CONCRETE CONSTRUCTION
MAKING THE PROCESS WORK
FOR A GREEN ENVIRONMENT

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ABSTRACT: Concrete is man's most versatile building material. The resources needed to produce a durable concrete structure are available any place in the world. The author first presented the basic concept of making the concrete process work to the American Concrete Institute in April of 1976. According to the editor’s note in the paper published in 1977, that paper made a difference in that committees became more conscious of the needs of contractors.

The 21st century brings new restrictions and new opportunities. While this document addresses the nine original design phases they are looked upon as a appropriate for “green concrete” technology. We are still in the learning stage and, as many will find, it must be done to meet new – often more demanding – needs.

INTRODUCTION: Over the past 30 years there have been many changes that must be considered today. 30 years ago no one heard of “green buildings or green highways?” The term “sustainable” is used today to stress the need for long-term durability of the infrastructure. We never questioned the effect of the amount of portland cement used in a cubic yard concrete on global warming. No one considered availability of aggregate.

Today it is recognized that for every ton of portland cement produces 0.9 ton of greenhouse gases are added to the atmosphere leading to global warming. The most desirable concrete aggregate are in short supply in many parts of the country. Much of the aggregate used today in San Francisco is shipped by barge from Canada. Chicago constructors are questioning the future availability of sand. We, in Texas, are faced with depletion of the most desirable aggregate sources. The sand and gravel sources between Dallas and Ft. Worth are now covered by Hwy 360, residences, and golf courses. It is necessary to conserve our non-renewable resources for future users.

The term “process” is used in the title. The dictionary uses the terms "process" and "operation" as being synonymous. In our judgment they are very different. The concrete process requires that all parts to the planning and design fit within a system. The references are not all the same as in past years. This concept requires that engineering meet the often-neglected definition of engineering as “the science dealing with the conversion of materials available in nature into products usable by man.” Now, we must think “green.” As one contractor said when asked what was required for a green project, he said, “Follow the specifications.” This clearly puts the responsibility of increasing green house gases on design professionals.

The total concrete system from materials at the pits and quarries to the completed structure is being scrutinized whether it is for a highway or a building. The jigsaw puzzle, Figure 1, represents the parts of the puzzle that must be resolved. Each part must be planned and specified within the contract documents to fit within the total system. "Operation” relates to the contractor’s work,
such as putting a table-form in place for construction of a slab in high-rise construction and placing the concrete.

**WORKING WITH “GREEN”:** The July issue of CIVIL ENGINEERING includes an article titled Senate Bill would promote the "Green" Approach in Construction for Federal Agencies. The Senate bill titled “High Performance Green Buildings Act (S 506)” has been approved by the Senate Committee on Environment and Public Works vote of 14 to 4. The bill is intended to "encourage the federal government to act as an example for state and local governments, the private sector, and individuals by building high-performance green buildings that reduce energy and environmental impacts." A high-performance green building is a building "for which, during its planning, design, and construction; the environmental and energy impacts of building location and site design are considered." That bill has yet to be introduced in the House bill though that action is planned. The ASCE has written a letter to the appropriate House Committee commending their action on this subject for the infrastructure.

According to the US Green Building Council ([www.usgbc.com](http://www.usgbc.com)) the definition of a green building is:

"Sustainable, or "green building," design and construction provide an opportunity to use resources more efficiently, while creating healthier and more energy efficient homes and commercial buildings. Successful green buildings leave a light footprint on the environment through conservation of resources, while at the same time balancing energy efficient, cost-effective, low maintenance products for construction needs. You know the words, if Green building design involves finding the delicate balance between the [structure] and a sustainable environment.

"As the green philosophy continues to grow, specifiers will increasingly face pressures to use or not to use certain products. In a handful of states, proposed regulatory language and tax incentives have already been introduced to incorporate, or not to incorporate, certain products based on "green" attributes. However, specifiers are cautioned to focus less on products and more on the sum of the products as a whole."

Sustainability is one of the key points of the green concrete construction James A. D’Aliosio PE described the 10 parts in the June 2007 issue of STRUCTURAL ENGINEER. As follows:

1. "Develop an awareness of the environmental costs of construction materials and systems ... But, the worldwide production of portland cement generates about 8% of the carbon dioxide that is emitted into the atmosphere.
2. “Minimize the use of materials with high environmental impact. ... for example, he suggests the use other cementitious materials as partial replacements for the portland cement.”
3. "Consider the demolition, or deconstruction, of what you design." He cites a negative related the possible use of higher strength than required for a slab on grade as it requires greater energy to break apart and crush.
4. "Strive for synergy of sustainability of ideas with the rest of the team." He cites the need to deal with all the members of the team including the architect. "The proactive approach is to familiarize yourself with the basic principles of sustainable design and not understand how these mesh with the architectural design intent."
5. “Understand the building envelope installation requirements and coordinate with the team. Since the building envelope is essentially part of the structure -- or literally tied to it -- structural engineers should understand the insulation system intended.

6. “Understand resource-efficient M/E/P systems and coordinate with the team.” A significant factor is the rooftop photovoltaic cells, minimize use if water by using gray water recycling systems, and the like can make the overall design process runs smoothly, with fewer surprises down the road for anyone." the use of other sources of electricity.

