NAC Executive Insights

Technical Fundamentals for
Design and Construction
April 20, 2020

Design and Construction of Concrete Structures

Key Points

- Concrete is an extensively used building material.
- Delivering quality concrete requires appropriate aggregates and carefully planned field operations.
- Technical fundamentals for concrete work include appropriate properties of materials, design of concrete mixes, construction resources, and field operations.
- The important field operations for concrete construction include batching, testing, transporting, placing, consolidating, finishing, and curing.
- Formwork used to hold and mold fresh concrete until it gains strength is a key part of the concrete construction process.

The purpose and scope of concrete work differs for various types of constructed facilities. In the case of *infrastructure* work, the main applications of concrete are highways, bridges, canals, dams, and tunnels. For *buildings*, footings, columns, beams, and decks are often constructed of concrete. When well-known aggregates and mix designs are used with standard approaches consistently, concrete quality can be delivered. If the design criteria are more demanding than for normal concrete, special mix designs and construction methods may be required.

Concrete construction requires two additional work activities: reinforcing steel and formwork. Most concrete construction requires custom detailing and fabrication of reinforcing steel to provide the required load carrying capacity and conform to the design configuration. Steel mills provide a range of standard length and diameter bars. The fabricator bends the bars to the required configuration. Ironworkers position and support the reinforcing steel and use tie wire to connect the bars into the required configuration.

Formwork provides the molds that determine the final configuration of the concrete. Carpenters fabricate the forms in the configuration required by the design, set them in place, and brace them as needed to carry the load of concrete placement. Many options are available to complete these operations including different materials, standard or custom form panels, and hardware to connect or brace the panels. Using standard materials and configuration when possible allows reuse of formwork for significant cost and schedule benefits. Complex or highly repetitive concrete structures can justify additional initial cost to allow increased repetition.

Technical Fundamentals for Design and Construction

Concrete Structures

The main functions of concrete structures are to carry design loads (vertical or gravity and horizontal or lateral) along their load path to a footing and the ground without exceeding stress limits (tension, compression, bending, shear, or bearing) set by the design criteria. Structural members (mostly beams, columns, and bracing) and their attachments are the major components of standard concrete structures. Fairly recent structural design may include special devices to increase lateral resistance.

Code requirements (typically from the American Concrete Institute (ACI)) and the geometry of structures (typically determined by the project architect) are two major determinants of design criteria for concrete structures. ACI publishes codes to guide the design and recommended practices to guide field operations. The structural engineer prepares the design, including a model subset or drawings to define the structure.

Materials and Their Production for Concrete Construction

Standard concrete is a homogeneous mixture of cement, water, coarse aggregate, fine aggregate, and selected admixtures to increase specific properties. Good concrete has adequate strength, durability, and economy.

Technical Fundamentals of Construction Materials

Three key responses to loading-in tension or compression define key properties of materials. Illustrating Hooke's law, the stress–strain curve plots load per unit area (stress) against elongation per unit length (strain). The modulus of elasticity, also measured in load per unit area, is the slope of the stress-strain curve. For materials subject to extended cyclical loading, fatigue strength is a key property. The American Society for Testing Materials (ASTM) specifies the properties of materials, a classification system for materials, and tests to assure the required properties are met.

Cement types and applications. Sometimes termed the glue of concrete, cement is a variable mixture of selected raw materials, typically including limestone, clay, shale, and fly ash. The raw materials are mined, crushed, fed into a rotary furnace at high temperature, and changed chemically into a cement clinker or fused mass and cooled. These materials are then pulverized, ground to a fine powder, and gypsum is added. This energy- and emissions-intensive process produces several types of cement. They vary in: applications (Type 1, general purpose); resistance to potentially reactive sulfate (Type II); rate of strength gain (Type III); and other types with further specific properties.

While these classes are used for industry standards, cement provided by different manufacturers in the same class will not give the same concrete strength even when they use the same mix proportions.

