1765%
233	GGBFS (ACI)	2	1.1765%
200	Epoxy Protective Coatings	2	1.1765%
490/210		1	0.5882%
470/205	Molds for Forming Concrete Test Cylinders Vertically	1	0.5882%
171/171	Sheet Materials for Curing Concrete (ASTM)	1	0.5882%
321		0	0.0000%
302		0	0.0000%
233		0	0.0000%
224		0	0.0000%
182		0	0.0000%
157		0	0.0000%
	Sum	**170**	1



AASHTO Material Specifications- 2nd Degree

Designation	Description	#	% of Total
150/85	Portland Cement	31	5.6466%
318	ACI Building Code	25	4.5537%
33	Concrete Aggregates	24	4.3716%
595/240	Blended Hydraulic Cements	24	4.3716%
494/194	Chemical Admixtures	20	3.6430%
211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	19	3.4608%
260/154	Air Entraining Admixtures	19	3.4608%
618/295	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	17	3.0965%
308	Standard Practice for Curing Concrete	17	3.0965%
116	ACI Terminology	15	2.7322%
301	Specifications for Structural Concrete	14	2.5501%
304	Guide for Measuring, Mixing, Transporting, and Placing	13	2.3679%
125	C09 Terminology	12	2.1858%
306	Cold Weather Concreting	12	2.1858%
309	Standard Specification for Liquid-Membrane Forming Compounds for Curing Concrete	11	2.0036%
989	GGBFS	11	2.0036%
305	Hot Weather Concreting	11	2.0036%
1017	Chemical Admixtures for Use in Producing Flowing Concrete	10	1.8215%
1157	Performance Specification for Hydraulic Cement	10	1.8215%
223	Standard Practice for Shrinkage	10	1.8215%
219	C01 Terminology	9	1.6393%
211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	9	1.6393%
302.1	Guide for Concrete Slab and Flooring	9	1.6393%
347	Guide to Formwork	9	1.6393%
330/195	Light Weight Aggregates for Structural Concrete	8	1.4572%
465	Processing Additions for Use in the Manufacture of Hydraulic Cement	8	1.4572%
845	Expansive Hydraulic Cement	8	1.4572%
117	Std. Specs for Tolerances and Concrete Construction Materials	8	1.4572%
224	Control of Cracking in Concrete Structures	8	1.4572%
226		7	1.2750%
685		7	1.2750%
212.2		6	1.0929%
212.3		6	1.0929%
214		6	1.0929%
309	Guide for Consolidation of Concrete	6	1.0929%
311.4		6	1.0929%
311.1		5	0.9107%
313		5	0.9107%
92		4	0.7286%
171	Standard Specification for Sheet Materials for Curing Concrete (ASTM)	4	0.7286%
511/201		4	0.7286%
688		4	0.7286%
778		4	0.7286%
1240		4	0.7286%
1328		4	0.7286%
233		4	0.7286%
349		4	0.7286%
506		4	0.7286%
91		3	0.5464%
821		3	0.5464%
225		3	0.5464%
232.1		3	0.5464%
359		3	0.5464%
517.2		3	0.5464%
6		2	0.3643%
43		2	0.3643%
80		2	0.3643%
911		2	0.3643%
1005		2	0.3643%
1329		2	0.3643%
11		2	0.3643%
306.1		2	0.3643%
307		2	0.3643%
363		2	0.3643%
423		2	0.3643%
506.2		2	0.3643%
593		1	0.1821%
926		1	0.1821%
215		1	0.1821%
221		1	0.1821%
315		1	0.1821%
352		1	0.1821%
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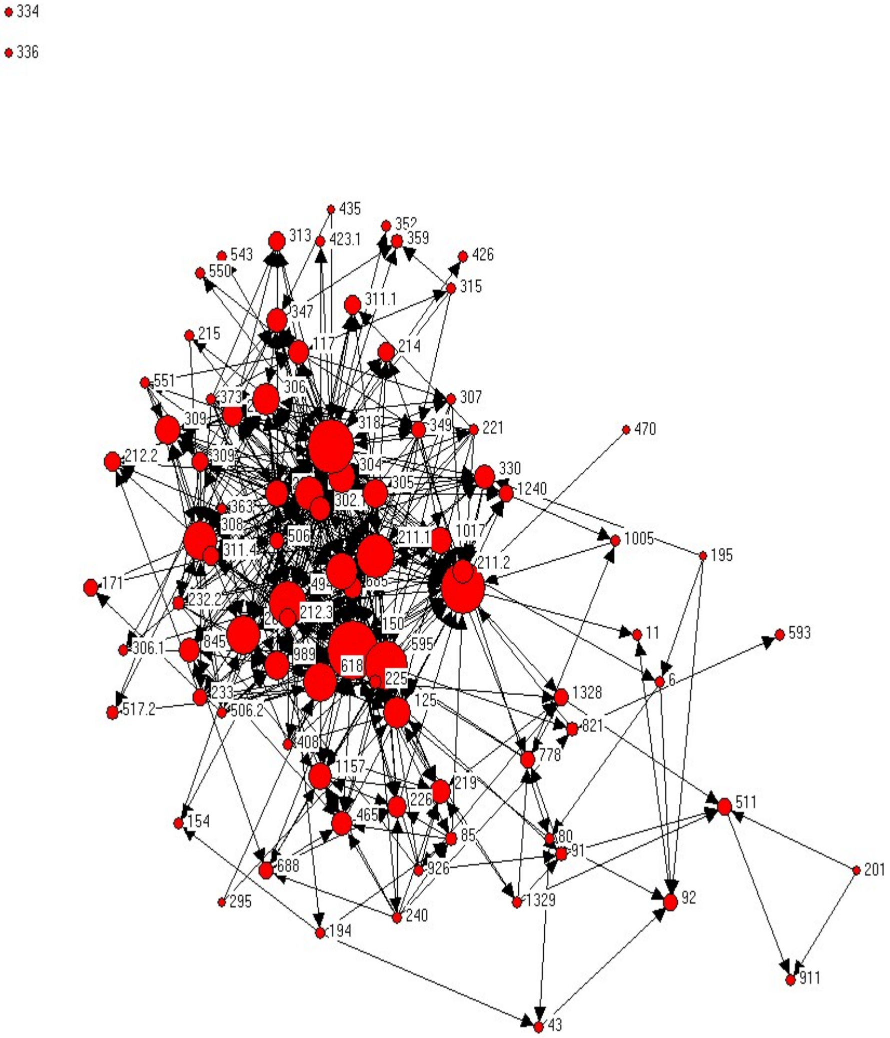
	Sum	**549**	100.0000%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240
1329
92
194
911
43