7. "Design buildings for adaptability and durability... make sure materials and systems are durable. If we can create flexibility for future use, we may be able to avoid premature obsolescence.

8. "Considered non-traditional structural systems. Some proven high-performance and low impact structural systems have not yet been well accepted into mainstream construction."

9. "Share the knowledge that you acquire. The Structural Engineering Institute’s Sustainability Committee will continue publishing articles of interest in the coming months... "

10. “Adopt sustainable practices in your business and personal life. We have many opportunities to make a difference. Structural engineers can act as champions for a more sustainable world.”

There are a number of key issues which must be addressed individually. The PCA’s BRIEFING KIT (www.concretethinker.com) provides definitions and other discussion of the subject:

1. “Sustainability refers to the ability to build for today and tomorrow without depleting future resources. A growing global population is beginning to strain the finite resources available on the planet. Sustainability seeks to balance the economic, social and environmental impacts, recognizing that population growth will continue. Sustainable development brings this evaluation to the design and construction industry.

2. "Recognizing that U.S. buildings to nearly 10% of the world's energy, there is an increasing demand for sustainable development and green building practices. In fact, US buildings use three times more energy than similar buildings in similar climates in Europe. Therefore, the US government is adopting green building programs and an increasing number of states are offering tax benefits for public green buildings.

3. "The US government defines green buildings as those that demonstrate the efficient use of energy, water and materials; limited impact on the outdoor environment; and provide a healthier indoor environment. Studies show that green buildings often improved air quality and more access to daylight in addition to energy and cost savings."

www.concretethinker.com/Applications.aspX lists 20 concrete applications. Those interested in details can review them in the document.

According to the US Green Building Council, a key to measurement in this operation and is: “Leadership in Energy and Environmental Design (LEED)”. It is described as "The nationally accepted benchmark for the design, construction, and operation of high-performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on the buildings’ performance. LEED promotes a whole building approach to sustainability by recognizing performers in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, material selection, and indoor environmental quality."
Walmart’s experimental green store in McKinney features the latest in environmental, sustainable and design including concrete parking lots and pervious paving. It is reported that workers in these environments and increased labor productivity, job retention, and days work. These benefits contribute directly to the company’s profits because of salaries of the largest expense.

Cast-in-place concrete is the primary application of concrete in building construction. It is the material of choice for slab on grade and foundations because of its long term durability and structural support. The current issue of ACI 302 covers the details and methods for optimizing the concrete mixture to achieve a flat, durable slab. It is sustainable because it can be reused in many ways if changes are needed for other operations. If it must be destroyed, the broken concrete can be reused as a base for a structural slab all or mixed with the aggregate to produce more concrete.

There is little waste. If concrete remains in the mixer truck upon completion of the work, it can be returned to the batch plant and processed so that the aggregate may be reclaimed and used in future work. Some of the cementitious particles remain in the water after washing. This is known as "gray water." Its use, when combined with tap water, and is treated in ASTM C 94. "Gray water" is to be expected in concrete construction. Some engineers object to “gray water” and other cementitious materials but their use is essential today.

Openings in Concrete Floor Slabs: The scope of this paper does not include engineering design details. Concrete Thinking includes an interesting discussion of "An Engineer’s Guide to Openings in Concrete Floor Slabs."

It was a surprise to many that “Green Roofs” is a recommended point to be considered. It is well established that parks and open spaces create that fits with the environment. The roof of the Chicago City Hall is among many such designs. The practice is well established in Europe. It is reported that though the initial cost is higher, the operational costs for air conditioning the buildings can be significantly decreased. The storm water from the roof, after supporting the needs of the greenery, can be used following storm water management techniques.

Pervious concrete is an excellent application for the environment. There is much concrete from residential driveways to concrete or asphalt parking lots move rainwater for the storm drains. The compressive strength of pervious country can vary from 500 to 4000 psi. Flexural strength range can be from 150 to 550 psi. The pervious mix has a voided content between 15 to 25% and allows 3 to 8 gallons of water per minute to pass through each square foot of the material. Other applications include use as a sub base for conventional concrete pavement, slope stabilization, well lining, hydraulic structures, and tree grates in sidewalks.

**CONCRETE PROCESS DETAILS**

The Puzzle: The need for effective interaction of concrete construction elements may be likened to fitting the parts of a jigsaw puzzle (Figure 1) together. For the puzzle to be workable, all parts must be present, be of the proper shapes, and fit the adjoining parts. If parts are missing, there is a surplus of parts, or the shapes do not fit the adjoining parts; that puzzle cannot be properly resolved.
As for the jigsaw puzzle, it is necessary to ensure that the key elements of the concrete construction process fit properly and interface so as to produce a product that meets the design objectives. By designing each part and establishing how it must function in regard to the other parts, it is possible to prevent problems from occurring.

**Contract Documents:** Of the nine parts, the central part with details for the construction because it is that part that establishes the requirements for all of the other parts. The surrounding parts are: ingredients, ingredients, the mix, reinforcing steel, formwork, placement, vibrators, equipment, and management. When asked about achieving green building construction, a contractor responded, "Follow the details of the specifications."

