Optimization of Concrete Mixes for Cost-Effective Construction

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Performance concrete is developed by optimizing concrete mix designs to more easily produce concrete that meets all structural and performance requirements of a project using the most cost-effective materials. Two projects with severe performance requirements are described, to show the importance and utility of this process. Selection of the basic mix ingredients as a function of the ultimate demands of a project is discussed. Developing performance concrete is concluded to be the most cost-effective way to approach a project, and optimization must be an integral part of the development process.

The need to optimize concrete mixture designs is becoming more important. Solving problems of concrete performance cannot be accomplished simply by adding more cement. It is critically important to ensure that the quantities and types of ingredients not only provide the characteristics required, but are also present in the proper proportions. Without the proper balance, some or all of the performance characteristics required might be missing. Additional expenses that result can negate the advantages of using a performance-oriented concrete mixture.

To optimize any concrete mixture, the constituents must be present in the correct proportions. Optimization involves numerous mixture iterations in the laboratory and in the field. Optimization of the components of a concrete mixture is the key to developing effective performance concrete mixture designs.

A significant difference exists between "ordinary" concrete and performance concrete. Ordinary concrete is a mixture that is prepared using conventional materials, proportions, and quality control methods. These mixes are typically prepared using the levels of control appropriate for concrete mixes requiring compressive strengths of 2,000 to 2,500 psi. For these mixes, compressive strength normally ranges between 2,000 and 7,000 psi; standard deviations normally range between 450 and 700 psi; and coefficients of variation normally range between 6 and 10 percent.

Ordinary concrete mixes normally have cement contents ranging between 5 and 7 sacks/yd^3. Increased strengths are achieved with more cement, resulting in decreased water to cement ratios. Ordinary concrete mixes may use normal range water reducers and can sometimes use high range water reducers. They rarely contain pozzolans, and their paste volumes are usually greater than necessary.

The biggest difference between a performance concrete mixture and an ordinary mixture is the amount of attention and control it receives. A performance concrete mixture, with properly optimized proportions, is designed so that the material properties (both fresh and hardened) will not vary outside narrow ranges. The ranges include coefficients of variation less than 5 percent and within-test coefficients of variation less than 3 percent. Typical concrete mixes have coefficients of variation closer to 7–8 percent. In addition, one or more of a performance concrete mixture's properties are normally maximized to realize particular project objectives. Maximizing these properties commonly taxes the ability of the ready mix plant and the contractor. Table 1 compares an ordinary concrete mixture design with actual performance concrete mixture designs.

The increased effort required by the producer and contractor usually cause the unit cost of performance concrete to be higher than that of ordinary concrete. However, the overall cost of a project using performance concrete will be substantially less. In the free-market system, performance concrete mixtures will be used only if they result in decreased overall project costs. The cost savings result from the elimination or substantial reduction of required quantities of concrete and associated building materials, such as steel. The reduction is possible because of the improved properties of the performance concrete. Overall project savings of as much as 30 percent are common.

Performance concrete mixes must be properly developed if they are to be successful. Individual characteristics required on various projects include high slump, long-term durability, high compressive strength, high flexural strength, high modulus of elasticity, sulfate resistance, penetration resistance, workability, and hard trowel finishability. All of these characteristics will probably not be needed, or even wanted, on any given project.

Understanding of the internal mechanics of concrete is increasing, and properties are being achieved that have never been considered possible. These properties result from altering the constituents and proportions of standard concrete mixtures in new ways. Consequently, some negative effects are created in the process that are difficult to predict and often difficult to eliminate. Some of the negative side effects include excessive retardation, segregation, difficulty in mixing, plugging of hoppers at the plant or in the truck, plugging of pump lines, excessive plastic shrinkage cracking, and various placing difficulties.

Two examples of projects that successfully used demanding performance specifications are described to illustrate the different approaches that can be taken. The Pacific First Center project in Seattle, Washington, shows one way to develop a proper mixture. The second project is an example of the more common approach and its consequent problems.

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TABLE 1 TYPICAL CONCRETE MIXTURE PROPORTIONS

	Ordinary	10,000 psi	19,000 psi
Cement (lb-Type II)	611	799	893
Fly ash (lb-Class F)	0	160	135
Silica fume (lb-solid material)	0	-	90
Water (lb-total)	280	280	216
Sand (lb-SSD)	1,540	1,210	1,009
Gravel (lb-SSD)	1,650	1,650	1,814
Normal range water reducer	-	-	67 oz
High range water reducer	-	190 oz	268 oz

The mixture for the Pacific First Center project required a compressive strength of 14,000 psi at 56 days of age and a modulus of elasticity of 7.2×10^6 psi, and it had to be pumped to about 700 ft above the ground. The concrete was to be placed inside steel-encased columns by pumping the material into the bottom of the column. The maximum height of each column pour was to be 30 ft. These criteria are difficult to meet. If the components of the mixture were not present in exactly the right proportions, at least one of these requirements could not have been met.

