Ensuring Quality Concrete

From Mix to Plant to Placement

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Over the past decade, the use of high-strength concrete has gone from the exception to the norm. Uses of concrete strengths exceeding 10,000 psi are easily achievable on any building. The use of cold or hot weather concrete, high-performance concrete, self-consolidating concrete, architectural concrete, etc. is increasingly common, even for small projects. The material itself is not the same as it once was. The standard mixture of cement, water, stone and sand that the Romans perfected now regularly comes with a wide range of chemical admixtures that can vastly improve the composition, strength and performance capabilities of the concrete.

Most engineers may not be directly responsible for the concrete mix design; however, almost all structural engineers are responsible for the review and evaluation of the mix design for their project. Whereas the lab, plant, and contractor may be directly responsible for ensuring the concrete meets the specified design strength, it often falls to the Structural Engineer of Record to control the variables in the field conditions, assist in troubleshooting and make suggestions for improvement. The goal of this article is to provide a general overview of primary concerns and highlight the many common issues experienced in the field on typical projects. For some professionals, this information may be new and informative, for others, it may just be a refresher.

The Pre-Concrete Conference

The pre-concrete conference is the forum to get together all relevant players, architect, engineer, owner, contractor, concrete sub-contractor, concrete supplier, testing laboratory, special inspector, and ensure that the entire design-construct team is on the same page. Even in small projects, it is essential to have this meeting as it can help avoid future misunderstandings, streamline the submittals process and expedite the project. Key components include an agenda, distributed before the meeting, a respectful discussion during the meeting, and timely written confirmation of the decisions arrived at during the meeting. On larger projects, a written acknowledgment of the Meeting Minutes by all attendees and relevant parties is mandatory.

The Mix

One of the most important steps in ensuring concrete quality happens well before placement of the first batch of concrete. The concrete mix must be reviewed and approved by the Structural Engineer of Record (SEOR), and must happen well before the first placement of concrete occurs. While the formats of design mixes will vary slightly between producers, the basic information required includes:

- ✓ Name of Project
- ✓ Date of Mix Design
- ✓ Compressive Strength of mix and Required Compressive Strength
- ✓ Number of days until specified strength is reached
- ✓ List of ingredients and their quantities
- ✓ Slump or Slump Flow
- ✓ Density
- ✓ Percentage of Air
- ✓ Type of Cement
- ✓ Supplementary Cementitious Materials
- ✓ Water to Cementitious Content Ratio
- ✓ Initial Setting Time

Test results or trial data, mill reports for cement, and specification sheets on the admixtures to be used must accompany the mix design.

Admixture

The admixtures available for concrete are numerous. While the discussion of each admixture is beyond the scope of this article, it is important to be aware of the general types of admixtures available. General categories for admixtures include:

- *Water Reducers/Superplasticizers* – used to increase slump (and often strength) with less impact to the water to cementitious material ratio
- *Retarders/Accelerators* – used to accelerate or delay the setting time of the concrete
- *Air-Entraining Admixtures* – used to increase the air content of the concrete.
- *Other* – Corrosion Inhibitors, Coloring Admixtures, etc.

Test Results/Trial Data

Per ACI 318, the design mix must achieve a required average compressive strength (f'_{cr}) higher than the design compressive strength (f'_c) specified. This requirement for the over-strength accounts for expected deviations in the strength of the delivered concrete. This design strength needs to be justified, either by field experience or by trial mix. The use of field experience to justify concrete strength involves the use of cylinder test results from previous placements to justify the specified strength. ACI 318 provides factors for adjusting the field results based on the quantity of data sample available. For concrete strength substantiated based on field results, f'_{cr} is calculated as follows (Table 5.3.2.1 of ACI 318-11):

For f'_c equal to 5,000 psi or less, f'_{cr} shall be the greater of the following equations:

$f'_{cr} = f'_c + 1.34S_s$

$f'_{cr} = f'_c + 2.33S_s - 500$

For f'_c greater than 5,000 psi, f'_{cr} shall be the greater of the following equations:

$f'_{cr} = f'_c + 1.34S_s$

$f'_{cr} = 0.90\, f'_c + 2.33S_s$

where S_s is the sample's standard deviation.

The use of trial mixes involves the preparation of several design mixes in a laboratory with varying water to cementitious ratios. The results are plotted on a graph of the trial mixes. The mix is selected from the curve. For concrete strength substantiated based on trial mixes, f'_{cr} is as follows (Table 5.3.2.2 of ACI 318-11):

For concrete strength less than 3,000 psi, $f'_{cr} = f'_c + 1000$psi.

