

Accelerated, Early, and Immediate Evaluation of Concrete Quality

By Edward A. Abdun-Nur

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

**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 Bisailon (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 outlining 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 abnormal 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 prestigious Laboratoire Central des Ponts et Chaussées 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

development stages, of such continuous plants, are processes that augur for more sophistication of this newborn technology, and that will permit the application of Professor Cordon's concept of attaining desired workability by adjusting aggregates, keeping the water-cement ratio constant and therefore the quality constant.

CONCLUSIONS AND RECOMMENDATIONS

It is seen from the above that:

1. Accelerated curing of concrete specimens for testing cylinders at early ages developed as a solution to the accelerated construction schedules and the large increase in the volumes of concrete handled in the shortened construction schedules. ASTM Designation C684 provides three methods that are reasonably representative of the multiplicity of such methods that have sprouted in the last few years.
2. These methods seem to fall into two main categories, basically those that maintain the concrete at temperatures below roughly 150°F - 160°F (66°C - 71°C) and those that subject the specimens to higher temperatures--some as high as 300°F (150°C). The latter are thought to develop hydration products that differ from those of concrete subjected to the lower temperatures and those found in actual structures. Therefore, conclusions from the latter may not have the validity or credibility claimed for them. The minor modification of the Bisailon (4) accelerated procedure, suggested in the main body of the paper, provides probably the simplest and most expedient method that can be recommended for accelerated testing.
3. There seems to have developed a fashion of so-called "pre-dicting" 28-day strength from these accelerated tests, even though the ASTM committee had cautioned against it. This has, hopefully, been out to rest in Bob Philleo's "Lunatics, Liars, and Liability" (9).
4. The continuous quest for faster evaluation of the quality of concrete has resulted in the maturity concept of degree-hours being applied to concrete cylinder tests to get around preset rigid time schedules for testing and thus provide flexibility and applied also to concrete in the structure itself for decision-making on form stripping and post-tensioning readiness, as well as the actual strength being developed in the structure.
5. Finally, the approach so ably put forth by Bryant Mather in his "How Soon Is Soon Enough": Batch It Right and It Will Be Right, is coming to the front. To implement this immediate evaluation of the quality, as the construction tempo has accelerated more and more, there is the development of "Integral control" that evaluates quality as the batching process is taking place and rejects (if necessary) before the batch is released.

6. Thus, all this has been the completing of a circle from the old-fashioned volumetric crude batching by prescription to the sophisticated automatic weight batching by prescription that can reject a batch before it is dumped from the weighing hopper or mixer.
7. And on the horizon there are emerging the continuous mixing plants as the next step, where continuity of the process decreases the variability and therefore reduces the cement needed to obtain a required strength level. And, still slightly below the horizon, developments that will combine the water and cement more effectively, thus reducing the required cement still further over ordinary concrete, where, as a rule, some of the cement remains unhydrated.

This is how the evaluation of the quality of the concrete has moved progressively and at an accelerated pace from the 28-day cylinder tests, to accelerated testing, to early maturity evaluation, to immediate evaluation before the batch is released from the plant.

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Experience in the Use of the Accelerated Testing Procedure for the Control of Concrete During the Construction of Tunnel “Emisor Central” in Mexico City

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Synopsis: Over one million cubic meters of concrete were poured during the construction of a huge project known as Deep Drainage System designed to eliminate the risk of floods in Mexico City. The main structure of this system is a tunnel 49.8 km (30.95 miles) in length, 6.50 m (21' 4") in internal diameter, and with a 0.70 m (27 1/2") average thickness of concrete lining.

The most outstanding part of the product control of concrete was carried out by testing specimens cured in boiling water (procedure B, ASTM C-684). More than 1700 samples, consisting each of four specimens, were tested. Two specimens of each sample were tested at 28 1/2 hours and two at 28 days.

Functional relationships were established for predicting the 28 day compressive strength from the data obtained in the 28 1/2 hour test, with very satisfactory results. These relationships allowed to adjust opportunely the mix proportions to the optimum amounts of ingredient materials in order to fulfill the strength requirements of the job specifications.

Keywords: accelerated tests; compressive strength; concretes; cylinders; fresh concrete; quality control; sampling; tunnels.

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INTRODUCTION

From 1971 to 1975, in the Valley of Mexico, the construction of a huge project known as Deep Drainage System (Sistema de Drenaje Profundo) took place. The main structure of this project is a tunnel named "Emisor Central", 49.8 km (30.95 miles) long, 6.50 m (21'4") internal diameter, and 70 cm (27 1/2") average concrete thickness. The aim of this project is eliminating the risk of floods in Mexico City, carrying both rain water and sewage disposals to the Mezquital Valley in the State of Hidalgo.

For the construction of this tunnel, the production and placing of over one million cubic meters of concrete was required, a record in construction in Mexico. The project utilized nine concrete plants of 45 m³/hour (58.9 Yd³/hr) capacity. These plants were placed at intervals along the tunnel at points where special shafts, built for construction purposes, were located. The concrete was introduced through these special shafts by means of vertical steel pipes with shock absorber tanks at the bottom; transportation inside the tunnel was done by means of trains of interconnected agitators, and the placement in the forms took place with concrete pumps and concrete guns.

Concrete product control was carried out by testing specimens cured in boiling water, following procedure B, ASTM C-684 (slightly modified). During the construction of this project, more than 1700 samples, consisting each of 4 cylindrical specimens, were tested. Two specimens of each sample were tested at 28 1/2 hours and two at 28 days.

The purpose of testing 28 1/2 hour specimens was to obtain advanced evaluations of strength variations and of the quality levels reached during the work, in order to establish, opportunely, the corrective measures necessary to accomplish the requirements of the job specifications.

QUALITY CONTROL PROGRAM

Responsibility for Quality Control

The concrete quality was the responsibility of two inspection and testing agencies, one, representing the owner, was responsible for verifying the quality of the whole job, and the other, representing the contractor, was responsible for the control of the production of concrete. This report describes the activities of this latter group.

Sampling of the concrete for product control included approximately one sample for strength test for each 600 cubic meters (785 Yd³) of concrete. With a daily average production of nearly 1800 cubic meters, this resulted in an average of three samples per day. These samples were, invariably, obtained at the discharge point of the concrete mixers.

Concrete Specifications and Mix Proportions

Concrete for tunnel lining was proportioned for several 28 day design strengths, varying from 175 to 300 kg/cm² (2500 to 4250 psi); maximum size of aggregate was either 19 mm or 38 mm (2/4" or 1 1/2"). The transporting and placing system adopted imposed the necessity of using rather high design slumps, varying between 12 and 16 centimeters (4 3/4" and 6 3/8"), with a predominant value of 14 cm (5 1/2"), at the mixer discharge point. Coarse aggregates were of two classes: 1) crushed from basalt, andesite and limestone rock and 2) natural, from piroclastic deposits (quite abundant in Mexico City and surroundings). On the other hand, sand was in every case obtained from natural piroclastic deposits, even though, in certain instances, it was blended with crushed stone fines. Cement was supplied by one single factory and was type V (sulfate resistant). Also, water reducing agents and air entraining admixtures were used. The former were used in all concrete while the latter were used only in those plants using limestone crushed aggregate and natural sand from a deposit close to the end of the tunnel.

Cement content varied from approximately 300 up to almost 450 kg/ m³ (500 to 760 pounds/Yd³); design water cement ratio varied from 0.44 to 0.56; gravel-sand ratio fluctuated from 1.30 to 1.50; air entrained, when required, varied between 2.5 to 3.5%.

Verification of the Quality of Concrete Specimens

The laboratory representing the owner was in charge of verifying the quality of both ingredient materials and concrete. For this purpose, this laboratory obtained random samples consisting of 4 specimens that were tested

two at 7 days and two at 28 days. All concrete specimens were standard cured. Sampling of fresh concrete was invariably carried out at the discharge point of agitators which were transporting concrete inside the tunnel, before introducing it into the pumps or guns that placed the concrete in the forms.

PRODUCT CONTROL

Product Control Facilities

For carrying out the concrete product control, a field laboratory was installed in each concrete plant. These laboratories had the necessary equipment to carry out tests for prescribing corrections to mix proportions which took into account variations in moisture and in grading of aggregates, as well as for realizing fresh concrete tests and for manufacturing concrete specimens to be tested under compression.

In a location close to the center of gravity of the concrete activities, a central testing laboratory was installed. This laboratory was equipped with standard curing rooms with controlled temperature and humidity, accelerated curing tanks and a 200 ton (440,000 pounds) spring dynamometer compression machine, accurate to 50 kg (110 pounds) readings. The central laboratory personnel were granted due authority to modify the ingredient proportions, in view of accelerated test results, within certain limits.

Sampling and Testing of Fresh Concrete

As a part of the activities of product control, several tests of fresh concrete were carried out. Among these routine tests the following can be mentioned: slump, air content, unit weight and yield. Occasionally, other tests such as: time of set of concrete, bleeding, loss of slump, etc. were carried out. One sample of the fresh concrete was taken for strength testing from each 600 m³ (785 Yd³), as mentioned before, or one sample per shift. During night hours, no specimens for 28 1/2 hour testing were taken, in view of difficulties with hour schedule of the testing laboratory personnel.

Accelerated Tests.

During the whole concrete operation, a total of 1728 accelerated tests (two specimens each) at the age of 28 1/2 hours, using a method corresponding to procedure B, ASTM C-684, with some slight modifications, were carried out. The inspection and testing agency in charge of this work has been using single-use tin-plate cylindrical molds, 15 by 30 cm (6" by 12").