![Figure 1 – The Concrete Puzzle – All Parts Fit](image)

**CONTRACT DOCUMENTS:**

The central part of the puzzle covers the "contract documents" including both the drawings and specifications. They must guide the process to the attainment of the architectural objective and the structural criteria. A few structural engineers said in confidence they recognize that many structural elements in their design are too slender for the amount of metal necessary to make the element structurally sound and at the same time provide the workspace needed by the contractor to properly do the work.

Many project specifications reference to American Concrete Institute documents including:

- ACI 117 -- Tolerances,
- ACI 301 -- Specifications for Structural Concrete
- ACI 115 – Steel Reinforcement
- ACI 318 -- The Building Code
- ACI 350 -- Sanitary Structures

Among the documents cited in ACI 301 are 80 ASTM standards, the ANSI Welding Code for Reinforcing Steel, and 2 Corps of Engineers standards. Those documents can be cited in project documents. However, many other documents such as ACI 211 -- Concrete Mixtures is one of many documents include ACI Standards, Guides, Recommended Practices, and others cannot be
cited in the contract document. Specifiers are cautioned by a statement on each one of those
documents pointing out that those documents are not written in declarative terms so they may not
be cited project contract documents. Therefore the specifier should write parts of a document that
are important for the work in declarative terms and include them in his project specifications.

This author served for many years on the ACI 301 committee that prepared the 2005 issue that is
currently in effect. On many occasions there were extensive discussions of certain parts of the
document that were not felt appropriate without further explanation and caution for a contractor.
Unfortunately there are occasions where ACI 301 referenced and an obscure part

was called to the attention of the contractor after problems developed on a project.

A draft copy of ACI 318 -- 08 has been issued for review by ACI members. Chapter 3 --
MATERIALS, Chapter 4 -- DURABILITY REQUIREMENTS, and Chapter 5 -- CONCRETE
QUALITY, MIXING AND PLACING will have significant effect upon specifications. Many
other parts of the revision will be appropriate that is engineering design process. Only the three
above Chapters will be briefly discussed here.

**ACI 318 Chapter 3 – Materials:**

**Cementitious Materials:** This portion of the document changes the title from "Cements" to
"Cementitious materials" this portion of the document brings to the specifier greater attention to
fly ash and natural pozzolan and, ground-granulated blast-furnace slag, and silica fume. When
considering "green" concrete, the replacement of a portion of the portland cement with other
cementitious materials as a benefit. The other materials are by-products from other industries so
their use reduces the greenhouse gases contributed by the production of portland cement.

**Aggregates:** The specification reference to the ASTM C 33 must be interpreted as the latest
addition. The latest for ASTM C 33 is the 2003 edition. That document includes the following:
Section 1 -- Scope includes paragraph 1.3 "This specification is also for use in project
specifications to define the quality of the aggregate, the nominal maximum size of the aggregate,
and other specific grading requirements. Those responsible for selecting the proportions of the
fine and coarse aggregate and the addition of blending sizes if required or approved."

The foregoing paragraph on Scope has evolved over the past 10 years. This change was in
response to developments in concrete mixed technology that was initially developed by this
author. In ACI 302 -- Slabs on Grade and includes recommended practices for the use of the
grading of the combined aggregate rather than solely what is in stockpiles. This is a rational
approach to concrete mixed technology. In ACI 211 will include an Appendix that will treat this
detail that will affect concrete constructability, prevent segregation, minimize water, increased
strength and reduce cementitious materials. The reduction of cementitious materials will support
"green" interest as an aid to the environment. The background on this subject will be discussed
under the mix design portion of this document.

**Water:** The new specification is a very simple requirement for it to conform to ASTM C 1602.
Engineers for some time have been concerned about what is known as "gray water". Paragraph
3.2 .5 in the ASTM document includes the following: "water from concrete production operations
or water recovered from processes of hydraulic cement concrete production that includes the
wash water from mixers or that was part of a concrete mixture; water collected in the basin as a result of storm water wrote runoff at a concrete production facility; or water that contains impurities of concrete ingredients."

The concrete producer is responsible for the handling of the above quoted document. The matter is discussed in the requirements of ASTM C 94 - Standard Specification for Ready-Mixed Concrete.

**ACI 318 Chapter 4 – Durability Requirements:**

Before addressing the details of this chapter, a discussion of the paper titled “Concrete Durability - a Multibillion-Dollar Opportunity” published in the January 1988 edition of CONCRETE INTERNATIONAL is appropriate. It was a condensation of a 1984 publication via the National Materials Advisory Board of the National Research Council. The research was done at the request of and with the funding provided by the Department of Defense and the National Aeronautics and Space Administration.

Two institutional factors are highlighted in the report. The first is, "... the systems failure to make durability the responsibility of the organization which can most directly provide it -- the contractor. .. This report decries the lack of research funding particularly by contractors, but recognizes that the present system does not reward the contractor for the durability. The responsibility for durability is assumed by the specification writer. If the contractor has not been found in violation of the specifications at the time final payment is made, it is unusual for liability to be assessed later when the actual durability of the structure becomes known."

