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Accelerated, Early, and Immediate Evaluation of Concrete Quality

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Synopsis: Accelerated curing and testing of concrete cylinders came into being because of the need for faster evaluation of the quality control of the concrete, as a result of accelerated construction schedules and increased volumes of concrete required in structures, so that it was not practical to await the standard 28-day strength results.

This same speed-up of construction and increase in concrete volumes involved in structures, brought about faster or early evaluation needs, and the maturity concept of concrete (degree-hours) is supplementing and displacing the accelerated tests.

The continuation of this faster trend and increasing volumes has brought about immediate evaluation while the materials are still in the weighing hopper or mixer, so that if a batch is out of tolerance it can be dumped out, instead of sent out to the job.

To further meet today's needs, continuous mixing plants are appearing on the scene. Their virtues are lower capital costs, reduced variability of the process, and thus possibility of reduced cement content, lower operation and maintenance, and more satisfied operators.

And just below the horizon, as the next improvement, is a process that forcibly mixes the water and cement, so that every grain of the latter is hydrated, as against only partially hydrated in existing mixing processes, thus permitting still further reduction in cement content. This particular process is also the cheapest way to eliminate cement dust around concrete plants.

Keywords: accelerated tests; age-strength relation; batching; compressive strength; concretes; evaluation; history; quality control; temperature

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INTRODUCTION

The Classical Testing Approach

The standard accepted method of testing concrete to determine acceptability, or to evaluate the quality control of the production process has been on 6 x 12-inch (16 x 32 cm) concrete cylinder specimens prepared, stored, cured and tested in a standard prescribed manner (ASTM Designation C39-72, its earlier editions, and the related methods of making, curing, and handling of specimens)--the actual breaking of the specimens in compression being carried out at 28 days after casting. Occasionally, when faster results were deemed needed at an earlier date, the cylinders were tested at 7 or 14 days in the case of concrete made with Type I cement and at 3 days for concrete made with high-early-strength cement, Type III.

It should be noted that these tests did not provide a measure of the strength of the concrete in the structure, but rather the potential characteristics of the concrete being placed in the structure. Experience over the years had shown that with current American design procedures and construction methods, assuming that the concrete in the structure was adequately cured and protected, these test results, if acceptable, gave an indication that the concrete in the structure would serve its purpose. This may be called the classical method, and specifications were normally based on this approach that had proven satisfactory over the years.

Engineers expected all their test results to show strengths above the nominal design strength, and so specified--that is, that the nominal design strength was the minimum bottom, and that if results complied, then ipso facto all the concrete in the structure would be above this level. And concrete tests (in private work) either passed or failed and were rejected if they fell below that fixed bottom line.

Variability

In the early part of the century, the largest users of concrete were the public organizations engaged in building large dams, and naturally they were the ones that carried on the serious and detailed research and studies into concrete and its behavior and characteristics.

These organizations operated on the principle that the contractor was there to furnish men, materials, and equipment, and that all technical direction and decisions would come from the owner's engineers--in essence, these owners ran the job for the contractor. This resulted in specifications that did not specify strength, inasmuch as the engineers decided on the mix proportioning, controlled its execution, decided on the sources of aggregates and cement, and other materials, and so there was no room to reject concrete when the contractor was only following their directions.

But just the same large numbers of tests were made routinely on project after project, as each dam project would have a very fine and completely equipped testing laboratory at the site. Pretty soon, analyses of these thousands of tests indicated that the concrete was a highly variable material and that it performed its functions adequately even when a small percentage of the tests were below the nominal design strength--under the then prevailing design procedures and construction methods. Acceptance was predicated on a small percentage of the population being below this nominal design strength, and mix proportions were adjusted to maintain this proportion of "lows." It was generally considered from such analyses that had been studied over a period of years, that in strictly structural concrete members, a condition in which 90 percent of the concrete in the structure was above the nominal design strength would be adequate and safe, and in mass concrete or in pavement that rested continuously on the ground 80 percent of the population above the nominal design strength was ample. The reasons and justifications behind this were discussed in a paper by Abdun-Nur. (1)**

About that time, ACI formed a committee to look into this phenomenon and to develop a standard for evaluating the variability in concrete test results. Starting in 1946, this committee made a report in 1955, developed a recommended practice in 1956, and issued an ACI standard in 1957, the precursor of the existing ACI 214-65, an updated revision of which is being printed currently.