These molds have a cover that allows no loss of water and seals the specimens to constant weight. This fact permitted conserving concrete specimens for 16 hours at the field laboratory with the sole precaution of maintaining temperature within a range from 16° to 20° C (61 a 68°F). After the 16 hour period elapsed, the specimens were transported to the central testing laboratory with extreme care. At 24 hours, accelerated curing in boiling water was initiated. Boiling water temperature in Mexico City (2240 meters (7750 ft) above sea level) is approximately 90°C (195°F).

Accelerated curing takes place in thermically isolated tanks designed to hold 8 specimens. The total capacity of the tank is 135 liters (36.7 gallons) and is composed of an immersion iron-clad electrical resistance heater, 3000 watts and 220 volts.

On the other hand, specimens for 28 days testing were cast in standard steel molds, 15 by 30 cm (6" x 12"). These specimens were standard cured in a fog room with 100% R.H. and temperature between 21° and 23°C (70° and 73°F).

Strength Tests Results

It being the purpose of accelerated strength testing to obtain advance information that can be used to adjust mix proportions, thus guaranteeing the fulfillment of the required quality levels at the optimum cost, the main efforts were focused to establish correlations between anticipated strength data and standard strength at the established age of testing imposed by the project specifications. Therefore, correlation of 28 1/2 hour and 28 day compressive strengths of concrete, for various combinations of ingredient materials used during construction, was sought from the very beginning of the concrete operations. Fortunately, the only sources of difference of behaviour seemed to be the nature of coarse aggregate and the use of air entrainment, since sand was mostly obtained from similar deposits and cement type and brand were maintained the same during the whole job.

Figure 1 shows how the values of strength for crushed aggregate concrete presented a reasonable correlation and how an acceptable fit is a curve of the type $y=ax^b$. The correlation coefficient in this case resulted with a value of 0.806 for 1079 observations. For natural coarse aggregate, the correlation was better: a fitting curve of the same type yielded a value of the correlation coefficient of 0.915 with 649 observations, as shown in Fig. 2. When considering all the observations together, a fit curve of the same type was used, and a correlation coefficient of 0.883 was obtained as shown in Fig. 3. The three fitting

curves are very close one to the other as shown in Fig. 4. It should be noted that no differentiation whatsoever was considered necessary for the data obtained for different design strengths.

In the particular case where a limestone crushed coarse aggregate and a rather coarse natural sand imposed the necessity of using an air entraining agent, the fitting curve, being of the same type as the one used for other concretes, appeared to be steeper and a correlation coefficient of 0.885 resulted, as shown in Fig. 5.

Feedback of Tests Results.

As it was mentioned, from the very starting stage of concrete operations, a correlation of strength values at 28 1/2 and 28 days, was sought. During the initial period, when 28 day data was scarce, functional correlations obtained by the same testing agency in other projects, utilizing similar aggregates, were used. However, the cement characteristics differed substantially and the resulting predictions were rather poor.

Soon after, when available data became considerable, relationships obtained started to give fruitful results and a continuous modification of the functions took place. Very soon, the 28 day strength predictions from 28 1/2 hour data became reliable. For illustration purposes, Fig. 6 shows the correlation obtained in one particular concrete plant and Fig. 7 shows how the information of accelerated testing permitted one to estimate the standard 28 day strength distribution and how these anticipated predictions compared with the actual values. In this manner, the cement content, the water-cement ratio and even the gravel to sand ratio were continuously modified, in order to reach the desired goal of complying with strength specifications at the optimum cost.

FINAL COMMENTS

The benefits obtained with the accelerated testing of concrete specimens were innumerable. On one hand, it was possible to have available at opportune moments reliable data which allowed one to adjust mix proportions to reach the required strength levels and avoid eventual penalties that, according to the project specifications, could have occurred. On the other hand, this advanced reliable data permitted the utilization of the optimum quantities of ingredient materials with the consequent economy in cost of concrete production.

It has to be recognized, however, that the cost of the actual testing was considerably increased with respect to

the cost of conventional testing, mainly by the use of disposable molds for 28 1/2 hour specimens and for the payment of overtime to laboratory personnel. Also, this method of testing prevented sampling on Saturdays and at night, which was omitted in order to avoid personnel laboratory shifts on week ends and at night.

Finally, it is our belief that it is feasible to carry out an adequate product control of concrete based solely on the results of accelerated testing, complemented strongly by fresh concrete testing and process inspection.

ACKNOWLEDGMENT

The authors are indebted to Angel Borja, Héctor Hiriart, Manuel Salvoch, Raúl Borja and Andrés Moreno - all members of the engineering staff of TUNEL, S.A., the general contractor of the project - for their encouragements and support in the product control operations; also, to the engineers and city authorities of D.D.F., owner of the project, and to DIRAC, S.C., which represented the owner in supervising quality control. The authors wish to thank all of the above mentioned for their enthusiastic cooperation in the application of the accelerated method for product control of concrete.

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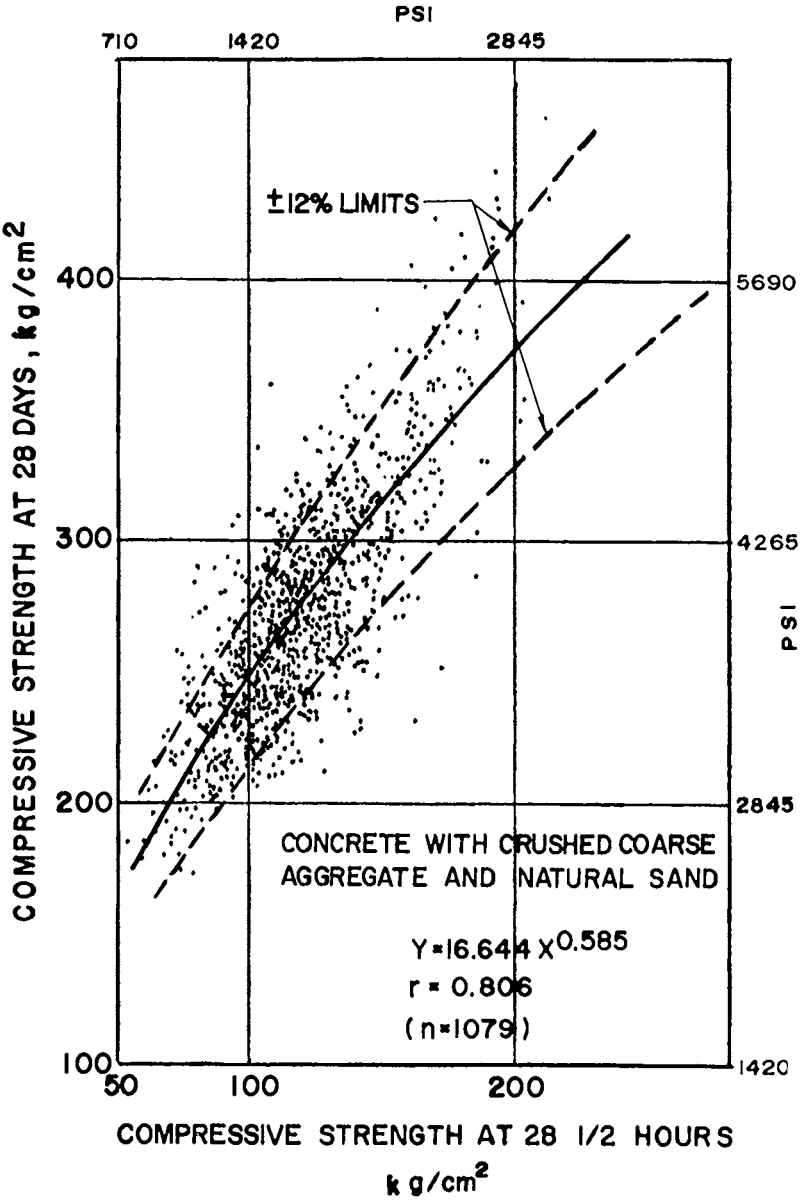


Fig. 1--Comparison of compressive strength at 28 days versus 28½ hr--Samples with crushed coarse aggregate and natural sand