AASHTO Material Specifications- 3^{rd} Degree (ACI Only)

Designation	Description	#	% of Total
318	Building Code for Structural Concrete	46	5.3864%
201.2	Guide to Durable Concrete	34	3.9813%
211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	33	3.8642%
304	Guide for Measuring, Mixing, Transporting, and Placing	32	3.7471%
306	Cold Weather Concreting	32	3.7471%
116	Terminology	31	3.6300%
305	Hot Weather Concreting	30	3.5129%
308	Std. Practice for Curing Concrete	29	3.3958%
301	Specifications for Structural Concrete	23	2.6932%
302.1	Guide for Concrete Slab and Flooring	21	2.4590%
347	Guide to Formwork	20	2.3419%
117	Std. Specs for Tolerances and Concrete Construction Materials	19	2.2248%
207.1	Mass Concrete	19	2.2248%
223	Std. Practice for Use of Shrinkage Compensating Concrete	19	2.2248%
309	Guide for Consolidation of Concrete	18	2.1077%
212.3	Chemical Admixtures for Concrete	15	1.7564%
504	Guide to Sealing Joints and Concrete Structures	15	1.7564%
207.2	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete	14	1.6393%
224	Control of Cracking in Concrete Structures	14	1.6393%
214	Recommended Practice of Evaluation of Strenth Test Results	12	1.4052%
311.1	Manual for Concrete Inspection	12	1.4052%
211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	11	1.2881%
212.2	Chemical Admixtures for Concrete	11	1.2881%
221	Guide for Use of Normal Weight and Heavy Weight Aggregates in Concrete	11	1.2881%
515.1	Guide to Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems	10	1.1710%
207.4	Cooling and Insulating Systems for Mass Concrete	8	0.9368%
222	Corrosion of Metals in Concrete	8	0.9368%
232.1	Use of Natural Pozzolans in Concrete	8	0.9368%
233	GGBFS	8	0.9368%
303	Guide to Cast in Place Architectural Concrete	8	0.9368%
503	Use of Epoxy Compounds with Concrete	8	0.9368%
506.2	Specification for Shotcrete	8	0.9368%
544.1	SOA Report on FRC	8	0.9368%
213	Guide to Structural Light Weight Aggregate	7	0.8197%
311.4	Guide for Concrete Inspection	7	0.8197%
350		7	0.8197%
506		7	0.8197%
207.5		6	0.7026%
209		6	0.7026%
212.1		6	0.7026%
224.1		6	0.7026%
225		6	0.7026%
304.2		6	0.7026%
309.2		6	0.7026%
345		6	0.7026%
503.2		6	0.7026%
517.2		6	0.7026%
544.2		6	0.7026%
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216		5	0.5855%
304.3		5	0.5855%
306.1		5	0.5855%
313		5	0.5855%
332		5	0.5855%
344		5	0.5855%
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309.1		2	0.2342%
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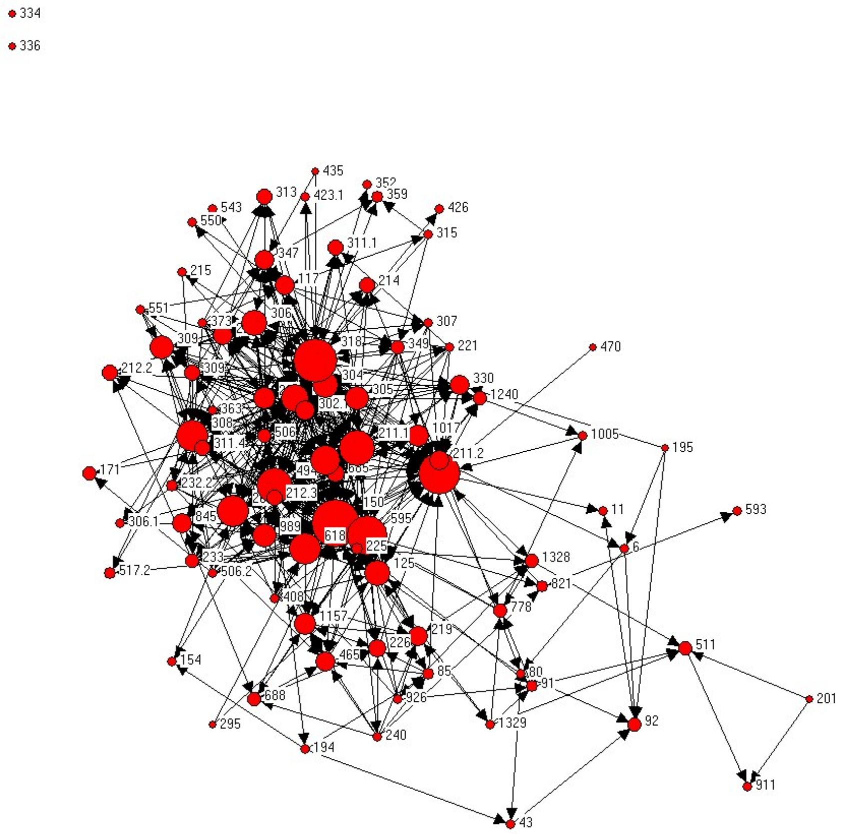
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ASTM C01 and C09- 1st Degree