The water cement ratio theory and its relationship to strength was reported in the 2nd Edition of “Design and Control of Concrete Mixtures” issued in January 1927. The 14th edition is in use today. The 1927 date indicates it followed completion of the 10-year Lewis Institute-PCA research program that led to the development of the water cement ratio theory. It provides an excellent foundation for understanding the practical implications of that research. The last page which provides a list of 18 projects completed in that era, was technical data about the construction and the mixture designs. Some of those projects are still in service and have been evaluated and found to have a low permeability.

The introduction to the 1927 document includes the following statement that is equally applicable to construction today:

"The fundamental requirements of practically all concrete are strength, durability and economy. These can be obtained only by the proper selection of the materials, and intelligent design of the mixture and the adoption of prop up methods of mixing and placing the concrete and protection during the curing period."

The next section is titled "Water--Cement Ratio Strength Law.” The more significant statements are:

"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 cement and water in this ratio.”
The third section title is "Effect of Water-Cement Ratio on Other Qualities." The opening statement recognizes that the water-cement ratio correlates with other desirable qualities including flexural strength, resistance to wear, modulus of elasticity, and bond between the concrete and reinforcement:

“The resistance of concrete to the severe conditions of weathering and to the action of sulfate waters is determined largely by the degree of impermeability. Impermeable concrete requires non-porous aggregates thoroughly incorporated in a cement paste that itself is impermeable. An impermeable paste requires in turn a low water-cement ratio; the thorough incorporation of aggregates necessitates a plastic, puddleable mix. Thus proper control of the mixing water is the vital factor in the production of durable concrete.” (Bold and underline used for emphasis.)

Early ideas of “low water-cement ratio” were very different from those considered “low” today. Table I in the 2nd Edition describes mixtures to be used for “Roadways, piles, pressure pipe and tanks. Thin structural members in severe exposure. Walls, dams, piers, etc., where exposure to severe action of water and frost.” It was suggested that construction of such projects required 3000 psi concrete at 28-days with a maximum mixing water content of 6.0 gal per sack of cement. Using the volumetric water-cement ratio of 6.0 gal volume of water to one cubic foot of loose cement volume produced a w/c of 0.80. Today, with mass units, 0.53 would be appropriate. A similar water-cement ratios were found in structures cast in that era and still in service.

Few recognize that in the early 1970s the characteristics of the portland cement used for the early research was changed. The C3A, C2S, and fineness of grind were changed. This produced a product that is in use today. There has been no thorough research on the water to cement ratio relationship with strength of concrete. However, the Iowa Department of Transportation analyzed the effect of durability based upon permeability. IDOT reported their findings in the arrived from testing concrete cores taken from pavements dating to 1914. They were measured for permeability and air content – the two key factors for long life durability. Permeability results are shown below. They also found that by applying the new technology the permeability was low while the entrained air content was still as traditionally specified. While some of the mixes with the higher air contents and higher permeability survived for unknown reasons. Other studies were done with higher air content pavements that deteriorated prematurely.

**Permeability of Pavement Cores**

![Permeability of Pavement Cores](image)

Figure 2 – IDOT Correlation between durability and permeability and entrained air
Unfortunately many engineers erroneously believe the water-cement ratio may be used to control durability. Per the above, that is not so. This author has been disagreeing with the Committee about this and the amount of air entrainment required for several years. Maybe the IDOT information may change the picture. Recently, we have worked with projects with a 0.45 water-cement ratio specified and found the 4000 psi strength is being met though the concrete mix was over sanded. When the engineer a record was asked what was the important part of the specification, he responded that strength was what he needed. As a result of that comment and the elimination of the specified water to cement ratio, the concrete producer was able to supply a better mix with a reduction of approximately 75 pounds of cement.

Chapter 4 Paragraph 4.2 discusses exposure conditions as follows:

- Category F. – Freezing and thawing exposure – Maximum 0.45 water cement ratio and minimum \( f'c = 4500 \text{ psi} \)
- Category S -- Sulfate exposure – Mild exposure: Maximum 0.50 water cement ratio and minimum \( f'c = 4000 \text{ psi} \); Moderate and severe exposure: Maximum 0.45 water cement ratio and minimum \( f'c = 4500 \text{ psi} \)
- Category P -- Contact with water requiring low permeability concrete – Maximum 0.50 water cement ratio and \( f'c = 4000 \text{ psi} \)
- Category C - Concrete requiring corrosion protection of reinforcement – Maximum 0.40 water cement ratio and \( f'c = 5000 \text{ psi} \)

Project engineers will have to use their own judgment about this portion of the Building Code and its applicability to the projects they design.

**ACI 318 - Chapter 5 - Concrete Quality, Mixing, and Placing**

This chapter deals with the details of selecting mixture proportions. While there are multiple options, with the primary emphasis is applying statistical analysis based upon strikes no more than 12 months old. From experience, these broad limits can introduce test results that vary widely.

![High Temp of Day vs. 28 Day Compressive](image)

**Figure 3 - Statistical data for one month**

Figure 3 demonstrates the variability of a mixture cast in northern climates during a single month. As happens in the north-central portion of the United States, the high temperature of the day can
vary widely. In this case, the high temperatures the early part of a month can be in the 40 to 50° range. Within a month, the temperatures ranged between 95 and 100°. The project in this question was for slip form paving. The mixture proportions and slumps were maintained constant so there should be no variability caused by different operational techniques as would be the case for commercial construction. The coefficient of correlation was 0.92.