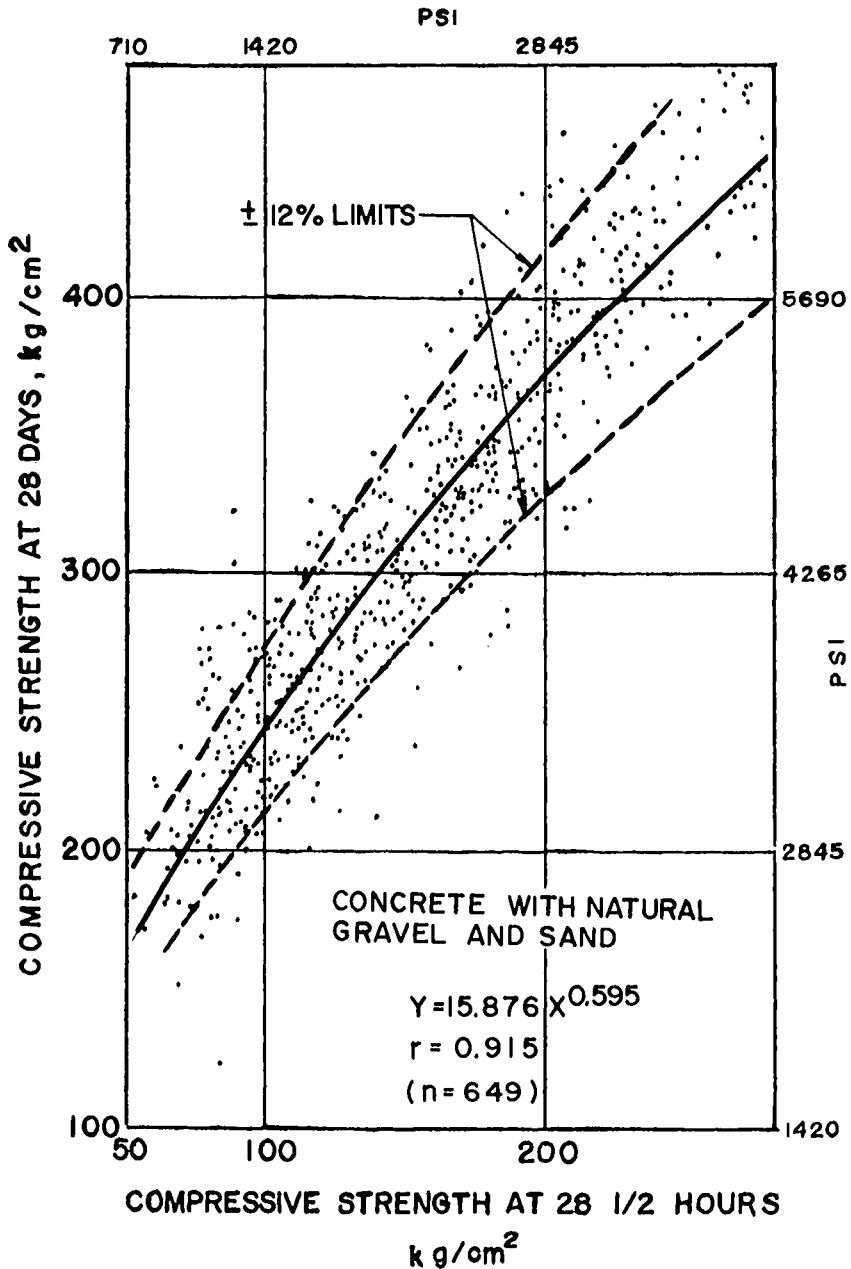


Fig. 2--Comparison of compressive strength at 28 days versus 28½ hr--Samples with natural gravel and sand

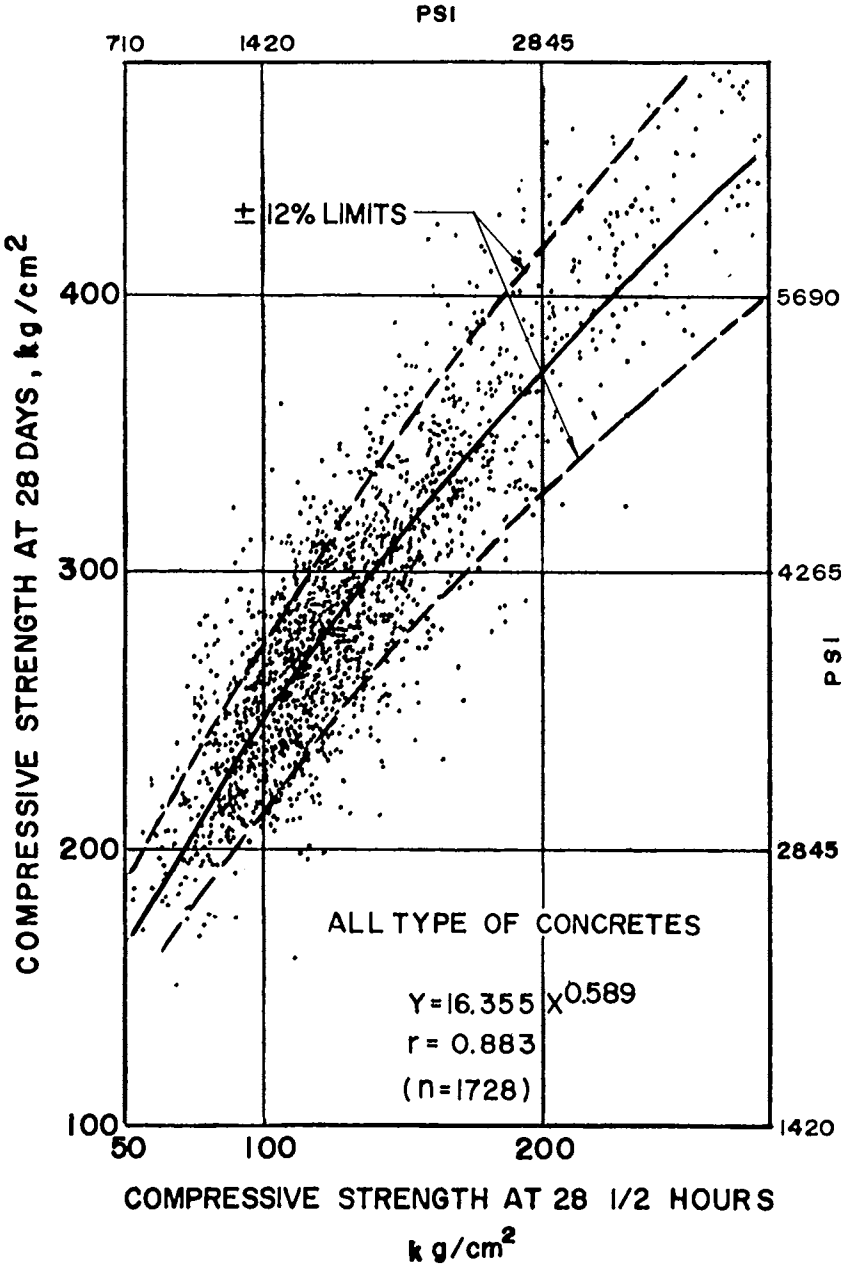


Fig. 3--Comparison of compressive strength at 28 days versus 28½ hr--All type of concretes

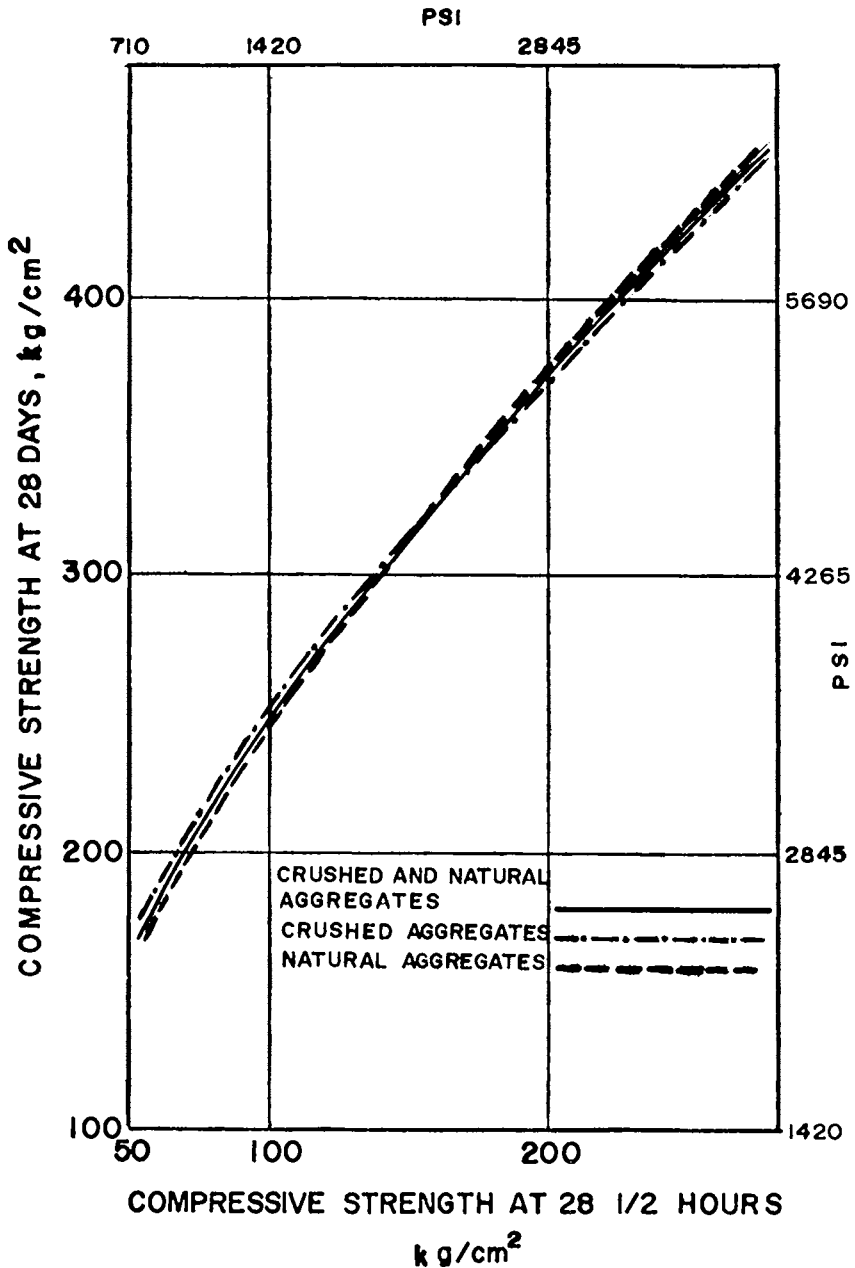


Fig. 4--Comparison of compressive strength at 28 days versus 28½ hr--All type of concretes