Designation	Description	#	% of Total
150	Portland Cement	28	7.3491%
33	Concrete Aggregates	25	6.5617%
595	Blended Hydraulic Cements	19	4.9869%
494	Chemical Admixtures	17	4.4619%
618	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture	15	3.9370%
125	C09 Terminology	14	3.6745%
260	Air Entraining Admixtures	14	3.6745%
211.1	Std. Practice for Proportioning Normal, Heavyweight and Mass Concrete	14	3.6745%
94	Specification for Ready Mixed Concrete	12	3.1496%
219	C01 Terminology	12	3.1496%
989	GGBFS	12	3.1496%
330	Light Weight Aggregates for Structural Concrete	11	2.8871%
1157	Performance Specification for Hydraulic Cement	11	2.8871%
318	ACI Building Code	10	2.6247%
301	Specifications for Structural Concrete	9	2.3622%
308	Standard Practice for Curing Concrete	9	2.3622%
1017	Chemical Admxitures for Use in Producing Flowing Concrete	8	2.0997%
306	Cold Weather Concreting	7	1.8373%
309	Standard Specification for Liquid-Membrane Forming Compounds for Curing Concrete	6	1.5748%
465	Processing Additions for Use in the Manufacture of Hydraulic Cement	6	1.5748%
685	Concrete Made by Volumetric Batching and Contiuous Mixing	6	1.5748%
1240	Silica Fume in Cementitious Mixtures	6	1.5748%
305	Hot Weather Concreting	6	1.5748%
226	Air Entraining Additions for Use in the Manufacture of Air Entraining Hydraulic Cement	5	1.3123%
270	Mortar for Unit Masonry	5	1.3123%
1116	FRC and Shotcrete	5	1.3123%
116	ACI Terminology	5	1.3123%