The rate of cement hydration and resulting heat generation can have a major influence on the workability of concrete. The ability to “keep the face of the concrete alive” through placement and consolidation is essential. The types of cement and admixtures determine the setting time or allowable duration from batching at the plant to consolidating in the form. The water/cement ratio has a significant influence on the workability and strength of concrete. A w/c ratio of about 0.2 provides enough water for hydration and strength of the concrete. Actual w/c ratios of around 0.4 are typically used to provide adequate workability. This reduces strength and increases the cost of the concrete, but provides important benefits for placement and consolidation.

Coarse aggregate. Either from natural sources or crushed, course aggregate occupies about 70 percent of the volume of concrete, but should not chemically interact with the cement. Gradation or range of aggregate sizes is an important determinant of concrete workability. A particle size of about 0.2 inches (5 mm) is generally considered the dividing line between course and fine aggregate. The spacing of the reinforcing steel is a key determinant of maximum size aggregate for the concrete. The maximum size aggregate should be less than one-fifth of the clear spacing between reinforcing steel in the most congested area. Aggregate from different quarries will provide different strength even when mixed with the same quantity of cement. Cement is the most costly ingredient in concrete, therefore combinations of other ingredients that reduce cement requirements for the same strength will result in cost savings.

Rounded or “river run” gravel, mined from natural deposits typically in stream beds, makes up about half of the coarse aggregate used in concrete. The other half is mostly crushed stone or quarry rock. Aggregate for concrete must be the correct size and clean, hard, strong, durable, and free of absorbed chemicals. For pavement work, the use of hard river run aggregates increases the cost of cutting joints.

Fine aggregate. Ranging from coarse sand to fine sand, fine aggregate is combined with cement to make the mortar or paste for concrete. Compliance with specified grading, the size distribution of particles, is a critical consideration. For example, concrete for placement by a concrete pump generally includes a higher quantity of fine aggregate.

Admixtures. These chemicals are added to concrete to influence various key properties of concrete, such as workability, strength, shrinkage, and durability. They also are added to increase key properties of both plastic and hardened concrete: air-entraining agents to decrease concrete damage from freeze-thaw cycles; accelerating admixtures to decrease the risk of concrete freezing or retarding to increase the time available for all operations; water reducing or plasticizers to provide very high slump or flowable concrete for highly congested placements; and corrosion inhibitors, shrinkage reducing, and many others. The increased availability of admixtures for special conditions, design requirements, or construction operations has led to characterization of mixes with several admixtures as “chemical cocktails.”

Water. For use in concrete, water must meet specified requirements for purity and must be carefully controlled to provide adequate workability while not reducing strength. One general guideline is if water is potable, it is safe for concrete. Seawater is not acceptable for reinforced concrete because of the greatly increased potential for corrosion.

Concrete mix design. One of the interesting anomalies of concrete construction is the division of responsibility for designing concrete mixes. Design engineers specify the key performance parameters for concrete, such as strength and shrinkage. They think in terms of a solid material. These choices may consider the availability of materials, such as specific types of cement and aggregate and other area factors.

Construction engineers think in terms of handling a liquid material.

Concrete engineers working for a ready-mix supplier prepare and test the mix designs. The project engineer generally has final approval authority.

Planning, Resources, and Activities for Concrete Placement

The following activities are required to: produce concrete; transport it to the point of placement; place it in the forms and consolidate it; finish to the specified surfaces; and cure as specified.

Planning concrete placements. Viewed from a production perspective, concrete placements are batch processes that produce specific parts of a concrete structure or feature. Large placements require careful planning. They are key in establishing major milestones for projects and create strong motivation for design engineers, materials management specialists, and construction engineers and crews to satisfy quality requirements and the schedule. Now termed product and process models (previously concrete lift drawings), this extremely important aspect of planning provides major new capabilities for planning concrete placements. For example, concrete lift drawings identify and locate all embedments in concrete placements.

Mixing and batching concrete. These two key activities typically use a *central mix plant* to combine the components proportioned by weight. These ingredients are then mixed either at the central plant or in the ready-mix truck. The truck transports the concrete to the point of placement and discharges it.