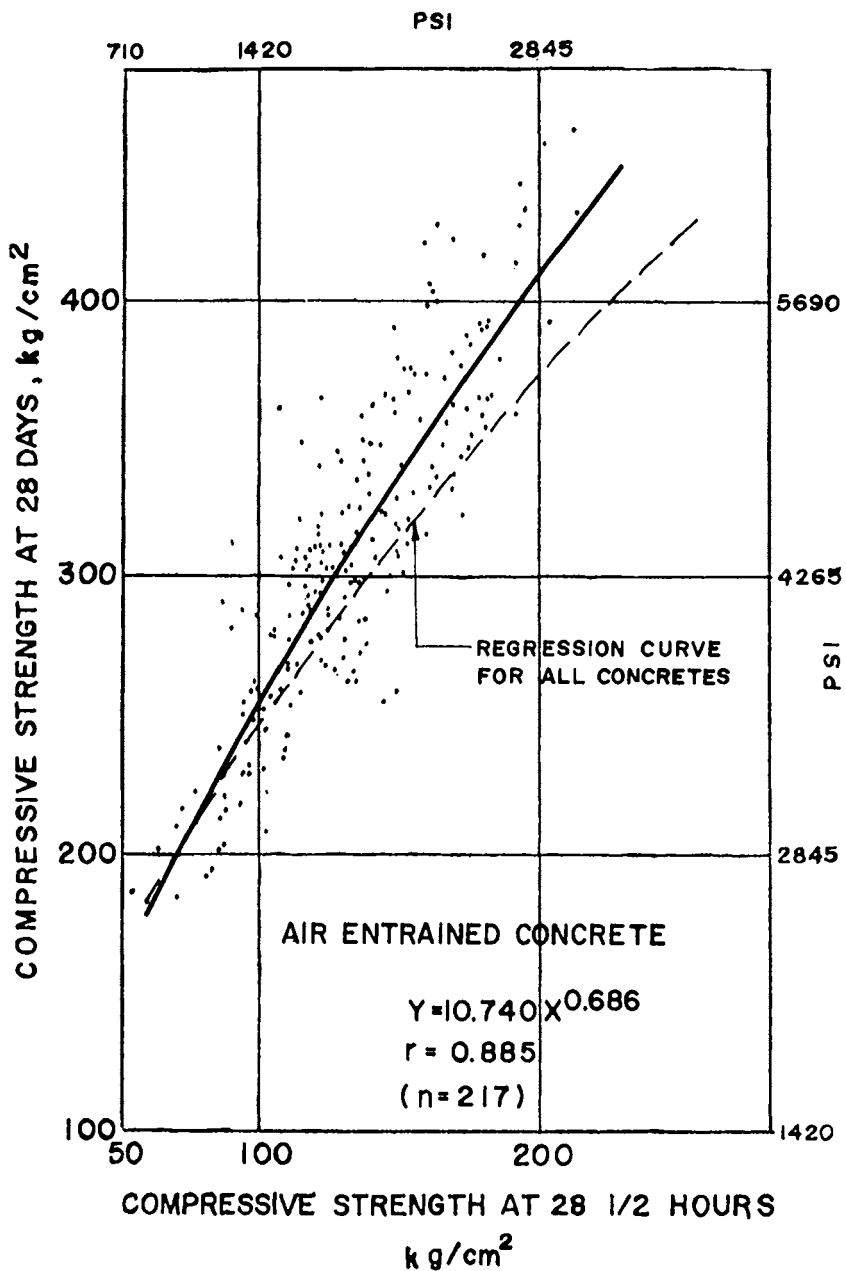


Fig. 5--Comparison of compressive strength at 28 days versus 28½ hr--Samples with air-entraining agent

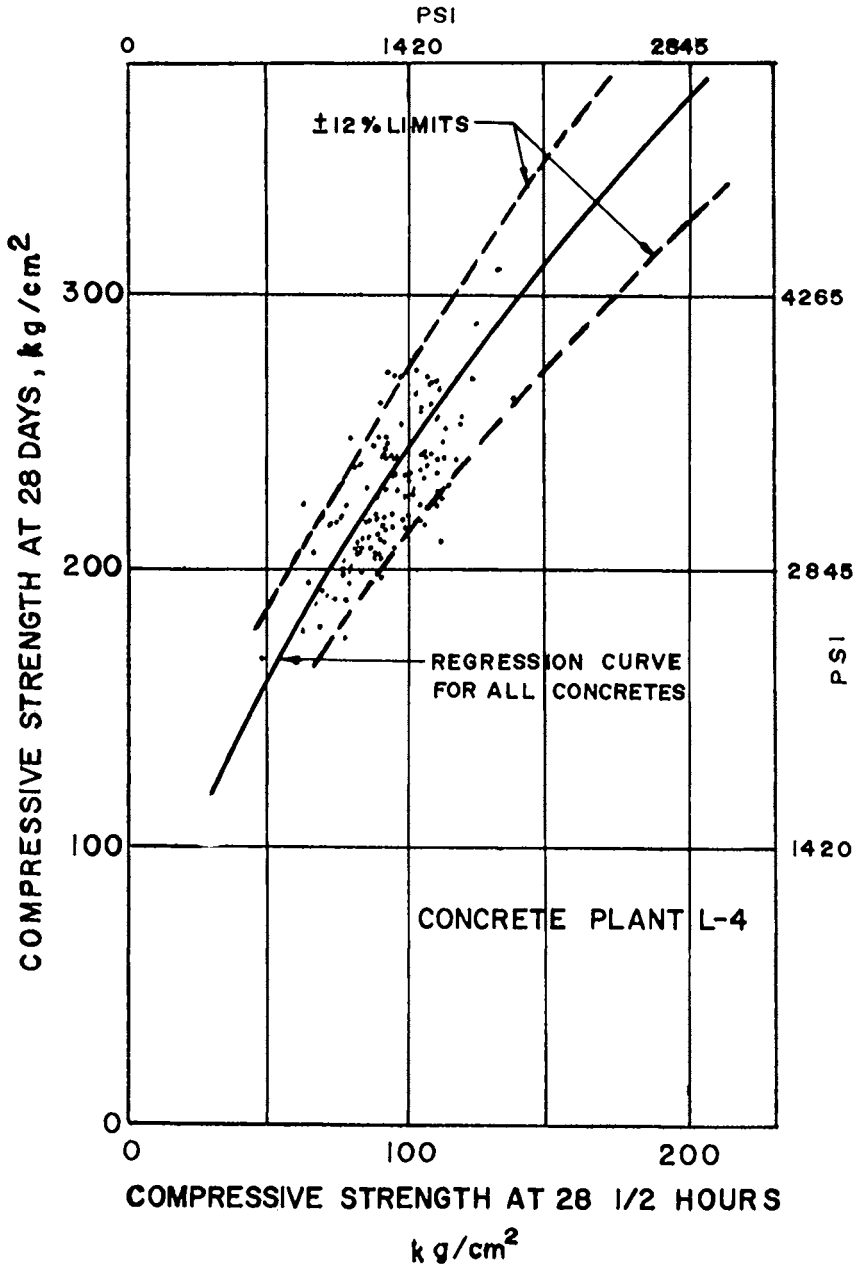


Fig. 6--Comparison of compressive strength at 28 days versus 28½ hr--Samples from Concrete Plant L-4

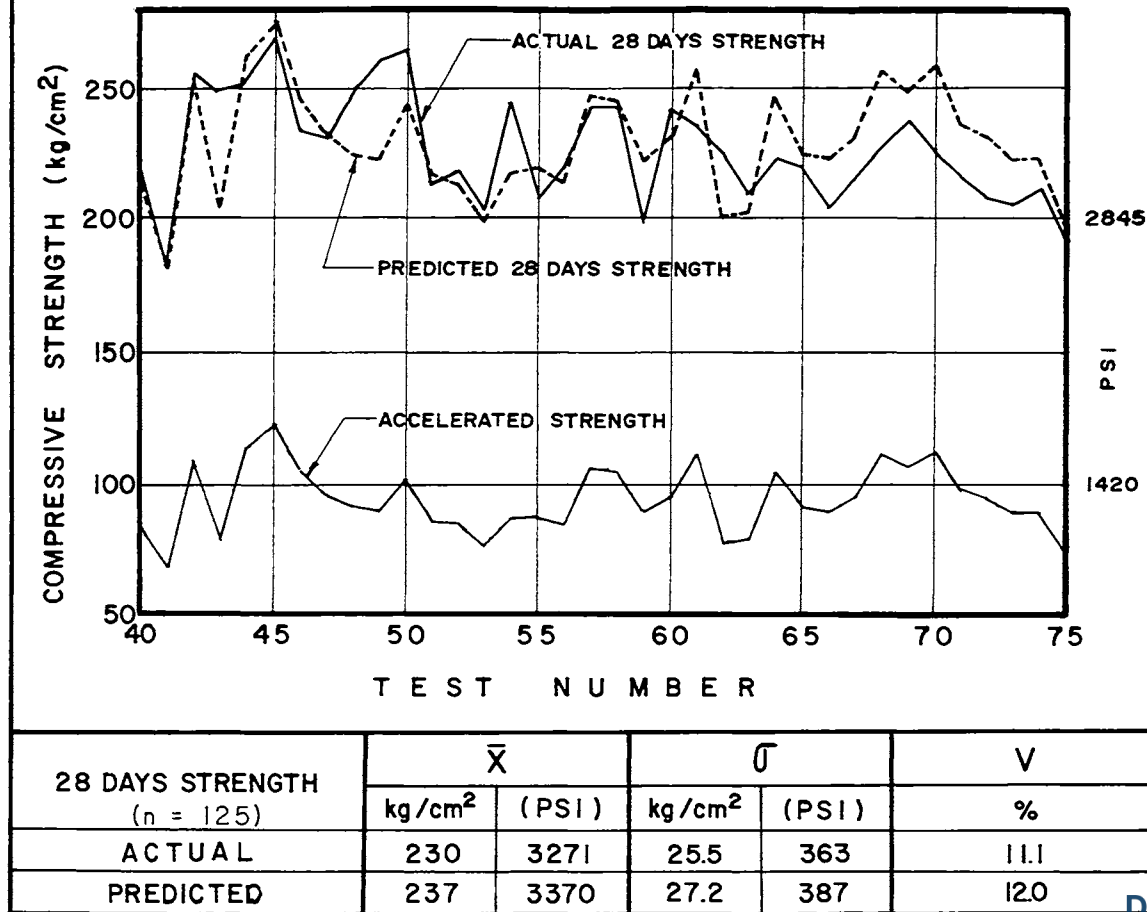


Fig. 7--Comparison of compressive strength at 28 days versus the predicted 28-day strength, using the results of accelerated testing