211.2	Std. Prctice for Selecting Proportions for Structural Lightweight Concrete	5	1.3123%
214	Recommended Practice of Evaluation of Strenth Test Results	5	1.3123%
637	Aggregates for Radiation Shielding Concrete	4	1.0499%
778	Standard Sand	4	1.0499%
845	Expansive Hydraulic Cement	4	1.0499%
506.2	Guide to Shotcrete	4	1.0499%
171	Sheet Materials for Curing Concrete (ASTM)	3	0.7874%
511	Mixing Rooms and Moist Cabinets, Moist Rooms, and Water Storage Tanks used in the Testing of Hydraulic Cements and Concretes	3	0.7874%
688	Functional Additions for Use in Hydraulic Cement	3	0.7874%
232	Use of Natural Pozzolans in Concrete	3	0.7874%
233	GGBFS	3	0.7874%
506	Specification for Shotcrete	3	0.7874%
51		2	0.5249%
91		2	0.5249%
144		2	0.5249%
387		2	0.5249%
593		2	0.5249%
821		2	0.5249%
1005		2	0.5249%
1141		2	0.5249%
1329		2	0.5249%
1438		2	0.5249%
506.1		2	0.5249%
206		1	0.2625%
207		1	0.2625%
230		1	0.2625%
331		1	0.2625%
332		1	0.2625%
404		1	0.2625%
881		1	0.2625%
887		1	0.2625%
911		1	0.2625%
926		1	0.2625%
928		1	0.2625%
979		1	0.2625%
1059		1	0.2625%
1107		1	0.2625%
1315		1	0.2625%
1328		1	0.2625%
1602		1	0.2625%
548.3		1	0.2625%
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869		0	0.0000%
937		0	0.0000%
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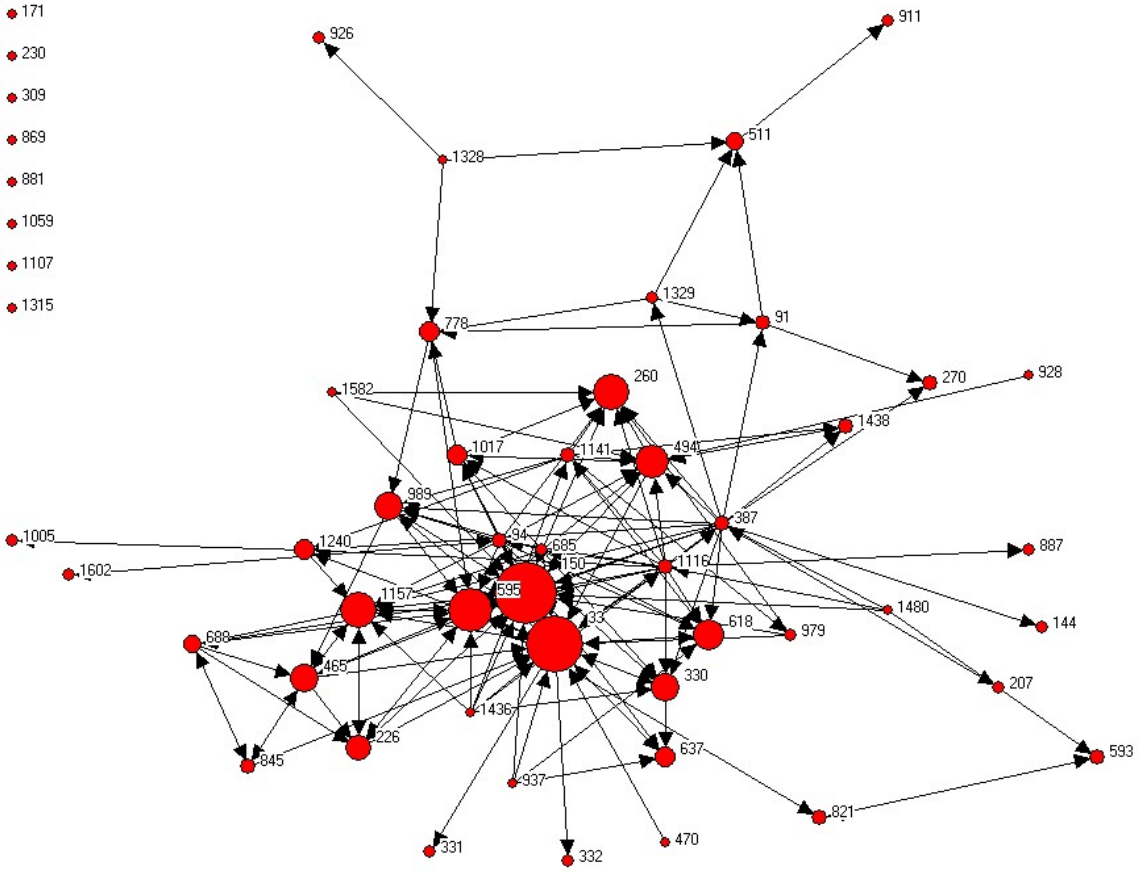
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Appendix B- University of North Dakota-Grand Forks and National Ready Mixed Concrete Association Mix Designs

