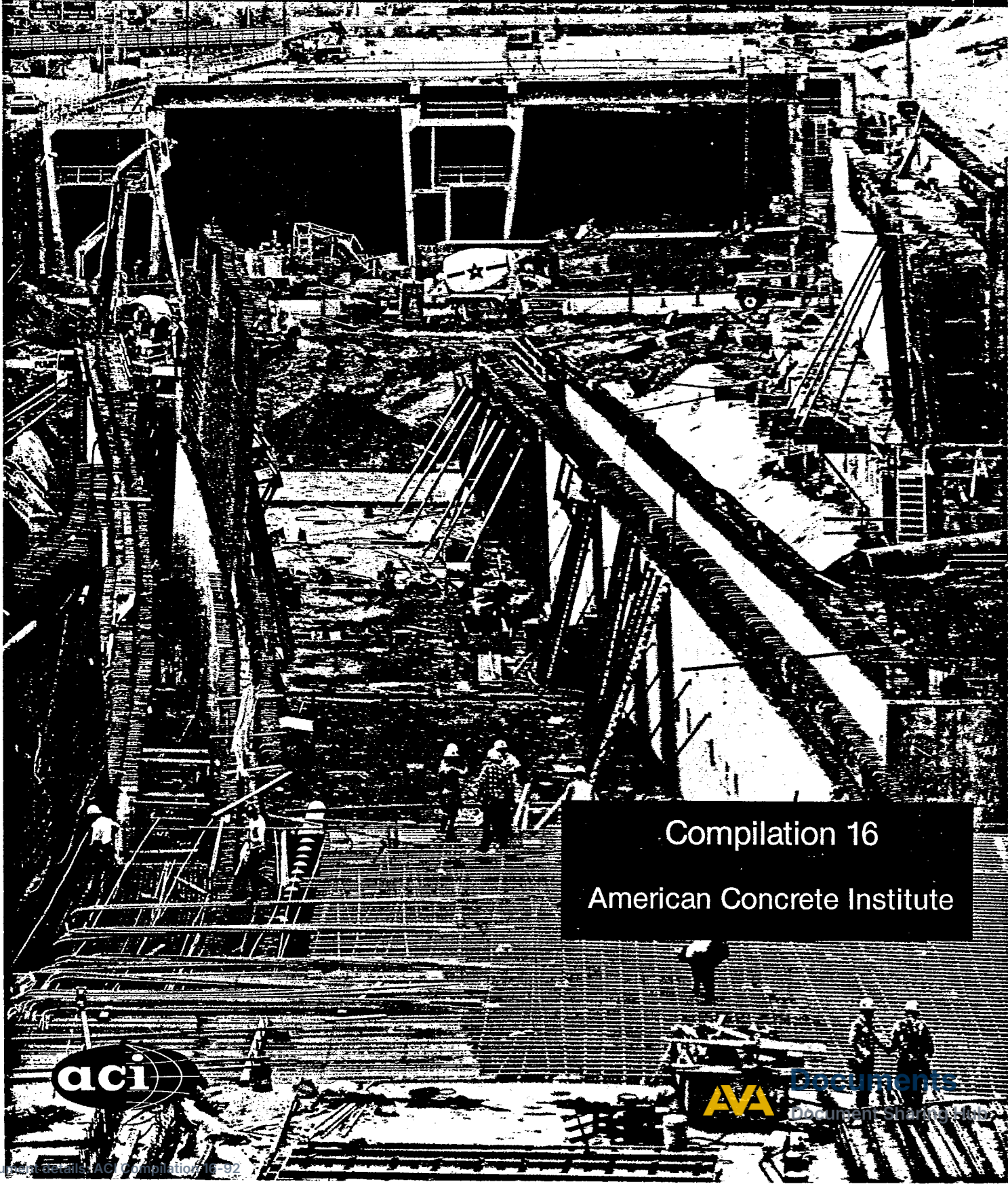


QUALITY ASSURANCE IN CONCRETE CONSTRUCTION



Compilation 16

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Preface

The ACI Compilation Series offers an opportunity to gather together materials previously published in Institute periodicals as a compact and ready reference on a specific topic. The material in a compilation does not necessarily represent the opinion of an ACI technical committee—only the opinions of the individual authors. However, the information presented here is considered a valuable resource for readers interested in the subject.

Joe Gutierrez

Chairman, ACI Committee 121

Quality Assurance Systems for Concrete

Donald E. Dixon

Chairman, ACI Committee 311

Inspection of Concrete

On the cover: More than one million cubic yards of concrete will go into the section of I-90 between Bellevue and Seattle in Washington state. Much of this concrete will be used in structures such as the Seattle Lid, designed to reduce the adverse effects of the heavily-trafficked expressway on local residential communities. (Photo by Robert I. Pearson, Engineering Editor, *Concrete International*.)

American Concrete Institute, Box 19150, Redford Station, Detroit, Michigan 48219



Obtaining quality in concrete construction

by Lewis H. Tuthill

Keywords: acceptability; concrete construction; inspection; performance; quality assurance; quality control; tests.

To get quality in concrete construction, it takes more than making a few slump tests and cylinders for strength tests. It includes all that influences the effectiveness of sufficient inspection and testing to insure that specified results are obtained at all stages of construction. It includes strong, clear specifications of requirements, standards, limits, and certain equipment and methods which do much themselves to insure quality if they are followed. It includes good training and able supervision, as well as meetings of all concerned at various stages of the program to develop interest in quality, understanding of problems, communication, and acquaintance.

Specifically, it is material-acceptance testing, concrete production inspection and testing, and inspection of concrete construction. These three areas are discussed in detail to show what is needed and what is not, particularly in tests for concrete strength, slump, and air content. The importance of records in establishing assurance of quality is stressed.

It is emphasized that the credibility of any quality construction program will stand or fall on whether or not the individuals doing the inspection and testing are free agents with the full support of management to say "no" when necessary and not have the rug pulled out from under them.

QUALITY ASSURANCE

In 1928, Franklin R. McMillan, then director of research at the Portland Cement Association, Chicago, Ill., wrote the first edition of his famous *Concrete Primer*.¹ In the three editions to date, it has been a popular publication of the American Concrete Institute. In his 1928 preface, Mr. McMillan said: "Many who have been interested in the cause of better concrete have noted the difficulty of making any real progress until someone in authority has been convinced that good concrete *can* be had, that it *should* be had, and having been so convinced, has sent out the word that it *must* be had." So, quality in concrete construction is the decision to have it, and to see that you get it.

And who does not want assurance that the concrete job with which he is concerned will be of the quality necessary to give good performance and the appearance of quality throughout its intended life? Probably no one. The designer wants it; his reputation and professional satisfaction depend on it. The builder wants it for much the same reason, but sometimes there are adverse influences such as time and money problems. The owner wants it; his money is in the project and he has to live with what he gets. Any governmental agency having surveillance responsibilities wants it for the general good of the public, and of its reputation.

Successful quality control requires managers who will not pull the rug out from under capable inspectors endeavoring to see that there is substantial compliance.