Accelerated Concrete Strength Testing at the CN Tower

By John A. Bickley

Synopsis: Recognition of the advantages of being able to judge the compressive strength of concrete much sooner than by the traditional 28 day test has led to a 50 year search for reliable and convenient accelerated strength testing methods. The autogenous curing method was used as an integral part of the concrete quality assurance programme during construction of the CN Communications Tower in Toronto. The results presented which are obtained from 547 sets of cylinders cast during the placing of 40,000 cu.yds. (30,580 m³) of slipformed concrete to a height of 1500 ft. (457 m) between July 1973 and February 1974 indicate that the 28 day or 90 day compressive strength of the concrete made with either low heat or normal Portland cements or a blend thereof can be accurately predicted from 2 day autogenous strength results. Accelerated strength determination played an important role in the control of quality and the overall structural safety of the concrete shaft of the world's tallest free standing structure.

Keywords: accelerated tests; compressive strength; concretes; low-heat cements; quality control; regression analysis; slipform construction; standards; towers.

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COMPRESSIVE STRENGTH TESTING PROGRAMME

When the specifications for concrete quality for the CN Tower were first drafted in 1969, accelerated strength testing methods were still in the final stages of the standardization process and authorities concerned with the project were skeptical and still imbued with a deep sense of history so it was agreed that compressive strength tests would also be made at 7 days and one and three lunar months after the concrete was placed. Otherwise accelerated strength testing was selected as the prime means of determining the potential quality of the concrete. Indeed, with a planned climb rate of 24 ft.(7.3 m)/day during the slipforming operation only a lunatic could afford to wait a lunar month for strength results that by then would be academic assuming disaster had not come first. The author grudgingly acknowledges that without such historical strength data, this paper could not have been written but he cannot really see the 28 day test catching on since the accelerated strength data obtained at two days was an equally satisfactory predictor of ultimate strength potential as judged by comparison with the 28 and 90 day results.

From consideration of the pros and cons of the various accelerated curing procedures, the autogenous method was selected because its essential simplicity and reported reliability made it very practical for use by the commercial testing laboratory concerned without additional elaborate and expensive site testing facilities being required beyond those needed for other inspection and testing purposes.

The compressive strength testing programme adopted required casting sets of five cylinders. The frequency of sampling was specified as one set at least every 75 cu.yds (57.3m³) or every 8 ft.(2.4m) rise of the slipform, or every 8 hours which ever gave the highest rate of testing. Each set of cylinders consisted of one for accelerated curing and testing at two days and then moist cured cylinders for testing, one at 7 days, two at 28 days and one at 90 days. Altogether 547 sets of cylinders were made from the 40,000 cu.yds (30,580 m³) of concrete placed: one set for every 73.5 cu.yds (56.2 m³).

The autogenous curing and compressive strength testing procedure used followed that in CSA Standard A23.2 - 1973 except that, since concreting operations were suspended over weekends and public holidays, those cylinders made on Fridays were tested at 3 or 4 days rather than at 2 days. Other interruptions led to a small number of cylinders being tested after 5 or 6 days autogenous curing. All compressive strength

test results were analyzed in accordance with the recommendations of ACI Standard 214 - 65.

CONCRETE MIX PROPORTIONS AND PRODUCTION

In order to control the properties of the concrete, when plastic and during the initial stages of hardening, and so as to facilitate the slipforming operation in relation to ambient conditions, two types of cement were used in the tower super-structure. Low heat Portland Cement, ASTM Type IV was used for the lower 400 ft (122 m) comprising about 40% of the volume of concrete used. Thereafter low heat cement was replaced by normal Portland cement, ASTM Type 1 in 10% increments as the weather got colder and the cross section of the structure smaller with height until for about the last 12% of the concrete only normal cement was used.

The concrete and constituent materials met the requirements of CSA Standard A23.1. The concrete mix proportions selected, as shown in Table I, were used throughout the work.

An air entraining agent and a water reducing admixture were used,

Specified slump: 4 in $\pm$ 1/2 in. (101.6 mm $\pm$ 12.7 mm)

Air content: 5% $\pm$ 1%.

The concrete materials were proportioned on site and the concrete was then mixed in stationary ready mixed concrete trucks prior to hoisting by crane and bucket.

SLIPFORMING OPERATIONS

Slipforming was originally scheduled to commence in March 1973 and carry on through the warmer summer months with completion in September of that year. A start did not prove possible however until July, and this threw a part of the slipforming operation into progressively colder Fall and Winter weather.

COMPRESSIVE STRENGTH TEST RESULTS

The compressive strength data from the 547 sets of cylinders made during the course of the work are summarized in Table II for each different age of test and for concretes in which low heat or normal cements were exclusively used and for a 50-50 blend of these cements. Data for intermediate blends is not presented because the small number of tests, ranging from 4 to 29 sets for particular blends, renders these disproportionately significant to the analysis made.

The individual strength data at each age of test for each combination of cement used (from 100% low heat in 10% increments of normal cement to 100% normal) were subjected to regression analysis. In all, 105 separate analyses were run and, as with other reported results of accelerated strength testing the data was found to best fit a linear

equation of the form $y = bx + a$. The results of these analyses for concretes containing normal and low heat cements exclusively and the 50-50 blend are shown in Tables III, IV and V respectively. In each case the standard error of estimate and correlation coefficient is presented as a means of judging the reliability of the relationships established.

In each of these tables and in Fig. 1, the following notation is used:

n = number of tests

$y(7\text{-day})$ and $y(28\text{-day})$ and $y(90\text{-day})$ = predicted compressive strengths at age noted

$R_a(48\text{-hr.})$ and $x(..\text{-day})$ = "Autogenous" and "Moist" cured cylinder strengths respectively at age noted

$S_{y.x}$ = one standard error of estimates

r = correlation coefficient

Analysis was based on "Method of Correlation and Regression Analysis" by Ezekiel and Fox.

In each case a high degree of correlation for the prediction of strengths at any later age from the test results at earlier ages was achieved, all correlation coefficients being significant at the 5% level. In addition to the predictions from 2 day autogenous curing results it is also worth note that the prediction of 28 day strengths from 7 day moist cured strengths was very good. No doubt a tribute to care and attention given to proper curing and handling of the cylinders particularly at early ages which is often lacking in the field on less well controlled projects. Considering that the 2 day test results are for single cylinders only while the 28 day tests comprised 2 cylinders the prediction of the 90 day strengths from the 2 day tests compares very favourably with the prediction of 90 day strengths from 28 day results. Indeed, in the case of normal cements the difference in the standard error of estimate was only 28 psi (2 kgf/cm²) and of course the prediction could be made 26 days sooner.

Fig. 1 shows a typical dispersion of test data.

The accuracy of prediction of strengths at later ages using this system is illustrated in Fig. 2 in which, from the analysis made for concretes containing normal cement, the standard errors of estimate and correlation coefficients are shown diagrammatically.

CONCLUDING REMARKS

Both for the general control of concrete quality as produced and for acceptance purposes, the experience at the CN Tower indicates that accelerated strength testing, in this case by the autogenous curing method, is a good predictor of strengths at later ages.

This finding is by no means new. Many other investigations referenced earlier have found similar indications. The significance of the CN Tower experience is that the quality and safety of construction, sometimes in most adverse circumstances of one of the most daring concrete structures ever built, hinged on the results of accelerated strength testing.

If more evidence is needed as to the reliability, usefulness and economy of accelerated concrete strength testing to replace the 28 day test, then any Doubting Thomases should at least try it for themselves.

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Table I
CN Tower Slipformed Concrete Mix Proportions

	lb/cu.yd.	(kg/m ³)	
Cement	620	(368)	
Coarse Aggregate	1900	(1127)	(3/4" (19.5 mm) crushed dolomitic limestone)
Fine Aggregate	1200	(712)	(natural sand)
Water	260	(154)	

Table II
Summary of Compressive Strength Results
At All Ages

Age of Test Days	Type of Cement (ASTM Type)	n	Mean Compressive Strength		Standard Deviation		Coefficient of Variation %
			psi	kgf/cm ²	psi	kgf/cm ²	
2	100% of IV	139	3610	249	433	30	12.0
	50-50 Blend	67	3909	270	255	18	6.5
	100% of I	43	3950	272	372	26	9.4
	All results	341*	3760	259	345	24	9.2
7	100% of IV	237	5060	349	506	35	10.0
	50-50 Blend	116	5279	364	369	25	7.0
	100% of I	63	5490	379	502	35	9.1
	All results	547	5210	359	432	30	8.3
28	100% of IV	237	6925	477	501	35	7.2
	50-50 Blend	116	6991	482	350	24	5.0
	100% of I	63	6509	449	594	41	9.1
	All results	546	6940	479	433	30	6.2
90	100% of IV	237	7980	550	718	50	9.0
	50-50 Blend	116	7946	548	512	35	6.4
	100% of I	63	7220	498	620	43	8.6
	All results	547	7890	544	604	42	7.6

* Remaining sets tested at 3, 4, 5, or 6 days.
Within-test variations calculated were in the
range 2.0 to 3.0%.