Figure 4 depicts the results of differing times test specimens are left in the field before being transported to the laboratory for curing. The high temperature of the day in which specimens were cast was 110° F. One set of test specimens was cast and cured in the laboratory. The one set left in the field for 24 hours produced a one day strength higher than the standard cured specimen but a lower 56 day strength. Contractors would like the field cured specimen strength because it is approximately 1000 psi than the laboratory cured specimen. However, the result was that the field cured specimen produced approximately 1000 psi last strength than the laboratory cured specimen.

Figure 4 -- A comparison on strengths for different periods of field curing.

ASTM C 31 – “Standard Practice for Making and Curing Concrete Test Specimens in the Field” requires that they test specimens be cured between the temperatures of 60 and 80° F. That is seldom done. There has been much discussion about ACI requirements for the field curing and the responsibility for ensuring that is done. Electrically controlled curing boxers are available at a cost from $1000-$3500. Some say that is the responsibility of the laboratory and others say it is a responsibility of the contractor. It is our opinion that it should be specified as a contractor’s responsibility. The contractor is the one who has electricity on the project. It is to his interest that the results are accurate.

Many contractors like the early strength for form stripping. They are of the opinion that the cylinder represents the quality of the concrete in place. That is not the case. The test cylinder demonstrates that the concrete supplier’s product is delivered to the project is equal to the quality of the concrete on which the design strength was selected. It is well established that the in-place strength is best measured by maturity meters all of the pullout devices.

MIX INGREDIENTS
Due to the abundance of materials in the United States, this is often one of the simple elements control. The competitive market has established producers of what we are now referred to as standard high quality materials. However, materials are becoming in short supply in many areas of the country. Chicago does not have enough sand in the area to support the planned operations. Therefore they are starting to require manufactured sand. Much in the aggregate used in the San Francisco area of California is marched from Vancouver, British Columbia.

We in Texas have aggregate limitations -- especially East Texas. This is caused by the buildup of the low of Mississippi River. The coarse aggregates settled to the bottom of the river to form sandbars resulting in only the fine sand being available from Memphis, Tennessee to the mouth of the river and from western Alabama to East Texas. As far as Texas is concerned, a line can be drawn from Dallas to Houston and everything east of that line is now fine sand. It is not well graded with a shortage of particles retained on the Nos. 16 and 30 sieves and an abundance of material retained on the Nos. 50 and 100 sieves. Much research has been done in Louisiana on the problems caused by this poorly graded sand. It was so bad on a highway that the fatty mortar rose to the surface and could be scratched off with a coin. This is caused by the survey of segregation.

The previous comment was made about the ASTM C 33 specifications that propose the use of the quality standards for the aggregate and a separate provision to allow the engineer to establish a nominal maximum aggregates size and other grading data. That grading data will be discussed and provided in the next part of the puzzle.

In order to provide "green concrete", the engineer must recognize the characteristics of the other cementitious materials including ground-granulated blast-furnace slag (GGBFS) and the various characteristics of fly ash and their effect upon durability. Type F fly ash will provide better protection against alkali-silica reactions and sulfates. Type C fly ash will act much like the portland cement and again early strength.

THE MIX:

In the past the mix was no great problem as suggested by the Building Code. The original procedure for developing mixture proportions was based upon the separation of the aggregate in the No. 4 sieve. The procedure involved measuring the dry and rodded unit weight of the coarse aggregate and the finest modulus of the sand. That system was introduced in 1938 under the title "For mixtures placed without the aid of internal vibration." It was simple but it produced strength.

Today, mixtures are being considered based upon the grading of the combined aggregate and the mortar. The basic technology was developed by this author working as a concrete consultant in Saudi Arabia in the early 1970s. There were no standards for aggregate all any other material. It was necessary to obtain the local materials and send them to a laboratory in Athens, Greece for research. Aggregate gradations and specific gravities were determined. The coarse aggregate and pea gravel were blended to facilitate use in a 2-bin concrete batch plant. Different blends of the coarse size and sand were cast and evaluated for workability, finishability, and strength. No admixtures or air entraining agents were used. Care was taken to determine the water requirement for each batch. It soon became apparent that the optimum mix required the least amount of water, responded best to vibration, and produced the highest strength.
Based upon the site investigation it was recognized that a different way to develop the technology applicable for the project would be necessary. It was concluded that, before making decisions it was necessary to research literature of concrete mixtures. With the aid of the Portland Cement Association (PCA), a number of documents were made available for review. Or the most significant series of studies was the research work done by the Lewis Institute work during the period 1914 -- 1924. This research was undertaken as a joint effort by the PCA and Lewis Institute Professor Duff Abrams as Director. The first report was published was in 1918 and identified as Bulletin 1. This was the most significant of all reports because Professor Abrams reported that the only way to develop consistent results was through using a formula for the grading of the combined aggregate. Using that formula he developed the first knowledge of what is known now as the water-cement ratio theory.