Accelerated Construction

With the accelerated tempo of life, the increase in size of projects, and the push to get projects completed as fast as possible because of the economic benefits on the invested capital, a new era and new attitudes developed.

The quantities of concrete became so large and the speed of construction so fast that more than a mile of highway pavement a day was being completed and more than a story of a building per week was being erected. It became obvious that the 28-day test had ceased to serve its purpose, as concrete found defective at this late date would be buried under so much other construction or so far back in the highway

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**Numbers in parentheses refer to the list of references appended at the end of this paper.

(sometimes already open to traffic) that it became impractical economically and politically to tear it up and replace. A judgment on the adequacy of the quality control of the concrete was needed much sooner than even the 7-day test was providing. The main push for such a solution started in the late fifties. But even long before that Gerend in 1927 (2) and Patch in 1933 (3) had suggested accelerated tests that provided test specimen strength results in from 8 to 48 hours.

A few years later during the construction of Grand Coulee Dam, Patch developed so much confidence in the batching records of the recording batch plants that he discontinued the accelerated tests and accepted quality on the basis of such records, making tests here and there for confirmation--usually for testing at later ages.

In this respect he was the forerunner of Mather (13), and the Laboratoire Central des Ponts et Chaussées applying the philosophy based on the idea "batch it right and it will be right," except that he did not have (forty years ago) the sophisticated recording equipment and electronics and computerization that would follow the batching and mixing processes and reject a batch that was out of tolerance before it was discharged.

Patch was an inventive soul; he also developed at about that time what was known as "pop-corn concrete," made with pea gravel, cement and water (no sand) to form concrete with voids, to be used for drains.

This rapid construction development forced the "industrialization" of construction. And with this industrialization came the idea, borrowed from manufacturing, that the contractor should develop quality control of his own, similar to the manufacturer's control of his products. This would make it possible for the contractor to know that he is going to meet the specification quality requirements, before the concrete is proffered for acceptance by the owner.

All these factors--awareness of variability, that 100 percent of the population need not be above the nominal design strength, the huge increase in volume of concrete used, the accelerated construction schedules, and the industrialization of construction, with its quality control needs and requirements--culminated in today's high interest in what is known under the term accelerated strength testing of concrete.

ACCELERATED STRENGTH TESTING OF CONCRETE

General

Like all language, this term started with a specific meaning, and has undergone an evolution. Originally it meant in general the strength obtained through the testing of concrete specimens (usually standard 6 x 12-inch (16 x 32 cm) cylinders) at early ages, after their maturity [degree-hours after casting, calculated from some base, usually 10°F (-12°C)] had been accelerated, either through the application of outside heat, or through insulation that conserves the heat of hydration which acts then in a manner similar to the applied outside heat, to accelerate the rate of hydration, and thus the gain in strength.

In the past 20-25 years many such methods have been proposed, and nearly every week one learns of some new method that has been developed. Much of this work was carried out in England independently by several investigators, the principal ones being King, Akroyd, and Thompson.

Without attempting to compile a bibliography on the subject, one can find several papers in the Transportation Research Record No. 558 (4), and in a paper by Malhotra (5). The composite references from these papers provide, if not a complete, at least a reasonably comprehensive bibliography on the subject. In addition to these references the author is aware of two recent methods developed in France, one that heats the specimens in an oven at 60°C (140°F) and the other at 80°C (176°F), and a new method developed in Canada by Professor Nasser (6) that uses both high pressure (1500 psi) and high temperature (300°F) (150°C)--but it is certain that this by no means covers every method, for this purpose, that has been proposed.