The need for quality assurance

Why then, if all responsible parties concerned want quality, don't we have it automatically?¹¹ Why do we need to consider what it takes to get and assure quality? Perhaps the answer lies in the inadvertencies which are not uncommon in construction activities. Perhaps it lies in the deterioration many have noted in pride of craftsmanship. Perhaps it is something inherent in human nature. It is noted that more than a century and a half ago, to prevent inferior work during the construction of the Erie Canal in New York in 1817-18, the commissioners found it necessary to have their engineers "examine the works" and "employ faithful, active, and vigilant assistants — to inspect every job — and report — every departure from compliance with the respective contracts." And many centuries ago in 79 A.D., Frontinus, the operations and maintenance superintendent for the famous Roman aqueduct, noted, possibly with a touch of exasperation, after describing the

procedure necessary for making secure repairs, that these were things "which all the workmen know, but few observe." Perhaps it is because some are no different today that we need to do something special to insure quality in concrete construction.

But let us not feel inferior in the construction industry because of this necessity. We are not unique, either in having the need, or in doing something about it. It is very common in manufacturing and service industries today to maintain a rigorous program of inspection and testing, reporting independently to top management and with authority to say "No" and reject substandard performance. Increasingly I have noted that large concerns are emphasizing in their advertisements this aspect of their efforts to better serve their customers. The prime example in our own industry is the quality control maintained by the cement producer. Many of the ready-mixed concrete suppliers are also doing a good job in this respect.

Factors affecting quality assurance

Quality control and resulting assurance is no different on concrete construction work. Basically this is inspection and the related testing of materials and concrete. It is however, more than making a few slump tests and cylinders for strength tests. In addition to the full scope of the duties and responsibilities of the inspection and testing staff, if they are to be effective it must also include all that may affect them in that effort.

It includes a recognition by management of the worth of this wider concept, and accordingly, adoption of a policy that is in full support of it. For instance, it will require that engineers and architects firmly support their own specifications. It will not pull the rug from under capable inspectors endeavoring to see that there is substantial compliance and will not make concessions in obvious disregard of specification require-

The task of inspection will be easier and more effective if the specifications include as many requirements as possible.

ments, which presumably were the basis on which bids for the work were taken.

It also includes proper study and designation of such available materials as will make concrete with properties best suited to the purpose. But this is a separate subject of its own.

It will include specifications which clearly spell out requirements, limits, standards, and where necessary, equipment and methods. Proposals for "performance-type" specifications for concrete work of significance are totally unrealistic and merely reflect an utter unawareness that they can produce inferior results despite apparently acceptable performance or appearance, unless each step, which will be covered by the next step, is inspected as the work proceeds. Few constructions can be accepted only on the basis of final performance or appearance with certainty that all is as it should be, where it can no longer be seen. If quality throughout is to be assured, it must be definitely recognized, confirmed, and recorded with sufficient frequency during the entire performance of the concrete work, so that whenever it is not as it should be, prompt and effective action can be taken for its correction.

Specification inclusions

The task of inspection will be easier and thus more effective, and job results will be better, if the specifications include as many requirements as possible of the kind that tend to insure accomplishment of the intended result with relatively little inspection. This means requirement of such things as:

- finish screening and possibly rinsing the coarse aggregate

just before delivery to the batchplant bins²

- automatic batching and recording of at least the cement weighing
- rigid prohibition of separation during handling or placing concrete³
- positive forbiddance of adding water to plant-mixed or to truck-mixed concrete at any time during delivery of the concrete to and into forms
- low limits on concrete temperature as placed in warm weather
- a working limit on slump of concrete as placed, with a stated inadvertency margin or tolerance of 2 in. (51 mm) or less, and a stipulation that rejection would occur not only when that margin is exceeded, but also if prompt action was not taken to get the slump back to within the working limit⁴
- no air-entraining admixture except where air entrainment is really needed for durability, because readily varying air content causes troublesome variation in slump
- the largest and most powerful vibrators that can be used in the work, supplemented by late re-vibration where appropriate⁵
- sandblast or a demonstrated equivalent for final cleanup of construction joints
- only 1 in. (25 mm) lap and tight bolting of reset forms at horizontal joints³
- completion of repairs and cone-hole filling before half of the water-curing period has elapsed
- water curing with wet cover in contact with formed surfaces and wetted with automatically controlled soilsoaker hoses, and insulation for protection of new concrete in freezing weather.

These and other such requirements in strong, clear specifications will do a great deal to assure quality if they are followed.

This broader concept for getting quality construction with concrete will also include any pretesting of materials, mixes, and concrete properties needed to insure that they will be suitable for the work.

During construction they will be tested routinely for compliance and performance, and results will be recorded. Specifications will affirm that sampling, testing, and evaluation of results for acceptance will be based on statistical patterns, not on a single test.⁶⁻⁸ Basically, this will mean that when 4 out of 5 consecutive tests for each specified property of materials or concrete meet specified values, it will be considered to comply with that requirement. The principal of 100 percent compliance is now widely discredited and recognized as not only unrealistic but a needless cause of higher costs. Concessions made under it, though probably reasonable as to some aspects of materials, may tend to weaken firm requirement of compliance with non-material, performance aspects of the specifications.

Training and communication

Quality is best assured when the inspection and testing force is well trained and ably supervised. This includes seeing that the inspectors know at least what they need to know and that they have the correct attitude of firm but pleasantly detached authority, although endeavoring to be helpful wherever they properly can. For these important reasons of supervision and training, it is usually better to include these functions in the owner's or engineer's organization than to assign this great responsibility to an outside organization over which supervision and control is difficult at best. The cost of quality concrete work will be least when all concerned really want it and work harmoniously together to see that they get it.

An important early move in this direction is to hold prebid and preconstruction meetings attended by responsible representatives of the owner and builder, architect and engineer, inspection and testing people, and materials suppliers. Thus mutual understanding of specifications and potential problems is promoted, and acquaintance and communication is estab-

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lished. Such meetings during construction can also be helpful.

Inspection and testing

What inspection and testing then is necessary to provide the quality desired? This may be divided into material-acceptance testing, concrete production inspection and testing, and inspection of concrete placement and other aspects of construction. Together with these go sufficient recordkeeping to show what was done and what was obtained. The extent to which each is carried out may vary somewhat in accordance with the size and importance of the job, but this should only be in degree as each is an element in getting quality, regardless of size of job, from a house foundation to a nuclear powerplant.

Concrete materials other than aggregates can be accepted on certification of the producer but it should be required that these certifications be accompanied by a copy of his test results showing that the cement, pozzolan, admixture, or membrane-curing compound does in fact meet specification requirements. Random samples of delivered materials can be taken, possibly at one month intervals more or less as experience may indicate advisable, and tested for conformance with certification tests.

Concrete suppliers for the work should require their aggregate producers to see to it that material delivered to their batching plant conforms to specification requirements. Otherwise disagreeable and disruptive delays may result when there is persistent and significant failure to meet specified requirements.

Aggregates should be sampled at the time concrete is sampled but only moisture content and cleanness and grading tests should be made on each of these samples, depending on whether these properties have been marginal. Tests of other aggregate properties should be made only at one to two month intervals for the record to show that they are unchanged from those approved for the work. If it is thought that there has been change or significant encroachment on specification limits, additional such tests should be made as a basis for any needed action and for the record to show what was done.

Concrete testing

Concrete should be sampled for the various tests at least once each shift of concrete production. ASTM C 94 for ready-mixed concrete and the ACI 318 Building Code say to sample concrete for strength test cylinders each 150 yd³ (115 m³). The ACI standard "Specifications for Structural Concrete" says each 100 yd³ (77 m³). In any event, the sampling should be established on a completely random basis without any hint or taint of selection. Tests should include unit weight, slump, air content, and temperature. Cylinders should be made for tests of compressive strength, in number and ages prescribed by the specifications or pertinent code. A common requirement is for two 6 x 12-in. (15 x 30-cm) cylinders each for tests at 7 and 28 days. Sometimes tests at 91 days and 1 year are very reassuring and instructive.⁹ Applicable ASTM standards for sampling and testing the concrete should be carefully followed and the results recorded.