While other reports were studied, work by C. A. G. Weymouth in 1933 and the follow-up by Treval Powers. Weymouth identified one of the major problems in concrete construction – segregation. Powers clarified Weymouth’s work in his text PROPERTIES OF FRESH CONCRETE with the following explanation:

“At this Weymouth was originally interested in concrete mixtures, and was concerned with the effect of particle interference on water requirement and workability, including the tendency of different-sized particles to segregate during handling, he illustrated his concept in terms of dry mixtures of aggregates, using the model shown in Fig 6.1. Fig. 6.1”a” represents, in two dimensions, a mixture of two sizes of particles. The larger particles are few and are widely separated by the smaller particles; the average clear distance between is considerably greater than the diameter of the smaller particles. . . . In diagram “b”, the relative number of the larger particles is greater, and the average distance between them is supposed to be just equal to the diameter of the smaller particles. According to Weymouth, for the composition represented by either diagram, the mixture can be stirred without changing the uniformity of the “void pockets” defined by the smaller particles.

“In Fig. 6.1”c”, the concentration of the larger particles is such that the average clearance between them is less than the diameter of the smaller particles, making it impossible for the interstitial spaces of the larger particles to be filled uniformly with the smaller. Weymouth said that when such a one-layer mixture on a tray is stirred, there is a tendency for the two sizes to run into separate groups, each of its own kind; in other words, stirring such a mixture tends to produce segregation of the two sizes. To apply this observation to a deep mass, he visualized a given size group as forming a sort of grid structure through which the smaller particles move both horizontally and vertically during...
manipulation of the mixture; so long as they can move freely, the mass remains homogeneous, but if the larger particles interfere with the movement of the smaller, segregation occurs, and large void pockets are developed with a great loss of strength and workability.”

Edmund Shaw, Editor of ROCK PRODUCTS was Editor of the publishing company wrote in an introduction to Weymouth’s paper:

“With so many factors to take into consideration, it seems simpler to him to examine gradings of commercial aggregates and correct them by the addition of those sizes in which gradings appear to be deficient.”

Shaw’s recommendations were included in ASTM C33-93 and have been expanded since with the addition of new sizes. In 2004, ASTM was revised to provide for the use of combined aggregate grading with that standard governing on materials pertaining to materials quality. ASTM C-33-04 has modified the standard to allow the use of combined aggregate as a means to select mix proportions. This feature has now been identified by the Federal Aviation Administration and it will be a concluded in the coming P 501 specification for airport taxiways and runways.

With the foregoing as background, the decision was made to address the combined aggregate in terms of three sizes: coarse, intermediate, and fine. The process and findings were described in this author's paper "Optimizing Concrete Mixtures” published in CONCRETE INTERNATIONAL in 1990.

Figure 6 made it possible to see a relationship between the three segments – coarse, intermediate, and fine - of the combined aggregate. One mix was the optimum and the basis for further study. From this I calculated that the amount of fine aggregate required for a mixture was a function of the relationship between the coarse and intermediate aggregate. That concept was the foundation of the Coarseness Factor Chart that is a nomograph. Seven independent variables (up to four aggregates and three cementitious materials) can be coordinated and reported as a single point on the Chart.

Figure 6 is the first published results of the Athens research’s Coarseness Factor Chart. Studies of other mixes with known performance are identified by dots on the chart. The x-axis is the Coarseness Factor that is the percent of aggregate retained on the No. 8 sieve that is also retained on the 3/8-inch sieve. The y-axis is the percent minus No. 8 sieve. The term “Workability” was applied because it was the constituent that provided mobility for a mixture. There is an adjustment
made on the fine aggregate based upon the cementitious materials content. The original mix was cast with 6.0 US bags of cement (564 lbs.). A difference of one US bag of cement is approximately 2.5 percentage points on the Workability chart. If a mix contains 5 US bags (470 lbs) cement, the Workability is increased 2.5 points.

![Figure 7 – SANG Initial Chart and Other Mixes](image)

The diagonal bar is known as the “Trend Bar” that divides the sandy mixtures and the very coarse mixtures. The Trend Bar location reflects the changes in fine aggregate requirement as the two coarser sizes become finer. A “100” mixture has no intermediate particles so it is gap-graded. A “0” mixture is a pea gravel mix with nothing retained on the 3/8-inch sieve. A Bar is used to reflect the effects of aggregate shape and texture on mix workability.

The dots in the Trend Bar, or near it, represent intentionally gap graded mixtures – often using masonry sand – to assure a high density of coarse aggregate when the concrete was sand blasted. The SANG mixes were to be used in that manner.

The final SANG report was issued in September 1975. The third section was titled “Conclusions” ending with the statement:

“In summary, this limited scope and time study has been very rewarding and caused, through failure to comply with expected results, an in-depth research of the state-of-the-art and the evolution of a new concept which bares potential of being a significant breakthrough in simplicity for concrete mix designed technology in all structural work using hard rock aggregates appropriate for building construction.”

The Shilstone Companies Inc. developed MS DOS based software as a means to do graphic analyses using the CFC and the asphalt industry’s modified 0.45 Power curve and the Percent of Aggregate Retained on Each Sieve. It has been found that each chart has special applications.