Because of the stiffness requirement, the original project specifications required a minimum modulus of elasticity of 7.2×10^6 psi at 56 days. The requirement was waived because the ready mix supplier was certain neither of its ability to consistently produce a mixture with this modulus of elasticity nor of the ability of any testing laboratory to consistently test for this value with the dependability required for compliance documentation. The ready mix supplier therefore agreed to provide a mixture that would provide a compressive strength of 19,000 psi at 56 days instead of meeting the modulus and compressive strength requirements originally specified (see 19,000 psi mixture in Table 1). The mixture that was subsequently developed was placed easily and met all of the requirements.

To develop the performance concrete mixes, about 8 months was spent in the laboratory mixing various blends of concrete to assess their characteristics. This work was performed under contract to the structural engineer before any documents went out for bid. These mixes were initially designed using a special Type II cement, fly ash, silica fume, and a special gradation of sand. The cement was required to have a reduced amount of tricalcium aluminate and a maximized amount of dicalcium silicate; the fly ash was used to provide a more uniform gradation in the very fine range, to act as a water reducer, and to provide some pozzolanic reactivity; the silica fume was used for its extreme pozzolanic reactivity; and the sand was produced using a much coarser gradation than the standard ASTM building sand. Materials specifications included

- Cement: met minimum requirements of ASTM C 150, as well as
  - —C_2S, 20.0 percent minimum,
  - —C_3A, 6.0 percent maximum, and
  - —Blaine fineness, 350 m^2/kg minimum.
- Fine aggregate: complied with all material properties of ASTM C 33 and with gradation requirements of 1984 Washington State Department of Transportation Specification 9-03.1(2)B, except that the minimum amount of material passing the No. 50 Sieve was 5.0 percent.

Numerous mixes were prepared with various sizes of coarse aggregate, various sand to aggregate ratios, crushed versus rounded aggregates, various cement contents, and various cement to pozzolan ratios. In all cases, only one variable was changed at a time so that the results of the change could be more easily determined.

After a mixture had been developed that appeared to provide all the necessary characteristics, the first field trials were conducted. Field trials are necessary to determine whether the intended mixture can be used as desired. The trials also allow project personnel to familiarize themselves with the mixture in an environment that is not critical. It was necessary, therefore, to place the material in a manner similar to that planned for the project and to employ the same people who would be working on site.

Field trials were performed on this project using a 10-ft diameter "dummy" column 10 ft tall, similar to the 10-ft diameter columns used on the project. In addition, the field trial column was instrumented internally with thermocouples placed at the lower, middle, and upper sections. Embedded strain gauges were situated at the lower third and upper third points of the member to measure shortening. The maximum temperature measured was 201°F, and the maximum temperature differential was 18°F/linear ft. No strains were measured because the strain gauges were damaged during the placement.

The trial mixes were evaluated by trained laboratory personnel before being discharged into the pump. The material was then pumped through approximately 1,000 ft of line. Bends and loops were intentionally built into this run to simulate the pressure losses that would occur on site. The initial laboratory work proved to be effective for this mixture because all of the fine tuning was accomplished with just three field trials.

Approximately 10,000 yd^3 of this mixture were required to complete the project. The results of the compressive strength test from this mixture are presented in Table 2.

The second project shows what can happen if this procedure is shortcut. This project was a canal that was to carry varying levels of sediments, so both durability and abrasion resistance were important. Testing was conducted, under contract to the owner, to determine the relation between high-strength concrete and this type of abrasion resistance. A new test was developed to measure the effects of the high-shear forces typically developed by large rocks bouncing down the structure.

Abrasion tests were performed on five panels that represented potential linings for the project. The panels were cast using (a) ordinary concrete, (b) steel plate, (c) concrete with hardener (a topping mixture containing metal aggregates),

TABLE 2 HARDENED CONCRETE PROPERTIES FOR PACIFIC FIRST CENTER PROJECT (MEASURED WITH 4 × 8 CYLINDERS)

Age of Specimen (days)	Compressive Strength (psi)	Modulus of Elasticity (psi x 10 6)
7	12,020	6.7
28	16,830	7.2
56	17,960	7.6
91	18,370	8.0

(d) concrete with 20 percent Class F fly ash (high-strength), and (e) concrete with 20 percent silica fume (high-strength).