Mix Design Proportions per Cubic Yard for Rolag Mix Designs

Mix No.:	1	2	3	4	5	6	7
Mix Designation:	RO-GG-2%	RO-GG-4%	RO-GG-6%	RO-DG-2%	RO-DG-4%	RO-DG-6%	RO-OG-6%
Date	3/21/01	5/16/01	1/9/01	4/23/01	5/23/01	4/19/01	7/10/01
Cement (lbs.)	286.3	294	394.8	256.2	270.2	315	285.6
Fly Ash (lbs.)	122.7	126	169.2	109.8	115.6	135	122.4
Total Cementitious (lbs.)	409	420	564	366	386	452	408
Bags of Cementitious	4.4	4.5	6.0	3.9	4.1	4.8	4.3
Paste Volume (%)	24.2	25.7	31.3	23.0	25.4	27.8	27.2
Fine Sand (lbs.)	1375	1322	1222	939	954	879	877
Coarse Sand (lbs.)	0	0	0	644	621	578	590
Inter. Aggregate (lbs.)	0	0	0	92	90	90	89
Coarse Aggregate (lbs.)	2050	2027	1874	1762	1723	1747	1720
Expected Air Content (%)	2%	4%	6%	2%	4%	6%	6%
Adj. Workability Factor	36	36	36	33.6	33.6	33.6	33.6
Coarseness Factor	58	58	58	50.1	50.4	50.9	50.5
Air-Entrained Admixture (oz.)	0.0	3.4	10.7	0.0	3.1	8.6	5.1
Water (gallons)	28.5	27.0	27.0	29.0	27.8	26.0	26.5
Water (lbs.):	237.4	224.0	224.0	242.0	232.0	217.0	221.0
Water/Cementitious Ratio (w/c)	0.58	0.53	0.40	0.66	0.60	0.48	0.54