The great importance of this care and correctness in all the operations of making concrete strength tests cannot be overemphasized. In most acceptance confrontations the indicated strength of the concrete is the deciding factor. Usually other questions can be worked out if strength tests are good. If they are not, there is a

real problem. So it is important that they not be low due to carelessness and ineptness in sampling, molding, curing, and testing. Aside from dishonesty, there is little that can be done to make a test cylinder stronger than the potential of the original concrete. But there are many things that can reduce its strength.¹⁰ Well-practiced and supervised persons should do this work with care to see primarily that the sample is truly representative and that the cylinder specimens are evenly filled and fully consolidated without voids or rock clusters in any portion; that they are kept wet with visible moisture on the surface at all times and in moderate room temperatures until testing; that capping for testing should be strong, thin, precisely flat, and especially not convex. This need for perfect planes applies also to the two loading surfaces of the testing machine. Convexity or other irregularity of end surfaces has seriously reduced test values and caused needless trouble and concern on too many occasions. Don't let it happen to you.

The concrete mix and strength control

Either from previously established strength expectancy for the proportions and materials used, or from tests of preliminary batches of similar proportions, it should be reasonably well known before the concrete work starts what strength the mix should produce if the slump and air content are kept within the stipulated limits. Thus the strength tests of job concrete are primarily for the record to show to what degree the expected strength was obtained. Obviously 7 and 28-day tests would be too late to take any prompt action. If it is found that fewer than the required percent reached required strength, it merely means a slight encroachment on the factor of safety at that age. If it is deemed that probable higher strength later will still be insufficient, an appropriate adjustment can be made in cement content.

Eternal vigilance is the price of success in concrete construction just as it has been the price of liberty in the history of mankind.

Control of strength and any evaluation of strength tests should be carried out in accordance with ACI Standard 214, "Recommended Practice for Evaluation of Strength Test Results of Concrete" and its Appendix. The earliest indication from strength tests that corrective action is needed is when the moving average of the five last tests encroaches the stipulated value for f'_c at that age. Many times if an appropriate adjustment in cement content has been made, a modest encroachment on 28-day strength will be acceptable on the basis of companion 91-day tests which show strengths well above requirements. It is strongly recommended that these be made for the insurance they often provide.⁹

Along with the immediate plotting of all strength tests and the moving average, the corresponding air content, slump, and water-cement ratio determined for each test batch should be plotted.

The compressive strength of cement-mortar cubes from mill test reports on the cement going into the concrete should be plotted. It is also helpful to plot the corresponding influential aggregate properties, particularly percent moisture and fines in sand, sand equivalent values, and percent of significant undersize in coarse aggregate as determined on samples taken at the time of the test batch once a shift or a day, as may be appropriate. This plotted information kept faithfully up to date will often reveal trends requiring corrective action which will forestall later sags in the strength lines.

Slump and slump tests

Once concrete proportions and cement content have been selected for the strength required

and are being batched uniformly from the same aggregate, the consistency or slump of the concrete is the primary item for inspection and control. A variable slump is likely to add to variation in concrete strength. Excessive slump usually decreases strength through increase water-cement ratio or stratification. Concrete of insufficient slump, particularly at the start of a placement, is likely to lead to poor consolidation and appearance.

Unfortunately, slump is not subject to precise production or measurement. For this reason it is found most practical to specify a proper working limit on slump with a reasonable tolerance rather than a certain number.⁴ Because slump is critical to concrete placement, it is important to designate the specified value as placed. Thus if temperature, delay, or material conditions cause a loss in slump between mixing and placement, a suitable average compensating adjustment should be added to the slump of the concrete as mixed.

Tests are by no means needed on every batch as it can be seen and recorded that the slump is not out of limit. The only time a truck should be held up for a slump test is when it is marginal and the eyeball test is not sure enough for rejection. Practically speaking, in such cases it may be better to accept marginal loads now and then than to hold up smooth-running placement, unless there has not been prompt response to notification that the working limit was being exceeded and that the tolerance-rejection limit was being approached.⁴ When the rejection limit has obviously been exceeded by a wet batch, no time should be lost in making a test; an estimated value with note of rejection is enough for the book.

Inspection of construction operations

We have discussed the materials for making concrete and the concrete itself as a material. Specified numbers for various aspects of these materials are our guide to

the sufficiency of quality in them. Inspection of construction operations is less specifically defined than that of materials and concrete production. It is nonetheless important and that importance has prompted the preparation of several valuable guides to such attention. These include a number of recommended practices composed by working committees of ACI and the *ACI Manual of Concrete Inspection*.

Appearance tells much of how well the work was done but by no means all. And if it is not what it should have been, it is too late to do much about it. Unlike the neatly tabulated results of strength tests in proof of the quality attained, the often hidden good results of construction inspection are not readily documented even though daily shift reports are required. Accordingly, construction inspection will encourage quality by seeing and approving or disapproving, step by step, while action can still be taken if necessary for corrections.

Checkout cards for each concrete placement with initials of foremen and inspectors attesting that all elements were properly ready for concrete will do much to get quality construction. This will include such items as preparation and cleanup of foundation and construction joint surfaces, correct setting of reinforcement and other embedments, dimensions and tightness of forms, adequacy of facilities for each concrete placement including vibrators, proper use of suitable starting mixes, avoidance or scattering of separated coarse aggregate, flat-work finishing procedures, curing and protection, and repairs.

Inspection forces will be most effective in getting correct performance of these unnumbered aspects of good concrete construction when it is understood on the job that the work was organized and administered in such a way that the inspection staff was there as free agents of management expected to get the desired and specified performance paid for.

QUALITY ASSURANCE

If faithfully kept records show compliance with specification requirements and the general appearance of the concrete work is good, there should be no question of acceptance of the work.

Records

Assurance of quality in construction is not a reality without records that give that assurance. These records must be systematically and presentably kept. They must be accurate, consistent, and believable. But they need not be excessive in coverage and should not be redundant.

If faithfully kept records show compliance with specification requirements and the general appearance of the concrete work is good, there should be no question of acceptance of the work regardless of its size, complexity, or importance, or for what owner or agency it is built. It is emphasized that no other records of other tests or observations are necessary nor will they improve the assurance that can be taken from the fully adequate record herein advocated. In fact, any further testing and inspection, such as recording all batch weights, slump tests on most truck loads, or routine sampling at the end of pump lines, is likely to detract from the quality of the work through its many interruptions, and certainly will increase its cost unnecessarily.

Credibility

There is no question of the credibility of efforts such as these to get quality construction when they are conducted by personnel in the employ of the owner or architect-engineer. But unfortunately there is a trend in some agencies, and some engineers advocate, to place these activities in the hands of the builder.¹² This is inherently the case on turnkey projects. Some doubt of the credibility of such inspection and its freedom from conflict of interest may exist.

It has been suggested that such doubts of credibility would be largely allayed or eliminated if the owner or engineer had at least one qualified person working along with the builder's inspection forces. This person could not only make confirmatory observations but make confirmatory random tests as well, to insure that the record being produced by the builder was accurate. On turnkey work where the owner has no staff on the job, the builder can establish the credibility of his testing and inspection records only by convincing evidence that his quality forces are entirely free agents, responsible only to his top management. As one advertisement said about its quality managers:

"Their job is to help make sure that you get what you pay for. Their only allegiance is to quality. If they say 'no' due to non-conformance, then no it is. And no one reverses their decision. To insure that they remain free spirits, they are responsible to our corporate vice president for quality. He reports only to the Office of the President."