- The CFC shows over-all relationships,
- The 0.45 Power reflects trends and sharp changes, and

![Figure 8](image)
• The Percent of Aggregate shows details. Experience has indicated that the CFC is the most important but information from the other two graphics and their supporting data can over-rule what might appear to be a good mix. This is especially true for the Percent of Aggregate information. The sum of the percent of aggregate retained on two adjacent sieves should not be less than 13% of the combined aggregate. It has been found that when this occurs, that mix will segregate significantly. Figure 8 shows 5 “Zones.” Each indicates potential mix performance as follows:

Zone I mixes with a Coarseness Factor of 75 or more will tend to segregate, experience edge slump or slough, and/or spall or scale.

Zone II mixes with Coarseness Factor between 45 and 75 will generally perform well. Caution should be exercised if a mix plot falls near Zones I and IV.

Zone III mixes with a Coarseness factors less than 45 are similar to Zone II but for smaller top size aggregate.

Zone IV is the triangular portion of the chart above Zones I and II. Such mixes will generally exhibit the most undesirable features of concrete including cracking, spalling, and scaling.

Zone V is for mixes below the Trend Bar. They are too rocky to be readily placed and consolidated.

The CFC was widely tested in the field. The value became clear during construction of a large project that required two ready mixed concrete producers to supply the needs. Mixture proportions were selected by the responsible testing laboratory based upon historical data. When the effects of those mixes were evaluated using the CFC, it was found that the aggregates gradings from the two sources differed widely. One supplier’s mix would be superior to the other. It was necessary to decrease the fines and increase the coarse aggregate and by approximately 100 pounds per cubic yard to make the mixes equal. The sand absolute volume was modified to compensate to produce a 27.0 ft.³ mix. Observers thought the change was not necessary but, when the two mixes were evaluated on the project, there was no difference in placeability or strength.

In the intervening years, this technology has been used by the US Air Force for construction of airfields around the world, straight Departments of Transportation, and been recommended during a Federal Highway Administration meeting setting a Roadmap for the Future conference. It is now an integral part of ACI 302 -- Slabs on Grade and is in the process of being included as an appendix to ACI 211 -- Selecting Proportions for Concrete Mixtures.

**REINFORCING STEEL:**

In most cases, this is the focal point of construction problems. The reinforcing steel must meet the criteria established by the structural engineer to design the structure within the limits set by the architect. It must also be of a configuration to facilitate makes placement and compaction. While high-range water reducers can be used to facilitate placement on some projects, the mix must also have sufficient stability to avoid segregation as it is placed with a freefall over the steel reinforcement. Figure 9 depicts an example of reinforcing steel created problems in the field. The high-range water reduces are used at an increased in cost as does the increased effort to patch the work and assure the concrete is as sufficiently sound as to support the structure.
Figure 9 – Before concrete placement and honeycombed concrete soffit – high slump mix

Figure 10 is an example of a condition created by the engineer desiring to use a larger diameter bar in a wall and then have a $90^\circ$ bend into a thin concrete overlay for a building slab.

Figure 10 – Diameter of resteel bar to great for the desired bend

**FORMWORK:**

More emphasis should be given to the study of the formwork. The form is the module and not the concrete cast. The concrete is the mirror of the form. This is especially important for cast-in-place architectural concrete. Forms affect the labor demand, cycling of work, and tolerances. The forms are to shape the concrete material to meet the objectives and impart an architecturally acceptable face for the project. Forms must withstand the liquid head of all loads including those by the compact of effort. This is especially significant when, without prior forming plans, the contractor must use a high range water reducer. In such cases the form must be designed to withstand the full liquid head - for both the mixture itself and the energy imparted by the vibrators. Unfortunately, when forms are leaking, it is a normal reaction for construction workers to curtail the compaction effort, thereby reducing concrete in-place quality.

Figure 11 is an excellent illustration of differing means to provide a solution to the architectural intent of as-cast concrete. The project is one in which there were many openings to be provided in walls. The concrete finish was specified to be cast as to produce a boarded form surface. The first casting demonstrated that the contractor could not move the concrete horizontally under the form at the bottom of the opening. This was totally unacceptable to the architect who require that it be removed and replaced. This also was contacted to aid in providing a solution that would satisfy
both the architect and the engineer. The formwork planned by the contractor was steel with a form liner to maintain a wide spacing between form ties. The alternate solution was to use an elastomeric foam liner attached to produce the boarded surface and a smooth the elastomeric form liner attached to the surfaces that wouldn't not boarded. A significant benefit was derived by placing steel pipes between the top and the bottom horizontal lines in the opening. The contractor placed the concrete to the bottom level of the opening and then inserted the vibrator -- and a small amount of concrete - in the steel tubes. The contractor found this simplified his work and he had no more problems.

There are three other points have to be considered: form, corner, and construction joints. They must be properly treated to prevent leakage. While placing structural concrete does not have to comply with the most rigid efforts to prevent the appearance of those joints, the leakage and honeycomb created are undesirable if the concrete will be exposed the weather and allow the penetration of water to cover road the reinforcement. All of the three joint types, the construction joints are the most difficult. Figure 12 is an illustration all widely used approach to construction joints. The major need is to provide a key-way into the first construction and then a rustication at the bottom of our side edge of the following construction. A gasket is used on the face of the following construction rustication to prevent leakage.