Mix Design Proportions per Cubic Yard for Klocke Mix Designs

Mix No.:	1	2	3	4	5	6	7
Mix Designation:	KL-GG-2%	KL-GG-4%	KL-GG-6%	KL-DG-2%	KL-DG-4%	KL-DG-6%	KL-OG-6%
Date:	5/14/01	4/13/01	12/21/01	6/19/01	5/30/01	7/17/01	7/27/01
Cement (lbs.):	368.9	368.34	394.8	373.1	385	389.375	381.5
Fly Ash (lbs.):	158.1	157.86	169.2	159.9	165	166.875	163.5
Total Cementitious (lbs.):	527	526.2	564	533	550	556.25	545
Bags of Cementitious	5.6	5.6	6.0	5.7	5.9	5.9	5.8
Paste Volume (%)	26.5	27.6	29.6	26.9	28.7	31.3	29.8
Fine Aggregate (lbs.):	1387	1367	1284.733	1163	1125	1099	1203
Intermediate Aggregate (lbs.):	0	0	0	398.13	395.5	380	0
Coarse Aggregate (lbs.):	1883	1857	1824.5	1711	1669	1631	1926
Expected Air Content (%)	2	4	6	2	4	6	6
Adjusted Workability Factor	37.8	37.8	37.8	34	34	34	33
Coarseness Factor	70.6	70.6	70.6	60	60	60	54
Admixtures (oz.):	0.0	0.8	8.5	0.0	6.2	14.0	9.5
Water (gallons):	28.4	29.1	27.0	28.8	27.7	26.7	26.2
Water (lbs):	237.0	242.7	225.4	240.0	231.0	222.0	218.0
Water/Cementitious Ratio:	0.45	0.42	0.40	0.45	0.42	0.40	0.40

Mix Design Proportions per Cubic Yard for Klocke Mix Designs

Mix No.	1	2	3	4	5	6	7
Mix Designation	GL-GG-2%	GL-GG-4%	GL-GG-6%	GL-DG-2%	GL-DG-4%	GL-DG-6%	GL-OG-6%
Date:	8/30/01	9/10/01	7/26/01	10/10/01	10/8/01	9/18/01	12/6/01
Cement (lbs.)	296.8	326.9	394.8	340.9	320.6	354	319.9
Fly Ash (lbs.)	127.2	140.1	169.2	146.1	137.4	151.7	137.1
Total Cementitious (lbs.)	424	467	564	487	458	506	457
Bags of Cementitious	4.5	5.0	6.0	5.2	4.9	5.4	4.9
Paste Volume (%)	24.5	27.1	31.1	26.9	27.1	29.4	28.3
Fine Aggregate (lbs.)	1640	1600	1508	1650	1657	1598	1690
Intermediate Aggregate (lbs.)	0	0	0	239	237	230	0
Coarse Aggregate (lbs.)	1727	1667	1577	1355	1340	1303	1520
Expected Air Content (%)	2	4	6	2	4	6	6
Adjusted Workability Factor	35	36	36	35.5	35	36	34.3
Coarseness Factor	59	59	59	49.6	49.4	49.5	49.4
Admixtures (oz.)	0	3.3	9.5	0	3.4	7.1	5.5
Water (gallons)	28	27.6	28	30.4	28	26.7	26.3
Water (lbs.)	233.3	230.0	233.3	253.3	233.3	222.5	219.2
Water/Cementitious Ratio:	0.55	0.49	0.41	0.52	0.51	0.44	0.48