Table III
Regression Analysis - Strength Data

Normal Portland Cement

<u>n</u>	<u>y = bx + a</u>	<u>Sy.x (psi)</u>	<u>r</u>	95% Confidence Limits	
				Yes	or No
43	y(7-day)=1.1621Ra(48-hr.)+855	251	0.8685	yes	
43	y(28-day)=1.3027Ra(48-hr.)+1392	341	0.8227	yes	
43	y(90-day)=1.3484Ra(48-hr.)+1813	358	0.8195	yes	
69	y(28-day)=1.0132 x (7-day)+978	327	0.8437	yes	
69	y(90-day)=0.9978 x (7-day)+1775	421	0.7683	yes	
69	y(90-day)=0.8472 x (28-day)+1567	330	0.8472	yes	

Table IIIa
Regression Analysis - Strength Data

Normal Portland Cement

<u>n</u>	<u>y = bx + a</u>	<u>Sy.x(kgf/cm²)</u>	<u>r</u>	95% Confidence Limits	
				Yes	or No
43	y(7-day)=1.1621Ra(48-hr.)+59	17	0.8685	yes	
43	y(28-day)=1.3027Ra(48-hr.)+96	24	0.8227	yes	
43	y(90-day)=1.3484Ra(48-hr.)+125	25	0.8195	yes	
69	y(28-day)=1.0132 x (7-day)+67	23	0.8437	yes	
69	y(90-day)=0.9978 x (7-day)+122	29	0.7683	yes	
69	y(90-day)=0.8472 x (28-day)+108	23	0.8472	yes	

Table IV
Regression Analysis - Strength Data

Low Heat Portland Cement

<u>n</u>	<u>y = bx + a</u>	<u>Sy.x(psi)</u>	<u>r</u>	95% Confidence Limits	
				Yes	or No
147	y(7-day)=0.9139Ra(48-hr.)+1556	336	0.7394	yes	
147	y(28-day)=0.9162Ra(48-hr.)+3611	356	0.7173	yes	
147	y(90-day)=1.0360Ra(48-hr.)+4271	489	0.6468	yes	
236	y(28-day)=0.8321x (7-day)+2883	304	0.7919	yes	
236	y(90-day)=0.9344x (7-day)+3438	413	0.7314	yes	
236	y(90-day)=0.9900x (28-day)+1126	354	0.8106	yes	

Table IVa
Regression Analysis - Strength Data
Low Heat Portland Cement

n	$y = bx + a$	$Sy.x(kgf/cm^2)$	r	95% Confidence Limits
				Yes or No
147	$y(7\text{-day}) = 0.9193Ra(48\text{-hr.}) + 107$	23	0.7394	yes
147	$y(28\text{-day}) = 0.9162Ra(48\text{-hr.}) + 249$	25	0.7173	yes
147	$y(90\text{-day}) = 1.0360Ra(48\text{-hr.}) + 294$	34	0.6468	yes
236	$y(28\text{-day}) = 0.8321 x (7\text{-day}) + 199$	21	0.7919	yes
236	$y(90\text{-day}) = 0.9344 x (7\text{-day}) + 237$	28	0.7314	yes
236	$y(90\text{-day}) = 0.9900 x (28\text{-day}) + 78$	24	0.8106	yes

Table V
Regression Analysis - Strength Data
50% Low Heat
50% Normal Portland Cement Blend

n	$y = bx + a$	$Sy.x(psi)$	r	95% Confidence Limits
				Yes or No
68	$y(7\text{-day}) = 0.7833Ra(48\text{-hr.}) + 2166$	290	0.5572	yes
68	$y(28\text{-day}) = 0.7943Ra(48\text{-hr.}) + 3866$	301	0.5486	yes
68	$y(90\text{-day}) = 0.7934Ra(48\text{-hr.}) + 4777$	484	0.3779	yes
113	$y(28\text{-day}) = 0.7964 x (7\text{-day}) + 2837$	229	0.7640	yes
113	$y(90\text{-day}) = 0.8576 x (7\text{-day}) + 3413$	418	0.5725	yes
113	$y(90\text{-day}) = 1.0101 x (28\text{-day}) + 827$	363	0.7030	yes

Table Va
Regression Analysis - Strength Data
50% Low Heat
50% Normal Portland Cement Blend

n	$y = bx + a$	$Sy.x(kgf/cm^2)$	r	95% Confidence Limits
				Yes or No
68	$y(7\text{-day}) = 0.7833Ra(48\text{-hr.}) + 149$	20	0.5572	yes
68	$y(28\text{-day}) = 0.7943Ra(48\text{-hr.}) + 267$	21	0.5486	yes
68	$y(90\text{-day}) = 0.7934Ra(48\text{-hr.}) + 329$	34	0.3779	yes
113	$y(28\text{-day}) = 0.7964 x (7\text{-day}) + 196$	16	0.7640	yes
113	$y(90\text{-day}) = 0.8576 x (7\text{-day}) + 235$	29	0.5725	yes
113	$y(90\text{-day}) = 0.0101 x (28\text{-day}) + 57$	25	0.7030	yes

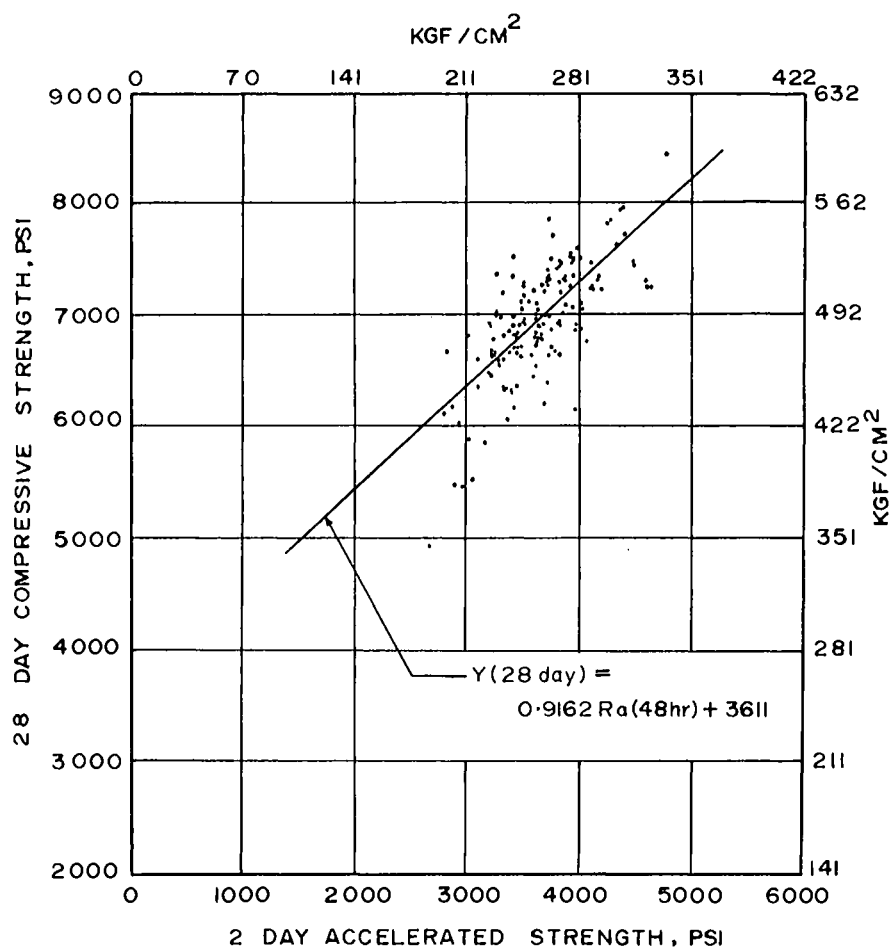


Fig. 1--Graph showing test data

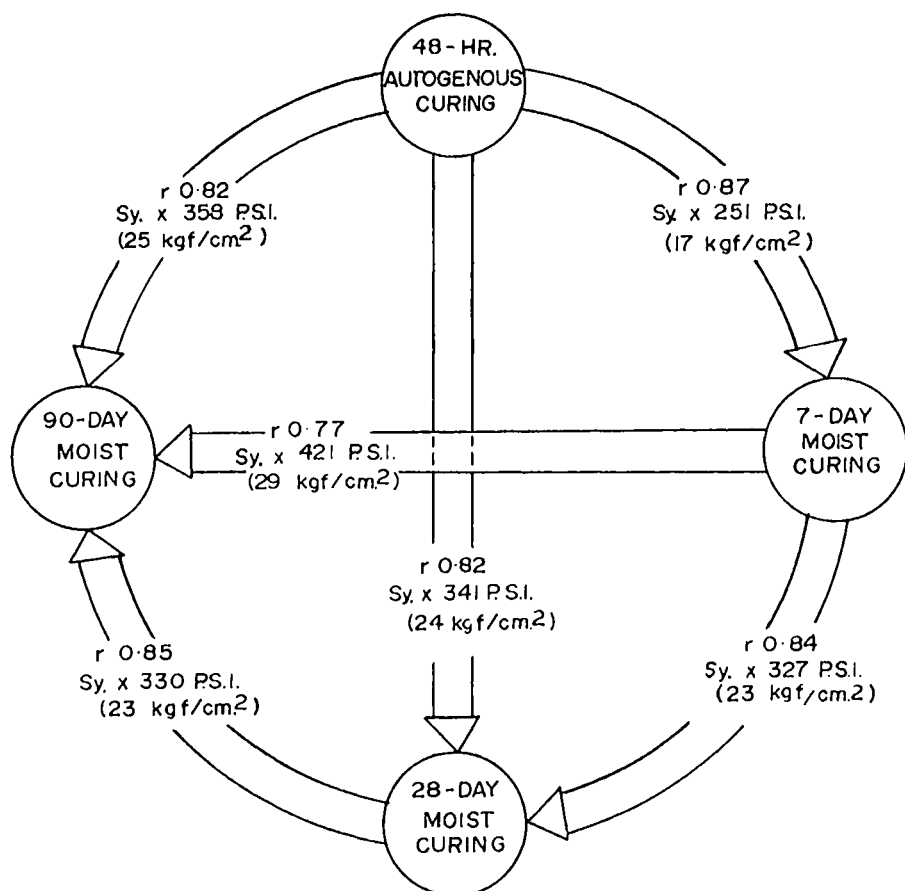


Fig. 2--Compressive strength prediction system--Illustration of accuracy using low heat cement concrete data