Whatever way our concrete construction work may be set up, if such firmly declared intent is established and so operated, quality concrete construction through effective inspection and proper testing will be accomplished in a fully credible fashion. And, as Mr. McMillan answered his last question in the *Concrete Primer*, "Is good inspection an important feature of concrete construction?", "Eternal vigilance is the price of success in concrete construction just as it has been the price of liberty in the history of mankind. Careful inspection should be enforced in all of the operations relating to:

- the selection of the materials;
- the design of the mixtures;
- mixing, transporting, placing, consolidating, and finishing;
- protection and curing.

By careful and intelligent control at all of these stages, enduring structures can be achieved.

The great importance of care in making concrete strength tests cannot be overemphasized. In most acceptance confrontations the indicated strength of the concrete is the deciding factor.

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Quality in concrete construction is the decision to have it, and to see that you get it.

Honorary ACI member **Lewis H. Tuthill** is a concrete engineering consultant, Sacramento, Calif. Until retirement he was a concrete engineer for 13 years for the California Department of Water Resources.



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Computers in Concrete Design

NEW

This publication is a compilation of useful articles and papers on the subject of use of computers in concrete design. The 16 reports cover topics including computers in concrete technology, spreadsheet applications for prestressed concrete bridge girder design, applying PC-base graphics to the display of loads on concrete, monolithic simplifying concrete mix design with the PC, integrated software for concrete design, concrete detailing using autopade, database-interactive-graphics reinforced concrete structure, a simple knowledge-base design approach and much more. This compilation offers an opportunity to gather together material previously published in Institute publications as a compact and ready reference on computers in concrete design.

C-14, 1991, 86 pages



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Computers In Concrete Construction

NEW

This publication is a compilation of useful articles and papers on the subject of use of computers in concrete construction. The 14 reports cover topics including an overview of computers in concrete technology, quality control, expert systems for concrete construction, computer-aided cusum analysis and evaluation of strength test results, PC analysis of construction loads on slabs and shores, concrete construction optimization, cold weather concrete curing, project duration estimation software, expert systems, shore and reshore scheduling, computer-aided equipment selection for concrete placing, interactive horizontal and vertical formwork selection, and automatic adjustment of concrete mixtures. This compilation offers an opportunity to gather useful information on computers in concrete construction in a compact and ready reference.

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Selecting Relevant Levels of Quality

by Bryant Mather

To do quality concrete work one needs to have both a proper set of criteria for the levels of properties being sought and proper procedures to control the quality of what is done so that these levels are attained. Failure to realize that adequate quality for certain work or in certain regions may be either more or less restrictive than needed for other work in other places and can result in excellent quality-control procedures being employed to produce highly uniform concrete to either wastefully expensive higher levels of quality than are needed or to lower levels than required to provide the desired service in use.

Keywords: concrete construction; costs; performance; quality assurance; quality control; serviceability.

Early in 1966 I learned that there was going to be held in May of that year, at the University of Virginia, a conference on "Statistical Quality Control Methodology in Highway and Airfield Construction." It seemed to me that there was a gap in the planning for that conference, because although much was planned to be covered in the fields of uniformity, variability, quality control, and quality assurance, little apparently had been planned for presentation on the subject of what levels of quality are appropriate and how are the proper levels selected. So I wrote, and later presented, a discussion called "Selecting Appropriate Levels of Quality" (Mather, 1966a). I started then, and it

seems to me to be still as relevant now as it was then with the premise that, in all construction, the intent is to maximize proper performance, minimize improper performance, and do this at the lowest practicable cost. Quality control and quality assurance can maximize the probability of obtaining the level of performance that will result if the construction meets the specified requirements. It cannot, directly, maximize the obtaining of proper performance unless the levels of quality that will yield proper performance happen to be those which result from compliance with the requirements that were established. There are an infinite number of quality levels that can be set. Sometimes the levels are set too low and the product, even if it meets the established requirements, fails to give satisfactory service. Often the levels are set too high, and the work is made more costly than it needs to be. Procedures are needed by which, using such tools as electronic data processing, all the relevant properties that a structure needs to have so as to give the desired service in the environment in which it is to serve are related to the properties of available materials and combinations of materials, construction systems, methods, practices, and schedules. Thus an infi-

nite number of alternatives can be considered, and the single, most economical, satisfactory solution selected. Thus the proper levels of quality will be established which, if met, will insure construction that will give the desired service at lowest cost.

Desired performance

As I said, what is wanted in any construction is work of the quality that will give the desired performance at the lowest cost that must be paid to get such work. We want concrete having the levels of relevant properties it should have to give this service, but we do not want to pay extra to cause it to have higher levels of properties that it does not need. Thus, the best concrete for any given purpose is the one that does the job satisfactorily at lowest cost, having due regard for both first cost and maintenance and repair (Mather, 1964). A concrete job that costs more than it should is a poor job and is poorer proportionately to the amount more that it costs than it should, regardless of whether or not one result of its costing more may be that it is structurally stronger or of better appearance than it has any need to be.

Different standards and criteria are applicable to different constructions as these constructions have different purposes. The fitness of concrete to do a job is similar to the fitness of a person to do a job. For some purposes a concrete—or a person—needs a much greater degree of any of many capabilities than is needed for other purposes. Such capabilities include the ability to carry load without undue strain or cracking, the ability to endure adverse environmental conditions, physical attractiveness, or the ability to remain relatively unchanged in dimensions with changes in ambient temperature or moisture conditions.

Concrete can be provided—even as people can be employed—having a great range in the degree to which these and other capabilities are possessed.

Concretes—like people—have certain minimal capabilities in these respects even when little effort is consciously made to select among the available alternatives; conversely, high degrees of capability in some of these respects can only be obtained by very rigorous selection.

Owners, architects, designers, structural engineers—and statisticians—do not always appreciate the degree to which the attainment of the best concrete for the purpose requires selection of quality level. Investigators have not provided an adequate body of interpreted knowledge relating the effects of the requirements that can be imposed to the levels of relevant properties that must be obtained in the finished work.

The result of this is that too often a contract is let in which it is required that the contractor do things that, if not done, or if done in a less costly way or with less costly materials, will not detract from the suitability of the concrete for its purpose. In the same way, the contract may fail to require that the contractor do other things that must be done if the proper concrete for the purpose is to be obtained.

Good specifications

The only good specification is that which requires only those things that need to be done to make the concrete suitable for its purpose. A good specification contains no requirements that can be ignored or slighted and is one that omits no requirements that must be met. It is not possible to write such a specification; it is only possible to try to do so.

With a "good specification" neither the contractor nor the inspector is in any doubt as to what must be done. With such a specification, any part of the work that is not in accordance with the requirements must be changed so that it does comply. The question of whether it is "good enough," even though not as good as required by the contract, will not arise.

The vast majority of concrete satisfactorily serves the purposes for which it was produced. Few examples of concrete are the best that they could have been. Most are better than they need to be and hence cost more than they needed to cost. A few do not satisfactorily serve the purposes for which they were made. It is this latter few that receive most of the attention.

The few jobs that do not satisfactorily serve their purposes do so, in nearly every case, for several reasons rather than a single reason. Some of these reasons are:

(1) Failure of the owner to understand what he needed.