Mix Design Proportions per Cubic Yard for Riverdale Mix Designs

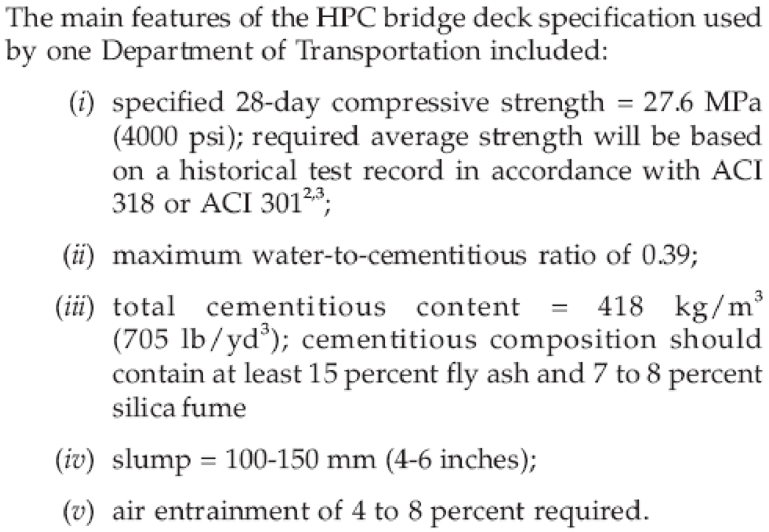
Mix No.:	1	2	3	4	5	6	7
Mix Designation:	RI-GG-2%	RI-GG-4%	RI-GG-6%	RI-DG-2%	RI-DG-4%	RI-DG-6%	RI-OG-6%
Date	11/20/2001	9/25/2001	8/21/2002	11/19/2001	12/13/2001	10/23/2001	4/10/2002
Cement (lbs.)	291.9	296.1	394.8	291.9	324.1	305.9	305.9
Fly Ash (lbs.)	125.1	126.9	169.2	125.1	138.9	131.1	131.1
Total Cementitious (lbs.)	417	423	564	417	463	437	437
Bags of Cementitious	4.4	4.5	6.0	4.4	4.9	4.6	4.6
Paste Volume (%)	22.7	23.5	28.4	23.0	25.0	25.3	24.8
Sand (lbs.)	1446	1432	1326	1533	1450	1465	1477
Inter. Aggregate (lbs.)	0	0	0	288	288	282	280
Coarse Aggregate (lbs.)	2030	2009	1881	1627	1622	1592	1590
Expected Air Content (%)	2%	4%	6%	2%	4%	6%	6%
Adj. Workability Factor	35	35	35	34	34	34	34
Coarseness Factor	71	71	71	59.5	59.9	59.7	61
Air-Entrained Admixture (oz.)	0.0	3.0	10.0	0.0	1.9	4.7	3.5
Water (gallons)	25.0	22.3	22.5	25.6	23.9	21.5	20.4
Water (lbs.):	208.5	186.0	187.7	213.5	199.0	179.0	170.0
Water/Cementitious Ratio (w/c)	0.50	0.44	0.33	0.51	0.43	0.41	0.39

NRMCA Performance Based Mix Designs and Test Results

Product description	*Mixture*			
	BR-1	*BR-2*	*BR-3*	*BR-4*
Cement, kg/m^3 (lb/yd^3)	326 (550)	253 (426)	178 (300)	253 (426)
Fly ash, kg/m^3 (lb/yd^3)	62 (105)	89 (150)	(0)	89 (150)
Silica fume, kg/m^3 (lb/yd^3)	30 (50)	14 (24)	(0)	(0)
Slag, kg/m^3 (lb/yd^3)	(0)	(0)	178 (300)	(0)
UFFA, kg/m^3 (lb/yd^3)	(0)	(0)	(0)	20 (34)
Total cementitious content, kg/m^3 (lb/yd^3)	418 (705)	356 (600)	356 (600)	362 (610)
Coarse aggregate (#67), kg/m^3 (lb/yd^3)	1068 (1800)	1140 (1922)	1151 (1940)	1154 (1945)
Fine aggregate, lb/yd^3 (kg/m^3)	665 (1121)	711 (1199)	717 (1209)	720 (1214)
Water, lb/yd^3 (kg/m^3)	163(275)	139 (234)	139 (234)	129 (218)
w/cm	0.39	0.39	0.39	0.36
AEA, ml/kg (oz/cwt)	0.26 (0.40)	0.29 (0.45)	0.26 (0.40)	0.26 (0.40)
Type A WR, ml/kg (oz/cwt)	2.61 (4)	2.61 (4)	2.61 (4)	2.61 (4)
Type F HRWR, ml/kg (oz/cwt)	8.49 (13.0)	6.14 (9.4)	12.02 (18.4)	7.25 (11.1)
Fresh concrete properties				
Slump, mm (in)	102 (4.00)	127 (5.00)	127 (5.00)	146 (5.75)
Air, percent	4.6	7.2	4.7	7.6
Density, kg/m^3 (lb/ft^3)	2334 (145.7)	2308 (144.1)	2411 (150.5)	2283 (142.5)
Temperature, $^\circ$C ($^\circ$F)	21 (69)	21 (69)	18 (65)	21(69)
Hardened concrete properties				
Compressive strength, MPa (lb/in^2)				
3-day	28.61 (4,150)	25.16 (3,650)	17.93 (2,600)	25.58 (3,710)
7-day	37.37 (5,420)	33.64 (4,880)	38.33 (5,560)	35.58 (5,160)
28-day	51.57 (7,480)	46.88 (6,800)	61.84 (8,970)	49.50 (7,180)
Length change (drying shrinkage), percent				
28-day	-0.037	-0.017	-0.021	-0.018
90-day	-0.045	-0.027	-0.029	-0.027
180-day	-0.043	-0.024	-0.025	-0.024
RCP, Coulombs				
45-day	1563	1257	1126	1244
110-day	541	434	541	479
180-day	327	275	375	242
Rate of penetration (RMT), mm/(V-h)				
60-day	0.019	0.018	n/a	0.023
120-day	0.0090	0.0070	0.0060	0.011
180-day	0.0058	0.0045	0.0054	0.0047
Rate of water absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$ at 69 days				
Initial	6.19	7.37	8.89	15.20
Secondary	3.47	4.59	4.52	6.37
Diffusion coefficient, x10^{-13} m^2/s				
180 days	7.17	5.38	4.31	9.59
Surface chloride, percent by weight of concrete				
180-day	0.74	0.84	0.58	0.67