For concrete strength between 3,000 psi and 5,000 psi (inclusive), $f'_{cr} = f'_c + 1200$ psi.

For concrete strength greater than 5,000 psi, $f'_{cr} = 1.10\, f'_c + 700$ psi.

For example, for 6,000 psi concrete, the required average compressive strength of the trial mix must be at least: 7,300 psi (=1.10 * 6,000 psi + 700 psi).

Regardless of the methodology used in the mix design preparation, it is important to ensure that the results being used to justify the strength of the concrete are current, as many of the ingredients in the mix are natural and their properties can change over time. Statistically, these methods should ensure that the average of the three concrete cylinder tests is greater than the specified f'_c virtually all the time. ACI 318 permits the use of concrete mixes without test data for concrete strengths of 5,000 psi and lower when permitted by the SEOR. This latitude is not recommended except in specific isolated circumstances. For high strength concrete mixes, the use of the higher f'_{cr} values, per ACI 363, is recommended.

Common Mix Design Issues

'Old' Mixes

The attempted use of 'old' mixes (test results not current, typically greater than the past 24 months) by suppliers is not uncommon. ACI 318-08 added the requirement that test results be no more than 12 months old. ACI 318-11 extended this period to 24 months. As many of the materials are naturally derived, changes in sourcing or other changes may greatly impact the concrete performance.

Mix Not Appropriate for Use

A lot of varying issues can fit in this category. Most commonly, these issues are related to the placement slump – for example, receiving a mix design with a 3-inch slump for a project where all concrete is to be pumped. Other issues could include the use of larger than appropriate aggregate specified for a pump mix. Imagine if the contractor tried to pour self-consolidating concrete (SCC) in concrete stairs (a contractor seriously attempted this on one of the author's projects). With the wide variety of available admixtures and concrete products, virtually every single desired performance requirement is attainable with the proper mix design, making the use of generic concrete mixes unacceptable.

Mix Usage Not Indicated

Often there will be numerous design mixes on a project, their presence dictated by the need for varying design strengths or varying workability and performance concerns. Clarity for a mix's intended use is vitally important, and it is up to the structural engineer to issue clear and precise direction on this subject.

Materials Not Available

There are times where the components that make up a concrete mix may not be readily available. Lately, with the closing of coal-fired power generation plants and the scarcity of steel mills, the procurement of Fly Ash and Blast Furnace Slag has become a serious issue. Slag can be shipped from as far away as Brazil. Approving a mix with a material that is not readily available is not beneficial to the project and not environmentally sustainable. While it should be the mix designer's responsibility to ensure availability before sending the mix for approval, it is still good practice to question any products which you believe may not be readily available.

Compressive Strength Test Age Incorrect

ACI 318 is explicit that compressive strength is based on 28 days unless the design drawings or specification indicate otherwise. For high strength concrete, 56-day and 90-day mixes are not uncommon. However, the design mix should achieve the specified strength within the period requested. 'Slow' mixes can sometimes affect the construction schedule as it relates to the removal of shores and reshoring operations. Remediation of structural elements where concrete has not met its design strength becomes more complicated when test information is unavailable for greater lengths of time.

Problems with Test Data

Errors in test data are hard to find and are mostly the results of a careless error by the preparer of the mix. These issues can include incorrectly specified concrete strength requirements (f'_{cr}), the omission of the modification factor for the standard deviation (S_s), and errors in numerous variables that make up data on which a mix design is based.

Mix Design Issues for High Rise Construction

High Rise Construction, along with other construction with high concrete demands, bring its own set of issues specifically related to the concrete mix design. Selecting the appropriate mixes for these types of projects is complicated, but it is worth mentioning some of the most relevant issues.

High Compressive Strength

Achieving high strength concrete goes beyond simple water to cementitious content ratio. Special consideration needs to go to the admixtures and the aggregate used. Carefully choosing the aggregate from specific quarries is important, and the sourcing needs to be consistent throughout the project.

Modulus of Elasticity

On tall buildings, it is often not only the strength but the stiffness of the concrete that is critical. The simple ACI equations to calculate the modulus of elasticity often are less accurate for higher strength concretes. ACI 363 provides recommendations for adjusted values when using high strength concrete, but it is still often inaccurate when higher strength concretes come into play. The testing associated with the original code writing is one reason for this fall-off in accuracy. The majority of the prescribed provisions for elasticity, shear, etc. have their genesis in multiple concrete laboratory tests performed at a time when compressive strengths in the 4,000 psi to 5,000 psi range were standard. Extrapolation of these test results to concrete in the 10,000 psi and higher range is circumspect. It is, therefore, important to establish an appropriate testing program specifically tailored to the needs of your upcoming building. Tests to arrive at the correct Modulus of Elasticity (MOE) for a high strength design mix are time-consuming. Not all testing laboratories are equipped to perform them, and even lesser numbers of engineers and technicians are qualified to interpret the test results.