Perhaps the simplest, most practical, and cheapest of all the methods that have been proposed is that advanced by Andre Bisaillon (4), using an expanded polystyrene mold to mold the cylinders in, transport them, and protect them, and provide autogenous curing. A small modification is suggested by this author to simplify it further, which consists of building into the bottom of the form a wire or string that can be pulled at the time of unmolding to separate the bottom (in one piece) from the sides that have to be torn off. Then this bottom and the mold top cover could be used as pads to test the cylinder without capping. A 24-hour period would be adequate maturity, and corrections can be made for longer periods required by weekends, holidays, or unforeseen delays. The mold itself is a telltale evidence as to whether the cylinder has or has not been mishandled--in toto: simple, cheap, quick, and effective.

On the whole, the accelerated methods can be divided broadly into two classes:

1. Those that use higher temperatures to achieve the acceleration--above 150°F-160°F (66°C-71°C).

2. Those that use low temperatures below, say, about 150°F-160°F (66°C-71°C), or use insulation and depend on the heat of hydration to accelerate the hydration process, which does not generate enough heat to raise the temperature above 160°F (71°C).

The first group involves undesirable safety hazards in the handling and in some instances from steam or oil coming in contact with the operators and causing burns. Also such high temperatures are suspected of developing different hydration products than developed by the concrete in the structure, or in standard or low temperature tests, so that these do not really provide valid comparisons. Because of these factors, and even though they provide quicker results in some cases, it is felt that they should not be used. Yet they seem to be the ones that have had the most promotional drive behind them.

The second class is safer to use, particularly those that are closer to the 100°F mark, which is about body temperature. These provide adequate strength in 24 hours to permit the evaluation of the quality control of the process. The most widely available standard on accelerated curing and testing is ASTM Designation C684-74.

ASTM Procedures

In 1971 ASTM published a Designation C684 outling three procedures for making and testing accelerated cured specimens. This standard has been polished and revised and is now C684-74. It was the result of work by a subcommittee of ASTM Committee C-9, that had tests run in 9 laboratories over several years, and made a very careful analysis of the results. The three methods are representative of the general range of types of methods that have been proposed.

Procedure A--Warm Water Method--Uses water at 95°F (35°C) with the cylinders immersed for 24 hours. By using flat plates for cylinder ends, the cylinders can be laid on their sides and tested without capping. It is doubtful that the water contributes to the accelerated maturity, but rather acts as an insulator, and thus permits the heat of hydration to provide accelerated maturity in the cylinders. Advantages are safety and regular working hours, but useful only where there is a laboratory on the jobsite. Falls in Category 2 above.

Procedure B--Known as the Boiling Water Method, or sometimes as the Modified Boiling Water Method, which provides results in 28 to 29 hours. The disadvantages are the odd hours requiring overtime, the danger from steam or hot cylinder burns, and the possibility of anormal hydration products. Falls in Category 1 above. Can be used on the job or cylinders can be shipped to a central laboratory.

Procedure C--Autogenous Method, where the cylinders are placed in an insulated shipping container and shipped to the testing laboratory, to be tested 48 hours after casting. Advantages are safe temperatures, regular working hours, and ability to ship from small jobs to a central laboratory. Falls in Category 2 above.

From the beginning the committee felt that the results of the accelerated curing tests should be used per se to evaluate the quality control of the process. This is best done through the use of a control chart, particularly one that has warning and action limits, so that corrections in the process can be made before the process gets out of control (7).

Unfortunately, every paper outlining or describing an accelerated curing method stresses the prediction of the 28-day strength from the accelerated test results, more than the usefulness of the method itself for evaluating quality control. This detracts from the early test usefulness because it keeps stressing the 28-day strengths. This predicting the 28-day strength from accelerated tests seems to have become a fetish of a sort.

Seeing that most published papers on the subject come up with predictions reliable within ±15 percent, such predictions are no better than guessing, as an educated guess, by someone familiar with concrete in question and working conditions on the particular job, will be as close or better. In addition, all these predictions are predicated on so-called correlations that show high coefficients of correlation. But all that this means mathematically is that the two sets of data go up and down together; it does not prove any relationship between the two. In some cases this correlation may be valid, but in more cases than not it may be illusory (8).