The mixing time for a uniform batch of concrete varies based on the mixer and the materials for concrete. Testing to determine the minimum mixing time required for uniform concrete is a part of qualification for new plants and for requalification for plants in service. Specifications may allow water addition and remixing if the concrete stiffens before initial set. Each placement includes the activities described below and creates a cycle.

	
1. Concrete batch plant showing cement storage, aggregate hoppers, and discharge to ready-mix truck. (Schexnayder)	2. Concrete ready-mix truck including mixing drum, front discharge capability for improved access to placement, and water storage. (Schexnayder)

Transporting and testing. The supplier typically transports concrete from the plant to the point of placement. A *ready-mix truck* that rotates slowly to agitate the concrete during travel is typically used. Other methods of transport on the job site include conveyors, buckets, tremies (tubes for placing concrete underwater), wheelbarrows, and buggies. Concrete specifications typically require testing at the point of discharge from the truck. This testing generally includes: slump (indicator of workability), temperature, air content, and sampling for strength testing. The test for compressive strength, the most commonly used, requires using a standardized approach in casting, compacting, curing, and testing cylinders cast at 7, 14, 21, and 28 days.

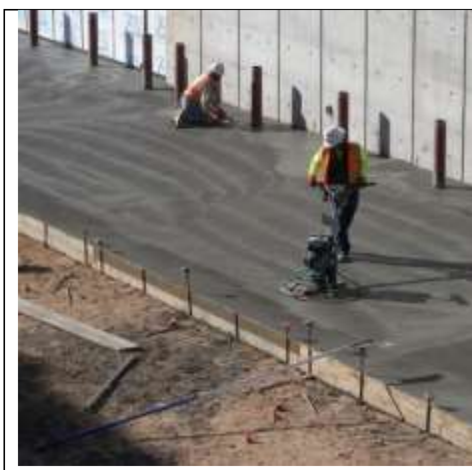
Concrete pumps. Typically mounted on trucks, concrete pumps and a boom extension are selected to reach the most distant parts of the placement. The flexibility and placement rates of concrete pumps have earned substantial market share for this equipment and the specialty firms that provide it. *Concrete conveyors* may offer higher rates of concrete placement for specific conditions, but require special equipment and additional time for setup and demobilization. *Concrete buckets* require cranes and access, but provide beneficial flexibility. They are frequently used as backup. Whether pumping or lifting with buckets, all obstruction, especially electrical power lines, must be considered.

Placing concrete. This key activity moves concrete from the means of transport, frequently a ready-mix truck, to its point of discharge in the forms, typically using a concrete pump or bucket. The rate of concrete placement is one selection criterion for placement method. Quality, however, requires equal emphasis to prevent changes in the properties of the concrete. The overall objective is to minimize the duration of placement and changes in the properties of the fresh concrete during it travel from truck discharge to inside the formwork. The plan for the placement should result in a uniform placement rate matched to the hydraulic pressure of the liquid concrete and the strength of the forms.

Concrete placements usually proceed from the most remote part of the placement back to the source of the concrete, such as the pump. The thickness of the concrete just placed is generally less than 12 inches. The next lift should cover the face of the prior lift to prevent cold joints. Concrete should not be allowed to freefall greater than three feet and should not be moved horizontally after placement.

Consolidating concrete. Typically using handheld vibrators, placement crews increase the density of concrete by removing the entrapped air in the concrete after placement. It is not to be confused with entrained air for which an admixture adds small bubbles to increase durability. Concrete vibrators are available in different sizes and required to obtain adequate consolidation. Each size vibrator has a rated radius of influence. The full volume of concrete should be vibrated. The vibrator should be inserted through the lift of fresh concrete just placed and into the top of the preceding lift. Then it is held until the sound returns to the frequency of the vibrator in air. After consolidation, the concrete paste should cover the coarse aggregate. Concrete consolidation also allows the concrete to flow into parts of the placement that include high density of reinforcing and thus decreases the potential for voids.