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These tests need to be planned and executed very early in the in the design to allow for adequate fine tuning of the design mix.

Extended Workability

Because of the quantities of concrete, the thickness of the members being poured, and the heights to which the concrete needs to be pumped, concrete for tall buildings requires extended workability. Hydration control admixtures and other admixtures help in keeping concrete workable for extended periods. They also help slow down the hydration process in large concrete members.

Mix Design: Looking Forward

As with many trends in the construction industry, there will be continued advances in concrete. Post-consumer recycled ground glass (ground glass harvested from municipal recycling programs) is already being tested as a substitute for Fly Ash and Blast Furnace Slag. The concrete using this sustainable material was designed to attain strengths up to 14,000 psi and will be commercially used on a cast-in-place concrete building sometime in the next few months.

Reduction in Cement

Because of the need to reduce the environmental impact of cement (one pound of cement releases one pound of carbon monoxide into the atmosphere), municipalities have considered or passed edicts which require a reduction in cementitious content in the production of concrete. If these efforts are successful, then they will undoubtedly affect mix designs in the future.

Self-Consolidating Concrete (SCC)

The use of SCC to increase the speed of placement, quality of the finished surface and reduce labor costs is becoming more and more prevalent. In the future, more and more sites will be using SCC almost exclusively for formed members for these reasons.

From The Plant to the Site

Few engineers ever see the inside of the concrete plant which batches and distributes the concrete to project sites. Most concrete projects do not require special inspections at the plant. The engineer is, therefore, reliant on the supplier to properly batch the concrete without supervision. It is important for checks and balances to occur on-site to help ensure that any potential issues with the concrete batching are caught and resolved before placement.

Initial Receipt of the Concrete on Site

When concrete arrives at a construction site, the special inspector must check the batch ticket to ensure the concrete mix conforms to the approved mix. Thus, every truck must come with a computerized batch ticket. The batch ticket must indicate the truck number, the total batch size, the strength measured in psi, the batch time, and the amounts of materials added at the plant. The ticket should also indicate the percentage of moisture within the aggregate. The printout from the plant indicating concrete strength and batch size alone is not sufficient for verification of the mix design and any truck without a full batch ticket ought to be rejected since verification of the mix is not possible. It is imperative that this review happens when the truck first arrives on site. The Inspector should reject incorrect concrete mixes and instruct the truck to return to the plant.

Adding Water on Site

The most common reason for low concrete test results is the addition of unauthorized water to the concrete mix at the site. Concrete must have no more water in it than is indicated in the approved mix design. The best method to ensure this is to prohibit the addition of any water on site. Unfortunately, when transit time to the site is excessive, and a loss of slump occurs by the time the concrete is ready to be placed on the site, the most common response is the addition of water. Occasionally, due to long travel times, a concrete batch plant will send a truck with less than the prescribed amount of water. In these cases, the plant, Special Inspector and SEOR have agreed on a plan of action to combat delayed arrivals and the balance of the water may be added to the concrete at the site. After placing concrete from the truck, adding water to the mix is difficult since it is not possible to determine the quantity of concrete left in the truck nor the amount of water that can still be added. The contractor should be required to keep superplasticizer on site, to be used in specific instances to increase workability. The use of superplasticizer in this method should be planned with the SEOR in advance, along with other placement parameters like mixing times and ambient temperatures. Test cylinders need to be representative of the concrete being placed and need to be taken at the truck and the point of placement. In the event water was added to the concrete mix after the initial batching (either authorized or unauthorized), take test cylinders after all materials have been added.

Site Testing

The standard tests done at each site include slump, air entrainment, temperature, and unit weight. Less common, but very important, is microwave testing. Microwave testing utilizes a microwave to remove the water from a concrete sample. Measurements of the sample before and after being microwaved allow for a field determination of the actual amount of water in the specific concrete sample tested. In high strength concrete, it is common to utilize this test for every concrete placement. For other projects, microwave testing may not be utilized but can be used as a tool in troubleshooting problems in the field. If concrete breaks are low on a project, implementing microwave testing can provide in situ information on the water to cementitious material ratio and can help pinpoint the issue, or at least eliminate the water content of the concrete as a potential issue.