Drum sanders, 12 in. in length were placed on the surfaces with only the weight of the machine resting on the belt. A 20-grit Carborundum paper was used for grinding. The sander was maintained in exactly the same position during testing to ensure consistent results. To eliminate error resulting from sand paper wear, sanding belts were replaced every 30 min. The grooves that resulted from sanding were measured at each belt change to record the rate of growth of each groove (abrasion resistance). The panels were subjected to abrasion for 8 hr per panel. This test design revealed the resistance of concrete to both high-point and high-shear loads. The test results are presented in Table 3. The ordinary concrete displayed substantially greater spalling and dusting than both of the high-strength concrete mixtures.

Test results showed the necessity of using 20 percent fly ash, by weight of cement, in the mixture. This percentage of fly ash ensures an adequate level of impermeability and the subsequent strength development inherent to fly ash. In the author's opinion, the improved abrasion resistance of the high-strength concrete results from improved adhesion of the cement paste to the aggregate particles. Accordingly, the strength on this project was specified to be a minimum of 10,000 psi at 56 days. Because cracking was a primary concern in this project, the amount of cement permitted in the mixture was limited to 799 lb/yd^3.

The sand available from the ready-mix supplier was significantly finer than desired and because this plant was a dry batch operation, consideration had to be given to mixing. The effects on overall water demand of the mix because of the fine sand and problems in developing uniform mixes were boundary conditions.

Problems first arose when the owner-designer team assumed that the concrete mixture could be pulled off the shelf, similar to ordinary concrete mixtures. After discussion, the owner and designer were convinced that the ready mix supplier had to be given advance notice to prepare the mixture. The time was already short.

The ready mix plant made a similar mistake. The mixtures used for the research work were prepared with different materials than were planned for the project. However, the suppliers believed that because their plant was the best operation around, they could easily produce a mixture that would meet the specifications. The laboratory phase of the suppliers' concrete development process was eliminated because they believed that field-oriented equipment should be used because they were trying to simulate field conditions. The need to fine tune the mixes using small, controlled loads in the laboratory became apparent in time.

TABLE 3 RESULTS OF ABRASION TEST

	Depth of Groove (in.)	Width of Groove (in.)
Steel plate	0.088	1.704
Concrete with 20 percent SF	0.183	2.228
Concrete with 20 percent Fly Ash	0.168	2.075
Ordinary concrete	0.215	2.586
Concrete with hardener	0.250	2.421

The field-trial concrete prepared did not have the control exercised that is necessary. Because no one from the owner-design team had been told where field trials would occur, no one from the design team witnessed them. The trial slab was placed, went down easily, and finished well, but was placed without the level of batch plant control desirable for these procedures. Furthermore, the ready mix plant was unable to reproduce this mixture later on in the project.

The first placement took place about 2 weeks after the field trial. The 7-day compressive strengths from the field trial were low, and because the 28-day results were not available, another theoretical mixture was prepared that had a substantially lower water to cement ratio. There was no time to test the mixture, either in the laboratory or in the field. This new mixture had a water to cementitious ratio of .23. It was hard to pump, and was difficult to place. The contractor had to put as many as 6 men on a 12-ft screed to strike off the concrete. Finally, the admixtures used retarded the mixture so that it could not be finished. The project was shut down.

What followed should have occurred initially. A series of carefully controlled trial batches were prepared using various combinations of ingredients. It was finally discovered that the sand to aggregate ratio was not correctly balanced for the maximum-sized coarse aggregate used. The sand to aggregate ratio had been determined on the basis of a gravel with maximum-sized aggregates of ⅜ in. The ready mix producer instead used a gravel with maximum-sized aggregates of ⅞ in. The change in gravel size was made without changing the sand to aggregate ratio.

By changing the sand to aggregate ratio from 39 to 42 percent of the total aggregate volume in the mixture, and bringing the water to cementitious ratio up to .25, the new mixture became easy to pump, required substantially less admixture, and could be troweled off nicely.

The remainder of the project went smoothly, and the finish finally achieved was extremely good. However, the level of mental and physical anguish to the team members and the added costs need not have occurred.

The lessons learned from the two projects are not new. There appears to be an inherent human tendency to compare what is being said with one's personal experiences. If words do not fit with beliefs, then they are ignored. This commonly happens in the process of developing performance concrete. Performance concrete can work effectively only if the team handling it is assembled soon enough, the research and laboratory work necessary are properly performed, the field trials are correctly carried out, and all individuals are willing to listen and work together. The potential for substantially improved performance characteristics on any project is profound. There is no question that using performance concrete on projects will provide a significant edge, which will, in turn, provide an incentive to ensure that within 10 years, performance concrete will be in common use throughout the country. Performance concrete mixes must be properly developed in order to gain widespread acceptance. Optimization is the key to the development of performance concrete.

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