Appendix C- NRMCA Performance Based Specification

Prescriptive Specification:



The main features of the HPC bridge deck specification used by one Department of Transportation included:

(*i*) specified 28-day compressive strength = 27.6 MPa (4000 psi); required average strength will be based on a historical test record in accordance with ACI 318 or ACI 301[2,3];

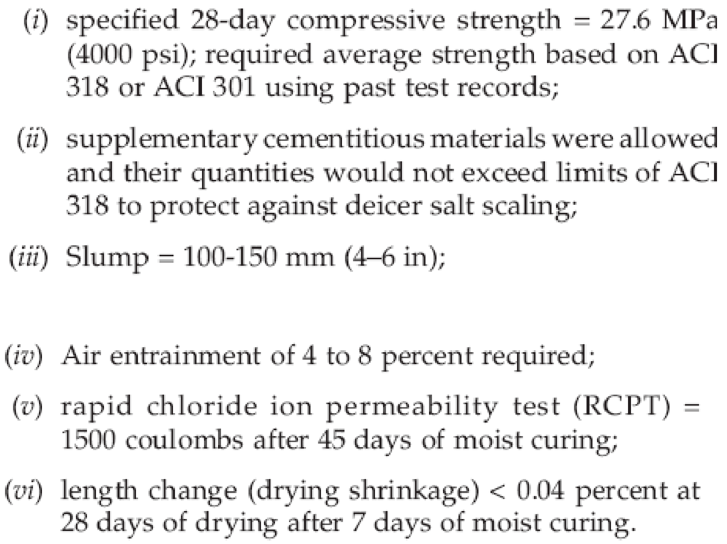
(*ii*) maximum water-to-cementitious ratio of 0.39;

(*iii*) total cementitious content = 418 kg/m^3 (705 lb/yd^3); cementitious composition should contain at least 15 percent fly ash and 7 to 8 percent silica fume

(*iv*) slump = 100-150 mm (4-6 inches);

(*v*) air entrainment of 4 to 8 percent required.

Sample Performance Specification:



(*i*) specified 28-day compressive strength = 27.6 MPa (4000 psi); required average strength based on ACI 318 or ACI 301 using past test records;

(*ii*) supplementary cementitious materials were allowed and their quantities would not exceed limits of ACI 318 to protect against deicer salt scaling;

(*iii*) Slump = 100-150 mm (4–6 in);

(*iv*) Air entrainment of 4 to 8 percent required;

(*v*) rapid chloride ion permeability test (RCPT) = 1500 coulombs after 45 days of moist curing;

(*vi*) length change (drying shrinkage) < 0.04 percent at 28 days of drying after 7 days of moist curing.

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