The author has no use for such predictions and finds no need for them. To satisfy a designer or architect who still thinks in terms of the 28-day test, 30 pairs of sets of cylinders are made during the usual studies prior to the starting of construction--one set to be tested in the accelerated fashion, and the corresponding set is tested by the standard 28-day method. An equation is established for the particular materials and mixes, and the architect or engineer is told that his 28-day requirement is met if the accelerated average is equal to or exceeds a certain value. After that only the accelerated test values are reported, as no further 28-day tests are made.

In a brilliant, light-vein paper that appeared in the ACI JOURNAL titled, "Lunatics, Liars, and Liability" (9), Past President Bob Philleo makes an excellent case against the predicting game, and hopefully has driven home the last nail in the coffin of the 28-day strengths. The money, and time and effort, and facilities spent in the studies that propose to provide formulas to "predict" 28-day strengths, will bring in many times more benefits to society, if used to evaluate the quality control of the process on the basis of the accelerated test results. This article is recommended for daily reading before starting work, till it becomes part and parcel of the reader's thinking.

Now let us examine the more recent developments that have sprouted from this push for accelerated curing and testing.

MATURITY EVALUATIONS

As mentioned above, maturity is a term that describes the increase in strength of concrete with age, measured in degree-hours from some base--usually 10°F (-12°C). There have been several methods that have relied on the relationship of the maturity (in degree-hours) and the evaluation of strength. Perhaps the most recent and one being used currently is the one developed by the West Virginia Department of Highways (10,11). This does not involve any accelerated curing, but simply normal curing procedures, but does attempt to predict the 28-day strengths from the maturity at early ages. The advantage is that there is not set rigid time schedule for the testing. Whenever it is convenient to test, one figures the maturity and from that the calculated or projected 28-day strength. Even though it represents a good exercise in mental and technological gymnastics, it leaves this author cold, for the same reasons mentioned above regarding the value of all the methods that aim at predicting the 28-day strengths. This, however, is an "early" test and not an "accelerated" test and can be adapted admirably for early evaluation of quality control in the same manner advanced above for accelerated test results.

Maturity as a concept can also be used directly on the concrete in the structure. This can be accomplished by embedding thermocouples in the concrete and reading the temperature at intervals, or having the thermocouples connected to a registering and recording instrument which permits, or automatically via computer integrates, the degree-hours at any time desired. This permits decisions to be made as to form stripping, permitted loading, post-tensioning, etc., at very early ages.

Perhaps the most sophisticated use of this modern combination of accelerated-early evaluation of concrete was on the construction of the C.N. Tower in Toronto, Canada (12). Here ASTM Procedure C--the autogenous curing in insulated boxes--was used and correlated with thermocouples embedded in the concrete so that decisions could be made on the stripping, or in effect in this case with the movement of the slip form used in forming the tower, to uncover the concrete only when the maturity indicated adequate strength. This is a far cry from waiting 28 days to know where things stand and shows excellent practical engineering, imagination, and the practical application of latest technical advances.

Similar in situ maturity studies have also been used to determine when the concrete was ready for post-tensioning operations, again indicating that we have already left the accelerated strength concept of rather recent vintage behind, and have advanced to methods that do not tie down the evaluation to a preset time such as 24 hours, 28-1/2 hours, or 48 hours (13). It is interesting to note that both the above sophisticated operations took place in Canada.

BATCH IT RIGHT AND IT WILL BE RIGHT

But it seems that man never rests on his laurels. First came accelerated testing to evaluate the concrete control, because fast moving, large concrete volume construction required knowledge of what was happening long before 28 days had elapsed. Then this turns out not to be fast enough and the maturity concept is applied to an earlier, more realistic evaluation of quality than the accelerated test methods and does so in the structure directly, and at any desired time without being tied down to a rigid schedule. This is the early evaluation in contrast to the accelerated evaluation.

And finally, to get results still faster, man goes back to the basic essentials; that is, that once the ingredients and materials have been tested and approved and accepted, and a proportioning mix formula has been developed that assures the concrete characteristics required, then all one has to do is to make sure that these ingredients are batched correctly and mixed properly, and the concrete cannot be but RIGHT.