Adaptation of Accelerated Strength Testing Methods for Concrete Quality Control and Quality Assurance

By Tarun R. Naik

Synopsis:

This paper presents modified boiling water methods (M.B.W. Methods) and discusses how these methods can be adapted for regular quality control and quality assurance of concrete for small as well as large projects. These M.B.W. Methods were found to be more suitable than other A.S.T.M. methods. Accelerated strength test data can be used in two ways: (1) for quality control, where actual accelerated strength can be used as an established target value; and, (2) for quality assurance, where, if required by the contract specification, the future strength, e.g. the 28-day strength, can be projected from the accelerated strength. In order to predict the future strength, a basic correlation curve must be established for a given set of conditions. A minimum of ten to fifteen sets of data were found to be adequate in order to establish this correlation curve. The A.S.T.M. boiling water method schedule requires the strength test to be performed at 28-1/2-hour age. In order to provide the greatest flexibility in scheduling, and to eliminate the overtime work associated with the 28-1/2-hour test, modified boiling water methods were developed in which the test is performed at either 24-hour, 28-hour, 48-hour or 72-hour age. Adaptation of these four modified boiling water methods not only eliminated overtime work required on a regular working day, but it also eliminated work on holidays and weekends. This study showed that any one of the commercially available single use cylinder molds can be used for the M.B.W. Methods. The single use tin molds, however, were preferable. An accelerated strength testing program, along with the reliability of results obtained, is discussed in detail in this paper. Some of the more important observations given in this study are: (1) overtime work can be virtually eliminated by adapting the methods given; (2) influence of initial concrete temperature had minimal effect upon the accelerated strength test value; (3) a job site testing laboratory is not needed; and, (4) the danger of being exposed to steam emanating from the boiling water tank and the danger in handling boiling cylinders was ill-founded.

Keywords: accelerated tests; compressive strength; concretes; cylinders; quality control; regression analysis.

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INTRODUCTION

The standard 28-day compressive strength test has served well for many years. In the more recent years, however, it has come under increasing scrutiny. One of the principal points of concern is that the 28-day wait, in assessing the quality of the concrete, is too long a waiting period.

The quicker pace of the modern day construction has brought this point of concern into sharper focus. Consider the case of the Hilton Hotel building construction in St. Petersburg, Florida. The foundation of this 15-story building "was placed in two four-hour placing sessions. The exterior and interior walls, including elevator shafts and stairwells were slip-formed in eight days. Finally, the slab forms were suspended on cables and placed from the top down in a period of 28 days."^{(1)*} The usual 28-day wait, in assessing the quality of concrete, is obviously too long.

In the accelerated strength testing methods, the accelerated rate of strength gain, for a concrete test specimen, is achieved by various techniques (using external heat or internal heat). By using these methods, the strength testing schedule is shortened, and the standard 28-day strength can be predicted at only one day age.

The accelerated strength test value can be used as a specified value in the contract specifications or it can be used to predict the normal 28-day strength. Even though the eventual goal might be to specify only the accelerated strength test value, in the interim of next five years or so, the accelerated test result can be used for predicting the standard 28-day strength.

HISTORICAL BACKGROUND

The first published work in the area of accelerated strength testing was in 1927 by Gerend. ⁽²⁾ He concluded that a concrete cylinder strength gain can be accelerated by subjecting the specimen to a saturated steam bath under pressure of about 80 to 100 psi, (5.6 to 7 Kg

* The numbers in parentheses refer to the references at the end of this paper.

per cm^2). Gerend's work, however, was not received very enthusiastically because of the high pressure steam curing equipment needed for the test procedure.

In 1933, Patch (3) published the results of his investigation conducted for the Hoover Dam construction. He subjected the standard cylinders, which were moulded in special jackets, to an 8-hour boiling test, 7 hours for boiling and one hour for cooling, capping and testing. Patch's work also did not gain acceptance because the 28-day strength predictions were not very reliable.

From 1933 until 1955, when King's work (4) was published, no significant progress was made and no research reports were published. Since the publication of King's paper, (4) however, many research reports and papers have been published in proceedings and journals. (1,4 to 37) Canadian researchers have been in the forefront of research in the field of accelerated strength testing since the 1960's. In particular, the excellent work done at the Mines Branch of the Department of Energy, Mines and Resources, Ottawa, Canada, deserve special recognition.

Malhotra and Zoldners' paper (26) attracted a very wide audience, as evidenced by the detailed discussion of their paper. (27) The contributors to the discussion (27) have done an outstanding job in sharing their practical experiences in adapting the accelerated strength testing methods to field conditions.

ACCELERATED STRENGTH TESTING METHODS

There are various accelerated strength testing methods in use today throughout North America and other parts of the world. A.S.T.M. C 684-74 (38) gives the "Standard Method of Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens." This specification recognizes three different methods: (1) Warm Water Method; (2) Boiling Water Method; and, (3) Autogenous Method. With minor modifications, however, the various accelerated strength testing methods in use today generally fall into the above three basic methods. The two most frequently used are the boiling water method and the autogenous method.

For occasional quality control testing at a ready mix concrete plant, (average size ready mix plant where concrete quality is not checked every day), and for the normal quality assurance program at an average size construction project, the warm water method is not very practical to adapt. The boiling water method, on the other hand, can be very easily adapted for occasional testing and for small as well as large projects.

THE MODIFIED BOILING WATER METHOD

The boiling water method adapted by the writer should be more properly labeled as the modified boiling water method (M.B.W. Method), because the procedure followed is not exactly in accordance with the A.S.T.M. C 684-74.(38) For accelerated testing by the M.B.W. Method,

the cylinders are brought from the field to the laboratory at approximately 23-hour age. They are then "cooked" in the boiling water, (the cylinders are not closed tightly with steel cover plates, (26) but are left open), water temperature $205^{\circ}\text{F} \pm 5^{\circ}\text{F}$, ($96^{\circ}\text{C} \pm 3^{\circ}\text{C}$), for 3-1/2 hours, beginning at 23-1/2 hour age. After cooking them, they are taken out of the boiling water at 27-hour age, are stripped, and then cooled for 50 minutes, at which time they are capped and then tested at 28-hour age (10 minutes after capping them with the standard hot sulfur capping compound). Cube tests conducted on this hot sulfur capping compound indicated that at 10-minute age the capping compound achieved over 6000 psi, (422 Kg per cm^2), strength. The cylinder strength, after accelerated curing, varies normally between 1000 and 3000 psi, (70 and 211 Kg per cm^2). For high strength concrete it is usually between 3000 and 4500 psi, (211 and 316 Kg per cm^2), rarely if ever reaching or exceeding 5000 psi (352 Kg per cm^2).

MOLDS FOR THE M.B.W. METHOD

For the modified boiling water method any one of the commercially available single-use molds can be used, such as cardboard molds coated with various types of coatings and single-use tin molds. All of these have performed reliably. There was an insignificant difference in the predicted 28-day strength from the accelerated strength, using the same prediction equation, when different types of single-use molds were used. The single-use tin molds, however, were preferable not only because of their usual advantages over the cardboard molds, but also because they were easier to handle and strip after taking them out of the boiling water bath.

CASTING, STORAGE AND TESTING OF CYLINDERS FOR THE M.B.W. METHOD

Cylinders are cast and stored in the normal fashion, in accordance with the standard A.S.T.M. procedures. The storage area temperature is maintained at 70°F plus or minus 10°F ($21^{\circ}\text{C} \pm 6^{\circ}\text{C}$). This temperature requirement sometimes is not followed rigidly in the normal practice. It should be emphasized, however, that this requirement should be enforced more rigorously for test specimens for the M.B.W. method, otherwise the test results are likely to fluctuate more than desired.

Besides controlling the curing temperature before immersing the cylinders in the boiling water, the testing schedule to be followed by the testing laboratory should be coordinated carefully. For the normal seven or 28-day cylinders, the testing could be performed during any time of a given working day, without any significant effect upon the end result. The schedule for accelerated testing, on the other hand, should be maintained for starting the boiling of the cylinders, taking them out, cooling, capping and testing them, much more rigorously to within plus or minus five minutes. This generally does not create any problem for a testing laboratory because there is usually a laboratory technician who is continuously working with recording, capping and testing of cylinders.