(2) Failure of the architect and engineer to understand the owner's needs and to translate these needs into proper quality levels of relevant properties and into correct specification requirements for the work.

(3) Failure of all concerned with establishment of specifications to include only what was needed and exclude what was not needed.

(4) Failure to require uniform compliance by the contractor with all requirements of the contract.

(5) Failure by the contractor to comply with all requirements of the contract.

In 1964 it was estimated that a ton of concrete was being produced each year for every living human being in the world (Mather, 1964a). Roger Corbetta (1964) estimated that 5 percent of all the money spent to buy concrete is spent to buy "bad" concrete. By "bad" concrete, he meant concrete that is below the proper quality level. It was my opinion, in 1966, that more than a billion dollars was wasted annually by setting quality levels higher than they need to be set. I do not have a reason to revise this opinion now. Roger added: "It would appear that we have reached a point where re-evaluation of custom, tradition and procedure in the building of concrete structures is indicated." Part of this "re-evaluation of custom, tradition, and

procedure" is what I am again suggesting here.

How should proper levels of quality be established? To be specific, how should appropriate levels of quality be established to insure that the concrete to be used in a particular part of a particular structure will give satisfactory performance by being able adequately to resist the deteriorative forces of its environment of service?

There is no variety of concrete, nor indeed any other material, either natural or man-made, that is entirely unchanging or everlasting (Mather, 1966). In the real world, all materials alter with time and exposure, no matter how mild the exposure may be. Thus, for a material such as concrete, when one speaks of freedom from deterioration, one necessarily speaks not in an absolute sense but in a relative sense. It is not necessary to avoid all change, however minor, for an infinite length of time; it is only necessary to avoid changes of a nature and degree such as to impair the ability of the concrete properly to serve its desired purpose for a period of time appropriate to the intended service life of the structure of which it is a part.

Service life

Different structures have different intended service lives—in military operations the service life may be days or weeks; structures at a World's Fair may need to remain serviceable for as long as one or two years; a dam or a seawall may, in some cases, be expected to endure indefinitely. Similarly, changes that impair the ability of concrete in one structure to serve its desired purpose would not necessarily impair that in another structure to the same degree. Surface defects produced by changes after construction on a surface with regard to which there was no requirement for smoothness or esthetic quality during construction may be of no concern; similar defects on an architectural concrete facade may render it unserviceable.

able unless repaired. Thus the appropriate quality level of concrete is not that which will provide for the complete absence of change and infinite durability. Differing quality levels for allowable degrees of change over differing periods of intended service free of excessive change will be applicable to concretes in differing structures. Thus the requirements for concrete—concrete materials, concrete mixture proportions, and concrete construction practices—*should* vary widely. More restrictive provisions—higher quality levels—*should* be required the less the allowable change or the longer the required period of freedom from a given degree of change—or both.

There is the additional important factor of the difference in the environment from place to place where concrete must manifest the desired freedom from change for the intended period of time. I include under the heading of the environment not only those obvious environmental factors such as weather and climate that affect temperature extremes and rates of temperature change, relative humidity, freezing and thawing, and wetting and drying, but also factors such as attack on concrete by natural or man-made agents or agencies, both chemical and physical, including acids, salts, sulfates, airborne corrosive gases, termites, and marine borers.

Now that I have indicated the complexity of the situation with which concrete, and those who make it and those who design, build, and use structures composed wholly or in part of it, are confronted, I will try to suggest how these complexities can be dealt with and how their potentially undesirable consequences can be avoided by selecting proper levels of quality. I leave it to others to indicate how by quality control methodology the proper levels of quality can be assured in the work.

There are only two ways in which it can develop that the con-

crete at a point in a structure has failed to maintain a satisfactory degree of freedom from change for a satisfactory period of time: either (a) the specifications under which it was built were not complied with, or (b) the specifications were defective in failing to include one or more requirements that should have been included, or both.

Failure to comply with the requirements of specifications is breach of contract, and remedial action following such failure should be taken by those concerned with legal and fiscal matters. The tendency for such failure to occur, however, is greatly increased by the inclusion in specifications of ambiguous, redundant, unnecessary, impractical, or impossible provisions. Ideally the contractor should obtain appropriate positive official clarification of all ambiguities and removal of all redundant, unnecessary, and impossible provisions before he is confronted with the time in the conduct of the work when they apply. In practice, too often, this is not done, and such provisions are merely ignored. On such a project the likelihood is that some other provision, one which must be complied with if the intended service is to be obtained, will also be ignored through failure to appreciate its significance.

Failure of the specifications to include all of the requirements that must be met, if the desired service is to be obtained, results either from lack of knowledge concerning what should be required or from failure to use properly the available knowledge. John McLaughlin (1965) stated that "if half the available knowledge on concrete was put into practice, 95 percent of the problems would evaporate." The report of a Royal Commission (1964) on the failure of a bridge in 1964 stated, "It is rare to find engineering disasters which have been caused by factors which were completely outside engineering knowledge at the time of design. . . . The Commission could find no ground for suppos-

ing that current engineering knowledge and practice, if properly applied, would have been inadequate to prevent failure."

Lack of knowledge results from the failure of research to have been carried out to produce the needed knowledge. This, in turn, results primarily from failure of the government and industry adequately to support the research that needs to be done. Lack of knowledge, especially in the field of construction practice, is also significantly contributed to by failure of those having such knowledge to record and publish it. Knowledge that has not been disseminated through publication is knowledge that is unavailable for use by others.

Failure to use available knowledge results from failure of specification writers to read, understand, and apply the information and conclusions given in the literature that is available. This failure is contributed to, at least to some extent, by the failure of some writers to include with the report of their findings the sort of discussion and interpretation of these findings that will facilitate their use by specification writers in setting quality levels in specifications.

We may then conclude that, while there are an infinite number of varieties of concrete and an infinite range of requirements that concrete could be required to meet, the concrete in any given point in a structure will be satisfactory if the specifications include the necessary requirements and they are complied with. Greater assurance of compliance with necessary requirements of specifications will be promoted by exclusion from specifications of ambiguity and unnecessary, redundant, and impossible requirements.

Computerized specifications

How many variations on a concrete specification must a specification writer have available to select among in order to pick the

right one for any particular work? Indeed, it might be asked if I am advocating an infinite number of variations of concrete specifications! The answer is yes, I am advocating an infinite number of different specifications! I suggest that the time is coming, sooner than many of us think, when specifications will be assembled by computers. One will feed into the computer a wide range of information concerning all the relevant factors, including the desired service life of the structure or the element of the structure; the kinds and amounts of changes that can be tolerated during the service life; the nature of the climate and the weather; the characteristics of the site; the nature and severity of all other relevant agents and agencies whose attack must be resisted and to what degree; a variety of structural data, including thinness or thickness, orientation, degree of restraint, thickness of cover over steel, ability to drain, and so on; a wide variety of data derived from tests of locally and economically available materials and mixtures of materials; and, if necessary, other data from tests of more exotic, less economical materials and mixtures; and finally data on construction systems, methods, practices, and schedules. In this manner, the truly infinite number of alternatives concerning combinations of materials and methods can be compared with the equally truly infinite number of alternatives regarding the service requirements for the concrete and the environment in which these requirements must be met so that the one proper solution that is most economical can be selected, indicated, and specified. Thus I suggest that the concrete specifier should have, in effect, an infinite number of alternative specifications and that only the best one will actually ever need to be assembled for use in the advertisement for bids on any given project.