Proper selection and application of form release agents is very important. While it is desirable to maintain the quality of the formwork for structural concrete, it is essential for architectural concrete. Figure 12 provides an example of proper application on the beam to the left and misapplication of the same release agent on an adjacent piece. The contractor was questioned
about the difference. He found that the concrete foreman had demonstrated how the work should be done and applied a minimum amount of release agent to assure that it would not affect the finish. A worker later applied the release agent to an adjacent form and felt that if a little desirable a little bit more would be better. This resulted in differences in color that would be a bad for many years.

Figure 13 – Differing application of release agent

Figure 13 illustrates means to protect wooden forms against deterioration after many uses. The upper form was not treated. Soon the calcium hydroxide from the mix filled wood pores. Without the sealer, a different color of concrete will be found for each use of the forms through about three uses. Unless high quality would forms are used, the formwork is deteriorated to the degree it must be repaired or replaced after about eight applications. High quality would forms were used for a major architectural concrete project in the Northeast. The first use reflected itself you of some of the calcium hydroxide product of the cement hydration process. It was not a serious consideration at that time. After three uses, the color of the exposed concrete had changed three times. The visual condition was such that the three layers were identified as "chocolate, strawberry, and vanilla. Five years later, due to the continuing hydration of the cement at the surface of the country, more calcium hydroxide coated the surface. As a result, the finish was a light colored, mellow concrete -- a very pleasing result.

Figure 14 – Sealer applied vs no sealer on wood form
PLACEMENT:
Placement can make or break the quality of the concrete construction. The placement technique must transport and guide the mixture to the point of deposit. One of the restrictions is that the placement technique must be adaptable to the concrete mix. In many cases, the often used concrete pump characteristics require the mixtures fit the pump capabilities. If a low slump concrete is required to produce the desired results, the pump must be capable of transporting that material. A 4-inch pump line and a high piston faced pressure can handle such a job. A lesser pump will require a mixture with a higher consistency.

Steep sided buckets may be the only way to place concrete with low slump mixes. Placement by conveyor belts has application but they should be used with caution as they can cause segregation even with a slump as low as 1/2". Figure 15 as an example of a wall in Illinois with problems caused by placement problems. The construction joints were well treated. Placement and the follow-up consolidation did not produce a pleasing exposed aggregate concrete for a state highway.

![Figure 15](image)

Figure 15 – Placement and inadequate consolidation for wall construction

COMPACTATION:
The term "compaction" is used here as different from consolidation and that the latter term does not truly address the importance of this action. There are two types of vibrators that are normally used form and spud. Few persons purchasing and using vibrators can give the reasons for their selection other than price and/or ease of maintenance. The purpose of the compaction is to transform the concrete into a uniform, high-density mass adhering to the reinforcing steel and filling the intricacies of the form. To do that task, the vibrator must have enough frequency to fluidify the mix, the amplitude to “kick” the mix into place, power to maintain effective operation under the load, and the size to overcome the resistance of the particles to move. Frequency alone will not do the work. The mix, section size, reinforcing steel details, and vibrators must be in perfect synchronization or less than optimal results can be produced.

The manipulation of a vibrator is seldom questioned. It is common practice for insertions to be 36 inches on centers for wall construction. Even the largest vibrators have a radius of influence of about 10 inches. If true compaction is to be achieved, insertions must be less than 20 inches on centers. One of the major problems for the contractor is a fact that he must supply a high cycle vibrator to surprise the level of energy under load as needed. The effectiveness is based not only
the combination of the above characteristics but also the circumference of the head. A square ahead vibrator is more effective than a round head.

Figure 15 – Placement and consolidation requires team-work

Proper placement and consolidation of concrete for wall construction is shown in figure 15. That process involves placement of the concrete in the form (not depicted here) and vibrator operators working as a team effort. A construction supervisor is watching the placement. One vibrator operator is "melting down the mix" and the second operator is compacting the mass.

CONTRACTOR MANAGEMENT:

The final piece in the jigsaw puzzle is contractor management. In the past, most of the construction was done by a general contractor who handled all the work except such specialties as electrical, mechanical, and HVAC. Most superintendents rose through the ranks starting with a labor foreman and then becoming a concrete forman. When discussing this approach years ago, a commentator said, "those people did not just build a form they build it to the precision of a watch." The general contractor built his team with knowledge of his staff and his subcontractors.

Today, more attention is paid to the lowest price subcontractors working under the direction of the construction manager. While construction management organizations have contributed much to the industry, they lack some of the knowledge of the materials and processes that were understood by their predecessors. In either case, an individual must be responsible for the quality management of the work -- not just the administrative management. He must develop a quality control plan verified by the design professionals to see that it fits within the limits of the contract documents.
An independent testing agency is generally retained by the owner to conduct tests on various materials and construction in the project. It is at this point that it will be found that the best interests of the project, contractors and subcontractors will be maintained when the testing is done according to ASTM standards. It was recommended earlier in this paper that a proper test cylinder field curing device be included as a requirement of the contract documents. Such a device can be a benefit to the contractor as well as the concrete producer. It will offer a means to assure that the concrete mixture is produced adequately and the standard deviation will allow a reduction in cementitious materials.

**CLOSURE:**

It will be recalled that this dissertation is addressed to not only building the job correctly but also meet the needs of the environment in which we live. **MAKE IT GREEN!**