BASIC CORRELATION CURVES

Even though the state of the art of the accelerated strength testing methods is well developed, the method is not practiced widely enough and the code authorities have not fully recognized the potential of these methods. The present day practitioner, therefore, must, for traditional as well as legal reasons, be able to predict the normal 28-day strength value from the accelerated strength test value. In order to accomplish this, the practitioner should establish a basic correlation curve for a given set of conditions. For a given concrete supplier, knowing his physical facilities, aggregate type, cement type, etc., one can set up a program which includes accelerated strength testing as well as the standard testing. As per example, during the time the mix designs are being prepared for a given project, two extra cylinders can also be made, which will be accelerated strength tested, and other cylinders will be cured and tested in the normal manner. An entire spectrum of mix designs, low strength, 1500 psi, (105 Kg per cm^2), to high strength, 7000 psi (492 Kg per cm^2), or higher if required by a given project conditions, should be established. After knowing the accelerated strength test results and the standard seven and 28-day test results, the data points can be plotted relating the accelerated strength to the actual seven or 28-day strength. After an adequate number of data points are established, a curve (regression line) representing these data points can be drawn. In the experience of the writer, a minimum of between 10 and 15 data points should be used. If necessary, similar curves can be established relating the accelerated strength with strength at other ages (e.g., 91 days and one year). Normally the relationship can be stated by an equation of the form $Y = AX + B$, where Y is the projected normal strength, say at the 28-day age, A is the slope of the regression line, X is the accelerated strength test value (normally plotted along the X-axis), and B is the intercept of the line on the Y-axis. Even though this writer and others (26,27,34,36) have found the straight line relationship to be adequate, there is ample evidence in the literature (17,26, 27, 34) that hyperbolic curves of the type $Y = X/(AX + B)$ provide a better prediction equation. Regression equations more complicated than these were also tried by Ryan, (27) with "generally more accurate predictions" of the normal 28-day strength.

In conclusion, it should be stated that one must establish his own basic correlation curves for each set of conditions, and, in establishing these curves, it is very important to include a range of low as well as high standard strength data points, along with data points in the normal range of 2500 psi to 5500 psi, (176 to 387 Kg per cm^2).

ACCELERATED STRENGTH TESTING PROGRAM

With the present day contract specifications requirement, where the accelerated strength test results are normally not accepted, one might have to make one more test cylinder than normally required by the specifications. As per example, normally three cylinders are made to represent a particular concrete placement sequence. In such a case, four cylinders could be made, and instead of testing one at 7-

day and two at 28-day age, two cylinders could be accelerated cured and the remaining two could be tested at the 28-day age after moist curing. From the previously established regression equation, the 28-day strength can be predicted for quality assurance and the normal 28-day cylinders can serve the legal requirements as well as provide confirmation of the regression equation. After adequate sets of cylinders are tested in this manner, the validity of the regression equation can also be confirmed or if necessary slight modifications can be made. At this point in the testing program, one can switch back to three cylinders per set to represent a particular concrete placement sequence, and continue to test two cylinders after accelerated curing, and one after the normal 28-day curing (for confirmation only). In the interim, therefore, when the project specifications still do not recognize the accelerated strength test results, additional testing will be necessary and, therefore, incur a small additional cost. The reward for the additional testing is a significantly improved knowledge about the quality of the concrete being delivered to the job site without having to wait a long period of time. In the future, when the accelerated strength testing will be more widely accepted, only two cylinders will be sufficient to represent a particular concrete placement sequence. These two cylinders will be accelerated cured, and there will be no need for the 7-day or the 28-day test cylinders.

SCHEDULING PROBLEMS AND ALTERNATE PROCEDURES

One of the persistent criticisms of the accelerated strength testing procedure is that the 28-hour test cycle requires overtime work the next day for any cylinders made in the afternoon the previous day. As per example, for a cylinder cast at the project site at 3:00 P.M. the previous day, the boiling for that cylinder will start at 2:30 P.M. the next day; it will be taken out of the boiling water at 6:00 P.M., stripped and then cooled until 6:50 P.M., when it will be capped, and then tested at 7:00 P.M. The consequence of this type of schedule to a commercial testing laboratory is obvious.

Alternate testing procedures, therefore, were developed which gave wide flexibility in scheduling the accelerated tests. Along with the normal 28-day procedure, 24-hour, 48-hour, and 72-hour procedures were established. The basic methodology for these four different procedures is the same, i.e., the cylinders are boiled beginning at a certain age for a fixed number of hours and then they are stripped and cooled for 50 minutes. They are then capped and tested one hour after taking them out from the boiling water. The boiling cycle for the 24-hour, 28-hour, 48-hour and 72-hour begin, respectively, at the age of 19 hours, 23-1/2 hours, 44 hours and 68-1/2 hours. The "cooking" time for these procedures is 4 hours, 3-1/2 hours, 3 hours and 2-1/2 hours, respectively.

All these different testing procedures, of course, have different regression equations in order to predict, say, the normal 28-day strength. These procedures, however, have given great flexibility in deciding whether to subject a particular cylinder to the 24-hour, 28-hour, 48-hour or 72-hour test procedure. The overtime work is virtually eliminated with adaptation of these four procedures. Cylinders

that are normally cast the previous morning are accelerated cured by the 28-hour test procedure, and the cylinders cast in the previous afternoon are tested by the 24-hour procedure. If for some reason the cylinders were not picked up or delivered on time to perform the 24-hour or the 28-hour test, or if the next day was a holiday, then the 48-hour test procedure is employed. The 72-hour test procedure is used for cylinders cast on Fridays and are, therefore, subjected to accelerated curing on Mondays. Cylinders received too late for the 1-day or the 2-day accelerated curing procedure can be also subjected to the 72-hour test.

RELIABILITY OF RESULTS

In the writer's experience, the modified boiling water procedures have consistently given very reliable results. If we compare the actual 28-day strength to the predicted 28-day strength from these various test procedures, then the accuracy was excellent. Generally about 70% of the predicted 28-day strength values were within 5% of the actual 28-day strength. About 85% of the results were within 10% accuracy and about 95% of the results were within 15% of the actual 28-day strength. Approximately 5% of the test results, one out of twenty, were generally in error by more than 15%, (but less than 20%) when compared to the actual 28-day strength.

OBSERVATIONS

The writer has used the M.B.W. Method since 1972 for quality assurance at many small as well as large projects, and for quality control at batch plants and for mix designs. Based upon these experiences the following observations can be made. It should be pointed out that some of these observations do not hold true for other accelerated strength testing procedures.

(1) The 7-day and the 28-day (and other later age) strength can be predicted the next day after casting the test specimen.

(2) Influence of various types and amounts of ingredients in a concrete mix, such as cement, admixture, and aggregates, as well as amount of air content and slump, had minimal effect upon the accelerated strength regression equation. This has also been confirmed by other researchers, in particular by Spratt.(27) Spratt, however, cautions that when calcium chloride was used, the predicted 28-day strength was higher than the actual 28-day strength.

(3) Influence of initial concrete temperature had minimal effect upon the accelerated strength value.

(4) Initial equipment cost is about \$400 for an accelerated curing tank which accommodates up to nine cylinders. Larger tanks, with a simple thermostat control for maintaining the water temperature, can be easily made.

(5) The overtime work can be virtually eliminated by adapting the 24-hour, 28-hour, 48-hour and 72-hour procedures.

(6) Job site laboratory is not needed. No special job site preparations are necessary. The process is conventional until the cylinders are brought to the laboratory for accelerated curing.

(7) The technique is easy to adapt and the M.B.W. Method accelerated testing program can be initiated at any time without any pre-planning except scheduling the laboratory, and it can be terminated at any time. If the cylinders from the site come to the laboratory too late even to use the 72-hour procedure, then they can be processed through the normal testing cycle without having affected its hydration process, unlike the autogenous method.

(8) Unlike the autogenous method, no special field curing boxes are needed. Stocking costs for these special field curing boxes could be prohibitive (in order to meet demands of a large or large number of projects).

(9) The danger of being exposed to steam emanating from the boiling water tank and the danger in handling boiling cylinders was ill founded. There have been more minor burns from the hot sulfur capping compound than from the boiling cylinders.

(10) The testing laboratory should preferably be located within less than two hours of travel time from the project site. This, however, is rarely of concern.

(11) The boiling water should be ready when the cylinders are ready for immersion. This usually is not a big problem because the boiling tank is equipped with a thermostat, thus the tank can be switched "on" even the night before and the water will be ready the next day without excessive evaporation overnight.

(12) The testing schedule should be carefully followed, preferably within plus or minus five minutes for the 24- and 28-hour tests and within plus or minus 30 minutes for the 48- and 72-hour tests.

CONCLUDING REMARKS

The accelerated strength testing methods are being used widely in small as well as large projects. The state of the art for these methods, particularly the modified boiling water method, has taken a giant step in the last decade and before the next decade is out, these methods will become part of standard construction specifications.

Many papers are being published in this field, and the collective experience should be invaluable to practicing engineers and to code establishing agencies.

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**Quality Control of Concrete by Means of
Short-Term Tests at La Angostura
Hydroelectric Project,
State of Chiapas, Mexico**

By Manuel Mena Ferrer

Synopsis: During the construction of La Angostura Hydroelectric Project, owned by Comisión Federal de Electricidad (CFE) of Mexico, quality control of concrete has been achieved by means of short-term tests, in addition to the standard 28-day tests.

Two types of short-term tests were performed: analysis of fresh concrete samples according to a non-standardized method developed at the laboratories of CFE, and autogenous curing compressive strength following Procedure C of ASTM Designation C 684.

This paper presents the results obtained in these tests after a three-year period of application at the job site; they have been analyzed statistically and correlations among them are discussed.

It was concluded that fresh concrete analysis tests were reasonably accurate to determine the actual composition of freshly mixed concrete, but the results did not allow the prediction of the 28-day concrete strength, because of influence of changes in cement characteristics.

The autogenous curing strength test represented a good means to predict the 28-day concrete strength for all types of mixes, save for 3-in. maximum aggregate size, possibly due to wet sieving.

Keywords: accelerated tests; compressive strength; concretes; dams; fresh concretes; hydration; quality control; spillways; water-cement ratio.