If we today approached the question of obtaining proper concrete by this process, by specifying

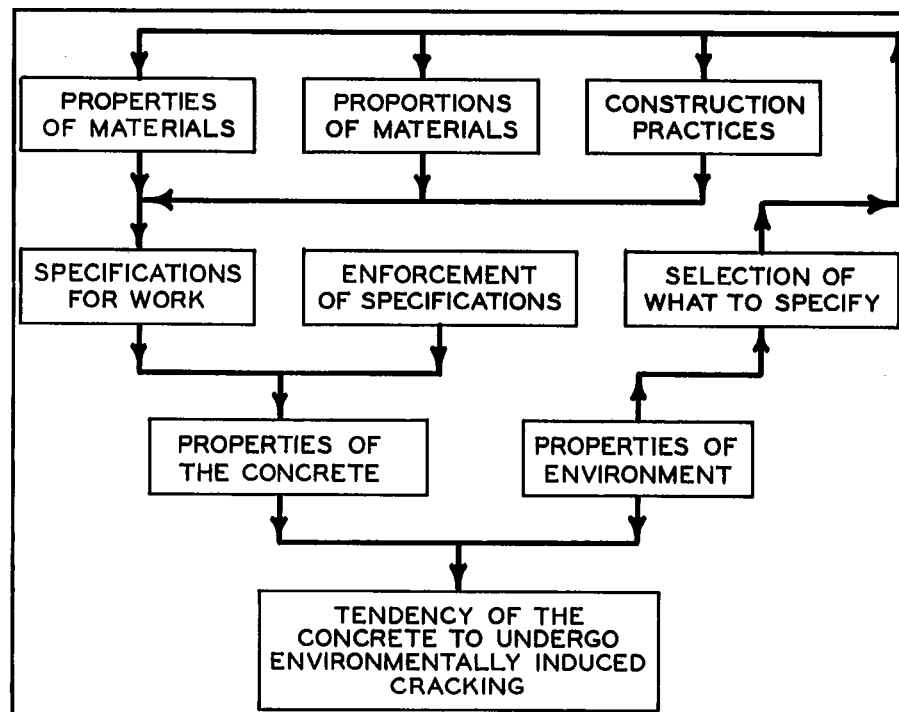


Fig. 1 — Factors affecting tendency of concrete to undergo environmentally induced cracking.

ing at appropriate quality levels only those things that need to be required, all of them, and no more, and had assurance that we would get what we specified, we would, of course, avoid the troubles that confront us when concrete manifests more deterioration than anticipated during its specified life.

Changes in concrete

All concrete changes with the passage of time. Changes in concrete are not a matter of concern unless the changes are of a greater degree or a different type than were anticipated and expected and therefore would have been tolerated in the time during which the concrete had been in service. Changes of undesirable types or to an undesirable degree can be prevented by including in the construction specifications those provisions which, if complied with, will cause the concrete satisfactorily to resist the forces of change to an adequate degree for an appropriate period of time and by insuring that these provisions are complied with. As more precise quantitative knowledge of the relationship of concrete properties and

properties of the environment becomes available, more precise specifications can be assembled that properly match the level of severity of service conditions and the quality level of concrete properties to provide the most economical concrete that can be guaranteed to give the desired freedom from deterioration in the service environment. Fig. 1, which is taken from a discussion of concrete cracking (Mather, 1968a) illustrates graphically the point that the tendency of a structure or a material to undergo change in a given environment is due to the interaction of the properties of the material or the structure and the properties of the environment. Assuming that one cannot modify the environment, it follows that one will therefore select for service in that environment, the material or structure that has those properties which, when they interact with those of the environment, will produce only those changes that are desired or can be tolerated. The selection of the appropriate levels of relevant properties is what this diagram is about. From a knowledge of the proper-

ties of the environment, a selection is made of items that should be specified—which are here shown to be classified into three groups: properties of materials, proportions of materials, and construction practices. Next is the selection of proper quality levels, the preparation of specifications. The diagram then emphasizes that it is the interaction of the selected quality levels and the enforcement of the specification requirements that produce the properties with which the material or the structure is finally endowed—and by means of which it must interact with the environment to give the performance of which it is capable.

It is perfectly possible to develop quality control and quality assurance methodology to go with unreasonable and indeed stupid specification requirements. This is not the way to get good construction. The Highway Research Board staff wrote (1965), “. . . specifications could be designed to meet specific needs rather than consisting of a compilation of more-or-less standardized terminology. . . . Specifications properly designed and implemented could have impact on socioeconomic benefits.”

In subsequent discussions of concrete deterioration and its avoidance (Mather, 1979), I noted that concrete can possess values over a very wide range for many of its properties. It can have a unit weight anywhere from less than 800 to more than 4000 kg/m³ (50 to more than 250 lbm/cu ft). It can have an ultimate compressive strength from less than 1 to more than 140 MPa (100 to over 20,000 ppsi). Its permeability to fluids can be from high to negligible. Its resistance to frost action and various forms of chemical attack can range from poor to excellent. But often the values approaching the limits of these ranges can be assured only by using materials and procedures which increase production costs. Thus, the specifier must require levels of values for the properties needed for the in-

tended service and avoid excessively high standards.

There are a number of relatively well-known mechanisms that can, under unfavorable conditions, produce premature deterioration of concrete. The opportunity for the mechanism to operate at a rate that will cause premature deterioration depends on the possession by the concrete of characteristics that it should not have had in the particular environment and on the fact that the environment had properties that many other environments do not possess.

These mechanisms have been classified by ACI Committee 201 (1977) into five groups: (1) freezing and thawing, (2) aggressive chemical exposure, (3) abrasion, (4) corrosion of steel and other embedded materials, and (5) chemical reactions of aggregates. To this list might be added fire and mechanical overloading. These causes of concrete deterioration have traditionally been discussed under headings of their own.

The specifier needs better information on the “properties of the environment” and how these control the needed levels of properties of the concrete. No precautions whatever are needed to prevent deterioration of concrete by freezing and thawing if the environment in which the concrete will be used is one in which freezing and thawing cannot occur. The specifier should, however, be aware that some precast prestressed members made in locations where freezing has never taken place in nature do get used in plants where frozen foods are produced. The specifier should also be aware that some floors in buildings that will never freeze in service may well freeze during the concrete's most vulnerable stage, after hardening but before full strength has developed, during construction.

Environmental influences

The failure fully to appreciate the significance of environmental influences on deterioration, espe-

cially the role of critical saturation in damage due to freezing and thawing, has obscured and delayed proper appreciation of the role of deicing chemicals in contributing to deterioration of concrete structures in service, especially bridge decks. When there was a dramatic increase in bridge deck deterioration associated with the great increase in the use of deicing salts, many students of the problem assumed that there must be a chemical attack of substances such as calcium chloride on concrete or that the growth of salt crystals within the pores of the concrete exerted disruptive pressures. In fact, the chemical action of the chlorides in producing deterioration is effectively limited to the phenomena of steel corrosion as has been well known for many decades in marine exposures of reinforced concrete, and the influence of deicing salts on the deterioration of the concrete itself is essentially limited to the indirect effects of ice melting.