When All Else Fails, Grab a Bucket

The world is uncertain, and stuff happens. Accordingly, basic contingencies need to be in place should things not go per the initial plan. One common issue is the concrete tester arriving late or not arriving at all. Without an inspector onsite, in most jurisdictions, no concrete can be placed. Unfortunately, many concrete contractors will place the concrete which results in the unfortunate circumstance that "placed" concrete will need to be removed and replaced, or the concrete strength verification will need to be done by the removal and testing of concrete cores from major structural elements. Neither option is desirable. One possible mitigation strategy is to fill several buckets with concrete, "rod" the concrete and then use this concrete mix to create cores. At a later date, test the cores and determine the strength after the application of appropriate reduction factors.

Low Breaks Happen

Even after meticulous planning, inspection, and execution, statistically low concrete strengths can and will happen. The concrete special inspector must document where the concrete from each concrete truck is placed within the structure. This "placement map" can help determine the specific location where concrete with low strength was placed and can be very helpful in evaluating the structural impact and the design of remediation measures.

Concrete Placement

Concrete placement consists of the conveying, depositing, and finishing of slabs and curing the concrete. Proper monitoring of each step is important. Once the concrete leaves the truck (or pump, or both) and placement begins, any changes that occur to the concrete will no longer be telegraphed through the concrete test cylinder results.

Conveying and Depositing

The primary concern when conveying concrete from the mixing apparatus to the point of placement is to avoid concrete segregation. Common issues where segregation can occur are:

Free Falling Concrete

Dropping concrete from heights over the reinforcement in columns and walls can cause the aggregate to segregate. In general, concrete shall be dropped from a chute when there is a concern about segregation.

Over Vibrating Concrete

To properly consolidate the concrete, the use of a vibrator is required. However, the use of the vibrator as a tool to move the concrete can over-vibrate and segregate the concrete. Segregated concrete often happens in beams or shear walls where construction personnel will set up the concrete placement on one end of the structural element and attempt to use the vibrator to push the concrete across that element. The problem becomes moot when using self-consolidating concrete (SCC) since SCC negates the use of vibrators. SCC should be used in all formed members.

Concrete Not Vibrated

Not vibrating concrete is only appropriate in a few instances. Even concrete on metal deck requires some form of vibration and consolidation, a condition often overlooked on steel framed buildings.

Curing

Proper curing after placement is important. It is not only a strength concern. Improper or no curing can affect the floor finishes and lead to shrinkage cracking. Curing options include wet curing and chemical curing. Address curing methods at the pre-concrete conference. The concrete inspector needs to ensure utilization of proper curing methods. Hot and cold weather concrete placement procedures dictate to keep concrete in a specific temperature range during curing operations. A simple way to monitor these temperature changes is by using a calibrated maximum-minimum thermometer. Thermometers are available with a probe on one end that can be tucked under a blanket or in the concrete form. The probe will track the approximate temperature on the concrete surface during curing. In addition to properly curing horizontal surfaces, the concrete cylinders taken need to be properly stored in an insulated curing box. During cold or hot weather days, the maximum-minimum thermometer can be used to monitor the temperature of the curing box. If there are low breaks during hot or cold weather, one of the first suspects is the curing method of the cylinders. By monitoring these temperatures, you can proactively eliminate this as a concern when low concrete breaks data.

Conclusion

For quality concrete, the entire design-construct team must understand the rules of concrete placement, execute an appropriate curing procedure and have pre-set corrective measures in place that can be cooperatively executed well before the first concrete placement.

For more information on mix design review and concrete placement and curing, some valuable resources include:

- *Manual of Concrete Practice* (ACI), including the following sections:
  - ACI 211.1-91 (Rev. 2009) Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.
  - ACI 301-10 Specifications for Structural Concrete for Buildings.
  - ACI 302.1-04 Guide for Concrete Floor and Slab Construction.
  - ACI 305R-99 Hot Weather Concreting.
  - ACI 306R1-90 (Re-approved 2002) Cold Weather Concreting.
  - ACI 308 (Rev. 2008) Standard Practice for Curing Concrete.
  - ACI 318-14 Building Code Requirements for Reinforced Concrete.
- *Design and Control of Concrete Mixes* (PCA)
- *Manual of Standard Practice* (CRSI)
- *Guidelines for Reviewing Concrete Mix Design* (SEAONC)

Please note that these resources along with the information in this article may vary based on your local building code.▪