Finishing. This step includes the operations of screeding, floating, and troweling. The start of screeding is delayed until the surface of the concrete surface is free of bleed water, which rises to the surface as a result of capillary action. Screeding is accomplished by moving a straightedge across the surface of the concrete at an elevation determined by the elevation of the side forms or special supports, termed screeds. *Floating* uses a hand float or a finishing machine to embed the aggregate, smooth out any imperfections in the surface, and compact the mortar at the surface. The final step of troweling is used where a smooth and hard surface is required, such as warehouse floors.



3. Concrete finishing by mechanical (foreground) and manual (background) methods. (Schexnayder)

Curing. This final step is essential to maintain moisture for the period of hydration required to meet the specified duration or strength. The two main methods are (1) to create a seal with a membrane coating or a separate watertight material or (2) to pond or spray water on the surface.

Reinforcing Steel for Concrete

Their nearly identical coefficients of thermal expansion allow using reinforcing steel in concrete to greatly increase its tensile strength. Codes issued by the American Concrete Institute define the process and criteria for design of reinforcing steel. These requirements include the definition of quantity and configuration of reinforcing steel. The design engineer or the reinforcing steel supplier prepare detailed drawings for the reinforcing steel using standard details. Specialty contractors or general contractors place the reinforcing steel in the placement and tie them to each other to maintain the correct location. Verification of the quantity, configuration, and support of reinforcing is a critical part of inspection to release the placement for ordering the concrete.

4. Reinforcing steel for concrete wall construction. (Schexnayder)

Materials and configuration of reinforcing steel. ASTM specifies multiple types of reinforcing steel based on the sources of the steel. The two most frequently used strengths are Grade 40 and Grade 60. Construction practice is to use only one strength on a project to lessen the risk of using the wrong one. ASTM standard reinforcing bars range from #3 (0.375 inches in diameter) to #18 (2.257 inches). The Concrete Reinforcing Steel Institute has developed standard details and dimensions to guide bar bends for fabrication and a numbering system to indicate strength and type of material.

Two main types of bar splices are used to meet design requirements and allow more efficient installation. Lap splices provide the length of overlap between the bars to meet design requirements. Mechanically coupled splices use special couplings and liquid metal or epoxy to develop the required strength.

Reinforcing steel includes several interesting aspects of practice. Design engineers determine size, shape, and quantity of reinforcing steel. Detailers, who typically work for the structural steel fabricator, complete the details to satisfy the design requirements. Construction input to detailing considers the layout of each concrete placement to assure it considers the location of construction joints, the potential for preassembly of reinforcing steel, and other factors influencing safe and efficient installation.

For example, the configuration of reinforcing steel is significantly influenced by the sequence of completing the concrete placement, the preference for including or excluding additional reinforcing at penetrations, and the means of supporting large concentrations of reinforcing steel, such as used formats. Another important practice is to detail the reinforcing steel through small penetrations and cut it after the penetration is accurately located and mounted on the form.

Installation of reinforcing steel. Placing reinforcing for mats or other large placements begins with installing support for groups of bars or prefabricated assemblies. Options for these supports include grout formed similar to bricks, standard metal supports, or special assemblies of structural shapes for large placements. Ironworkers then place individual bars or assemblies on these supports and attach them using standard tie configurations. The ties do not contribute to the strength of the bar or assembly, but rather hold it in the correct position for concrete placement. The temporary supports typically remain in the placement.

Formwork for concrete

Purpose of formwork. Formwork for concrete is a mold that will produce the desired concrete member or surface. The main objectives of formwork include: *safety* to prevent injury or property damage, *quality* to comply with specified locations and tolerances, and *economy* to lessen schedule duration and cost. Although forms for concrete are generally temporary structures, if they fail to meet these three objectives, they can have a major adverse impact on project results.