Concrete will be immune to frost action, with or without the use of deicing chemicals, if it remains below critical saturation. If it becomes critically saturated, it will continue to be immune to frost action if the aggregate and the paste are frost resistant. The aggregate will be frost resistant if its pore volume is small or if it is nearly impermeable and not critically saturated or both; a condition that can be tested readily in the laboratory using properly air-entrained concrete. The paste will be frost resistant if it is sufficiently mature when frozen in a saturated state, i.e., the fractional volume of freezable water at saturation is not too large; a condition that is achieved when the compressive strength reaches about 24 MPa (3500 psi); and the air-void system is proper, a condition that is normally achieved when the bubble-spacing factor is 0.20 mm (0.008 in.) or less, and the air-entraining material used meets applicable specifications.

I believe we now know how generally to assess the environmental

stresses that concrete must resist and to stipulate the appropriate levels of relevant properties concrete must have to resist these stresses. We can then generally specify the levels of relevant properties of materials to be selected as ingredients of the concrete mixture, we can specify the proportions of the mixture to be used, and we can specify the construction practices to be followed. Thus we can specify the concrete to be produced. Such a proper specification need only be followed to produce concrete that does not deteriorate. However, the specification actually used may either not be followed in some critical aspect or it may be deficient in some critical feature.

Long lasting concrete

If the nature of the environment in which the concrete is to serve is known, the levels of the relevant properties that concrete must have in that environment to yield the desired performance may be selected. When these levels of these properties are known, specifications may be prepared to produce concrete of these levels of these properties. These requirements must cover, directly or indirectly, the properties of the constituent materials, the proportions to be used, and the construction methods. When the specifications are properly prepared and complied with, the concrete will possess levels of relevant properties such that, as it interacts with the effects of the environment, it will not deteriorate.

When I said some of these things previously, Lew Tuthill (1980), one of America's greatest concrete technologists, wrote in part:

"I applaud his endorsement of very specific specifications and the strong support for their enforcement, which too often is weak or lacking. My concern is that someone may get the idea that it is feasible to put a concrete together that would have a level of resistance to deterioration just sufficient to offset a believed known

degree of deteriorating conditions, exposure, and circumstances. Presumably this would be expected to provide lifetime trouble-free service, and, in some cases, only for a predetermined number of years. There was also the hint that there may be worthwhile savings achieved by tailoring the concrete to have this just-the-right resistance to deterioration in each exposure condition, and no more, and for just the right length of time, and no more.

"But concrete is not like the fabled one-horse shay. Concrete can be very long lasting. It does not come to the end of its life and serviceability like turning off a light. It must be performing its intended service right up to the end without threatening, creeping deterioration. The only exception to this is when obsolescence brings an often untimely end to the usable value of an otherwise good structure. At the time of its building, who knows when this will be?

"When a large water project started 20 years ago, it was said to be designed and built for a life of 50 years; this was questioned, pointing out that come 50 years, everything would be expected of it little different from the first flow of water. Hence the agreed conclusion and policy became to build it 'the best we know how!'

"Such prospects of long continuing necessity for service life make evident the importance of building 'the best we know how' and 'the most durable we know how.' Each additional year of such trouble-free service makes the original small margin of extra cost for this quality a better and better investment, especially in view of current inflation. Of course we should not indulge in excessive strength and cement content in mass concrete where not required for durability. Nor do we need to provide resistance to a nonexistent deteriorating influence.

"So I urge that we not attempt to cut the cloth too close to the seam when there is any question of durability. The greater freedom

from maintenance can soon offset any minor extra costs for putting concrete together the best we know how, rather than something we think will be good enough, but may not be in the long run. Deteriorating conditions can prove to be, or become, more severe than they were understood to be in the beginning."

In my reply to this, I wrote (Mather, 1980):

"My paper was a part of the ACI magazine in the same month, as was published in the ACI JOURNAL, Adam Neville's 1979 paper on 'Essentials of Strength and Durability. . .' in which he remarked that strength and durability 'is about all there is to say about concrete' and then suggested that 'the issue is not good concrete but concrete which is good for the job in hand,' adding: 'It is uneconomical to seek perfection, to produce the best that money can buy; engineers should see what is good enough for the given purpose at lowest cost.'

"Lew urges that 'we not attempt to cut the cloth too close to the seam where there is any question of durability.'

"In reflecting on what I said, what Adam Neville said, and what Lew Tuthill said, I find I agree with all of it:

(1) We should do concrete work as well as needed.

(2) We should do concrete work the best we know how.

(3) We should provide the best concrete work we can afford.

(4) If we deliberately do less than the best, we should know why we did it and what to expect as a result.

(5) We should not waste money doing better work than is justified."

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Recent failures throughout the world have called into question the reputation of concrete as a reliable, durable, maintenance-free material. The causes of these doubts range from ever-changing social demands and expectations, to developments in materials and methods of construction, to economic pressures. Improvements will only be achieved when there is a proper appreciation of the realities of today's concrete construction techniques; the only changes necessary are in the attitudes of all concerned. The author concludes with a radically simple proposition for improving the quality of concrete everywhere.

*high quality concrete
can be produced worldwide
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common sense techniques*

Common Quality in Concrete Construction

by Ken Newman

Concrete is still the most important single material on earth for building and civil engineering. The word concrete has always been used as a synonym for something that is solid, reliable, immovable; a durable maintenance-free material with an almost infinite service-life. However, several recent well-publicized failures throughout the world have caused not only the public at large, but also the industry itself, to question this definition.

What has happened? The main areas of concern stem first from a variety of concrete failures, from significant changes in the struc-

ture of the construction industry and in the methods of concrete production and use, and finally from considerable social and economic pressures following the first oil crisis and the more recent recession.

Recent problems or failures, that have done much to tarnish the image of concrete, include:

- corrosion of reinforcing steel either due to the inclusion of calcium chloride or other salts from admixtures or aggregates, or externally from deicing salts, or in marine structures above the high tide zone;
- poor, hurried construction techniques, especially in the Middle East where ground salts contaminate aggregates and water;
- internal disruption of concrete from alkali-silica reaction, and strength reductions due to the conversion of high alumina cement concrete; and
- the occurrence of non-structural cracks during setting and hardening due to moisture and thermal effects.¹

These problems range from the annoying or worrying (as with early-age plastic shrinkage cracking) to the financially catastrophic, where major disruption may result in costly repairs, many times the initial construction cost as, for example, with bridge decks in the U.S. and Europe or balcony slabs in Sweden.² This has resulted in such descriptions in the press as "crumble-crete," "rot-crete," and "the concrete can

Keywords: acceptability; concrete construction; economics; quality assurance; quality control; responsibility; serviceability.

cer". These problems are no longer merely national or international, they are intercontinental.

It is a truism that good quality reinforced concrete is made from cement, sand, aggregates, water, and reinforcement — and so is bad quality concrete. So what has happened? There is, of course, no simple answer, but major contributing factors include:

- Over the years, the specifier and contractor have had to cope with major changes in methods of concrete construction. There is ever-increasing difficulty in finding staff with the necessary skill and experience, who are willing to carry out concreting operations onsite. Computerized design methods are removing the engineer even further from practical realities. It is still easier to assess and test materials and products than it is construction practices.
- In developed countries, engineers now face a situation where 25 percent of all concrete is precast and over two-thirds of site-placed concrete is ready-mixed. Unlike the early days, this means that most concrete today is manufactured off the job site and away from the direct control of the engineer. This has produced another contractual and communications interface where misunderstandings and mistakes can occur.
- The continuing worldwide economic recession, with little real sign of a return to the demand levels of even five years ago, has forced all sectors of the construction industry to cut costs and to look for savings from other suppliers. A third of the U.S. cement industry is now European owned. Construction materials, including ready-mixed concrete, are being delivered daily across European borders.
- Coupled with this economic pressure has been demands for environmental protection and energy saving that have led to

It is a truism that good quality concrete is made from cement, sand, aggregates, water, and reinforcement—and so is bad quality concrete. So what has happened?

greater planning restrictions on cement and aggregate material processing and pressure to use such by-products as pulverized fuel ash (PFA), ground granulated slag, and silica fume, often of unknown and variable quality. Again the lack of experience, proper understanding, and control over the use of these materials can lead to problems.