Most concrete engineers subconsciously have been aware of this and automated concrete plants have been available that could not only record the weights as they were batched and monitor the mixers for timing and consistency of the mix, but can also have statistical summaries of the day's work on the boss's desk, the following morning, showing averages, standard deviations, etc., so he could take appropriate action as needed. But for some reason this available technology has not come into general use, and at any rate it was 24 hours too late. Finally Bryant Mather came out and said it out loud in "How Soon Is Soon Enough?" (14).

But before Mather enunciated this bit of wisdom, the prestigeous Laboratoire Central des Ponts et Chausseées in Paris had been working for several years on the concept of "integral control." This referred to the idea that in addition to automation, feedforward can be made so that the machine can control itself or have integral control in the process. Such a self-regulating process equipment control was designed and assembled in a panel truck and sent out from plant to plant for actual trial. The sensors would be connected to the various parts of the plant and the operation was such that the sophisticated electronics permitted the rejection of a batch before it was discharged, if there were some error beyond the tolerances established. The operator had in front of him the traces of the weighings, the mixing, etc., so that he could override the machine if it malfunctioned, as all machinery occasionally does, or if he decided that it was not out of tolerance enough to dump out. They even have a booklet of various typical curves and their interpretation to help the operator in his work--here is Mather's wisdom in a fait accompli.

So here it is--from a delay of 28 days for evaluation to decision making before the batch is released--what more could one wish?

DISCUSSION

In looking back it can be seen that evaluating concrete quality has gone through a progression of technological stages or periods as more and more sophistication was introduced into the process. These may be summarized briefly:

1. In the beginning concrete was batched by volume of aggregates and water, and by bag of cement. It was assumed that the result would always be satisfactory because the process was slow and one had time to assure oneself that it was carried out properly.

2. This was later refined by accounting for the bulking of the sand at various moisture contents.

3. The period of absolute 28-day cylinder strength followed, with an absolute minimum that was not to be breached. This was the era of self-delusion, as it is pretty well known now that in

practice this minimum was always breached, even though the record did not show it, mainly due to the outlandish costs if it were implemented (1). The apparent compliance was due mainly to selective sampling; random sampling would have brought this out strikingly.

4. Then followed the period of awakening to the fact of variability, and the realization that under existing design and construction procedures, adequate structural integrity and serviceability are obtained even though 10 to 20 percent of the population is below the nominal design strength. Here, the theorists and statisticians have had a field day as from a humble statistical concept developed by ACI Committee 214 has come such complex treatment of the subject that it takes fancy, complicated, and costly computer support to come up with simple answers. This was still the day of the 28-day cylinder strength to measure the inherent qualities of the mix, as distinct from the concrete in the structure.

5. Accelerated construction schedules and fantastic increase in the volumes of concrete used brought about the need for an accelerated evaluation of strength, resulting in the ASTM Designation C684 in 1971, as representing the range of available technology in this area. This was followed by a large number of modifications and mutations of these procedures and a mania for predicting the 28-day strengths from these accelerated results, even though the original intent and stress of the committee that produced this standard was its use for the evaluation at early ages of the effectiveness for the quality control.

6. There followed the maturity concept period, which was applied to both concrete test cylinders under normal curing conditions, and to the structure itself to decide on form stripping and post-tensioning operations--this is a relatively new development.

7. And finally, the latest period just starting, in which sophisticated observation through automation and action to abort a batch if the process produced it outside of tolerances, before it is discharged for delivery--in other words, again the stress on batching accuracy, as in the early days, except a change to weight instead of volume, and automatic corrections for many of the variables.

Thus we have come around the whole circle. Each era was shorter than the preceding one, showing the influence of accelerated technology, knowledge, and construction speed.

Over the horizon the next stage will be that of continuous mixing plants that have lower variability than batch plants, lower plant cost, lower maintenance, and are easier on the operators. Already there are several such plants operating in England, three in France, and others undoubtedly in other parts of the world. Still in the preliminary