Components of wall and column forms and load path*.* The *sheathing* for a form, the part first subject to the pressure of the liquid concrete, spans between the *studs,* which are typically vertical members. The studs bear on the *wales* (typically horizontal) and span between the *ties*. Preparing a custom formwork design requires analysis of each of these members for bending, shear, and bearing. In other words, look inward for the loads and outward for the span.

Loads on formwork*.* Formwork for concrete must safely withstand several types of loads. *Hydrostatic pressure* from the concrete on the sheathing is the first type of load. *Vertical loads* include the weight of the concrete and any other items stored on the formwork, such as reinforcing steel. *Lateral loads* include wind and edge loads, such as from material handling. The design of formwork provides adequate strength to withstand these loads and maintain specified location tolerances as well as limiting deflection to specified values.

Standard types of formwork**.** The most frequently used standard types of formwork include: gang or large panel forms, patent (as from the U.S. patent office) or panel formwork systems, and custom forms. Gang forms are designed with the maximum possible size as limited by wall configuration, access, and crane capacity. Panel form systems offer a range of standard sizes, connections to wales if required, and hardware.

The type of formwork dictates the required fabrication and assembly areas. *Job-built gang or custom forms* require cutting to the configuration specified by design engineers. Patent forms may require assembly at the jobsite before lifting into place. For all types, the objective is to minimize the number of pieces to be lifted to the placement as well as the activities for assembly.

5. Form for concrete cap construction, including intermediate supports, panel forms, stairway access. (Schexnayder)

Materials and hardware for formwork. The availability of standard lumber sizes and standard plywood grades allows standard designs for formwork built on the jobsite. To better meet all three objectives of formwork, suppliers offer many different types of formwork systems and hardware. Examples include panels, braces, and ties.

Fabricating formwork. To improve all three objectives of formwork, managers of larger projects with available yard space wisely invest in a formwork fabrication area. In addition to space to store materials and completed formwork assemblies, this area may include an efficient carpentry shop, which can provide a large work area for woodworking and other specialized equipment such as welding if needed.

Using, removing, preparing, and reusing formwork. Careful monitoring the formwork during a concrete placement is a critical activity. This includes the integrity of the form, the location of the form, and any signs of potential overloading. Planning for the placement should include the decision on when it is safe to remove the form and move it back to the shop for inspection, repair, and further preparation for reuse. This is a major factor in the quantity of formwork needed for a project.

Quality control (QC) activities for concrete work include a detailed look at the formwork to verify compliance with both (a) the formwork design drawing and (b) the expected configuration of the permanent structure. The design of formwork also needs to consider ease of stripping and removing members and salvaging as much of the material as possible for reuse. Cleaning and proper stacking and storage are important activities to increase formwork reuse and decrease cost.

Conclusions: NAC Executive Insight for Technical Fundamentals of Concrete

This NAC Executive Insight describes technical fundamentals and their importance in design and construction, with emphasis on concrete structures and work. A solid understanding of these fundamentals can greatly enhance continued self-directed learning about concrete design and construction and technical and professional development.

Technical fundamentals for concrete work. Technical fundamentals from each of the major engineering disciplines and construction trades provide the basis for design of the different types of systems, from structural to process. These fundamentals provide a very useful structure for learning about the design of each type of system. This background also is extremely valuable in learning about construction practice. Many of the technical disciplines that designers apply for the permanent facility also apply to the resources and operations needed to build it.

Technical fundamentals as a foundation for continued self-directed learning. A solid foundation regarding these fundamentals is a key element in career development and success. Possible activities to increase the rate and scope of this learning include: continued review and practice application of the fundamentals using textbooks, publications of professional organizations that focus on a specific type of structure, and many other online sources.

Technical fundamentals and communication, rapport building, and management. The benefits of deeply understanding the technical fundamentals used by design disciplines and by construction trades do not stop with technical applications. Shared knowledge of technical fundamentals is a major benefit for communication and coordination between project participants. A demonstrated commitment to better understand what the project team is building and how it is being built provides major benefits in developing rapport and preparing for management responsibility.

About the Authors

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