What can be done to overcome these problems and restore concrete to its rightful place as the preeminent construction material? Failures are certain to continue unless there is a major reappraisal of the whole process of conception, design, construction, and final use of reinforced concrete structures. The solutions proposed are not revolutionary. They require only a marked change of attitude; an acceptance by all parties of their fair and proper responsibility, of the limitations of our resources, and of the need to use, in a realistic way, the benefits of modern computerized technology.

The aim of the construction process

Any user, whether government, public authority, or private company, requires assurance that his building or structure or works will:

- **Be suitable for his purpose**, i.e., that it will do the job he wants and provide him with all the facilities he requires. This is the task of the architect and designer.
- **Be properly constructed**, i.e., that it will be designed and built in accordance with the building regulations, using suitable ma-

terials, products, components, and standards of workmanship. This is the task of the contractor under the supervision of the engineer.

- **Perform satisfactorily in use**, i.e., it will be strong and structurally sound; resist fire, earthquake, flood, and other natural hazards; be weather resistant and durable; and retain its appearance with low maintenance costs. This is the task of the design engineer and the contractor.
- **Give value for the money**, i.e., provide a reasonable return on the initial capital investment and subsequent repairs and maintenance costs over the planned life of the structure. This is the task of the whole construction team.

How are these objectives achieved in practice today? In most cases the user is provided with a "just finished" structure: designed and constructed in accordance with national building regulations, and using materials, products, and components that experience has shown to be suitable for the purpose. The degree to which the "just finished" structure will perform satisfactorily in use and yield economic value depends upon the extent to which each of the separate parties involved (i.e., the client, designer, contractor, materials or components producer, and the eventual user) discharge properly their separate responsibilities (see Fig. 1).

The client receives assurance that his enterprise will be properly constructed through national systems of building control. Although these differ from country to country, their basic aim is to safeguard public safety and health through the establishment and enforcement of statutory laws and regulations. They involve procedures for granting permits, approving plans, regular inspection of works, checks on quality of materials and components, and final certification. Building control procedures naturally reflect each

country's constitutional and legal system. Those in Europe have been the subject of a separate study.³

Achieving assurance of quality

The concepts of quality control and assurance in construction have become the subject of increased study in the past two decades. In an important International Union of Testing and Research Laboratories for Materials & Structures (RILEM) Symposium organized by Professor S. Bergstrom and his excellent team at the Swedish Cement and Concrete Research Institute—Cement-och betong institutet (CBI) Stockholm in 1979, the quality control of concrete structures and the properties achieved in practice in finished structures, were examined in detail.²

Recently the Comité Euro-International du Béton (CEB), as part of its comprehensive program of defining rules and guidelines covering all aspects of concrete design and construction, published its *Information Bulletin No. 157* on

"Quality Assurance and Quality Control for Concrete Structures."⁴ This report, which is required reading, brings out the point that quality assurance must cover, not only the particular characteristics of the concrete construction industry, but the relevance of the human factor and the responsibilities of the different parties involved.

The construction process team. Fig. 1 shows, diagrammatically, the five main stages or activities of the construction process. The five different parties involved each has their own responsibility:

Client/ promoter	—promotion of project/structure
Designer	—design and specification
Producer	—supply of materials, components
Contractor	—construction, execution of works
User/owner	—use of finished project/structure, subsequent repair, maintenance.

The process starts with the user, because the main aim of the construction process is to satisfy his needs, and it ends with the user because the project is for his benefit. Complete satisfaction of assurance of quality for the user requires the integration of effort of all the different parties involved.

Components of quality assurance. Quality assurance has been defined as:

Planned and systematic actions necessary to provide adequate confidence that an item or facility will perform satisfactorily in service.

The total quality assurance system will comprise, for each of the five activities and parties, the following components:

a) **Standards** or specifications defining the most important criteria, method of assessment or testing, and levels of acceptance to satisfy the user's requirements. Whenever possible these should be expressed in performance terms to insure fitness for purpose and performance in use.

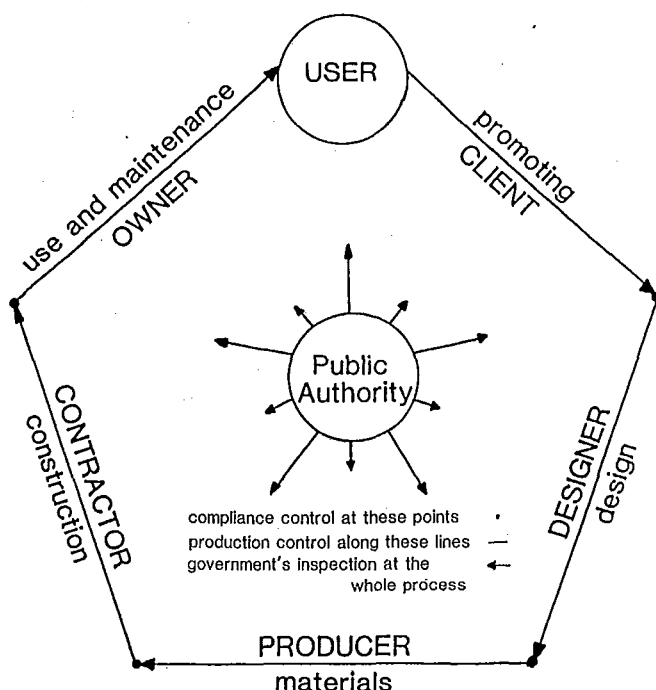


Fig. 1—Each of the parties involved in the construction process must properly discharge their responsibilities in order for the structure to perform satisfactorily.

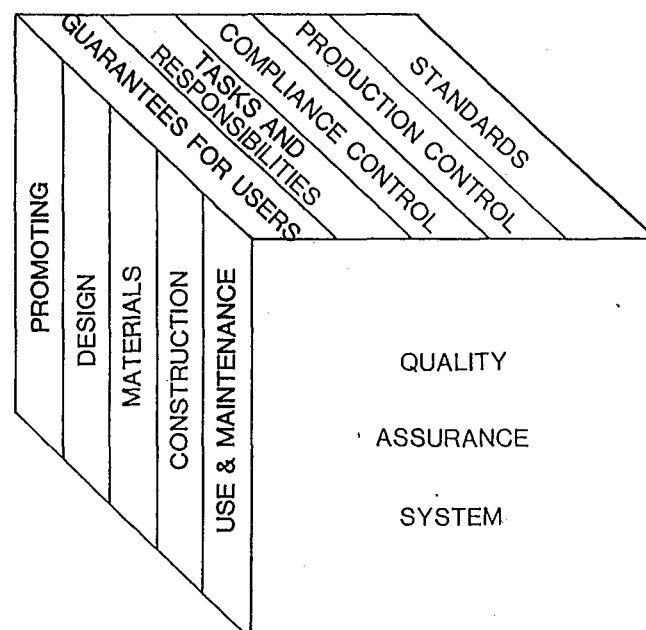


Fig. 2—The various components of the quality assurance system (across the top) apply to each of the five activities in the construction process.

- b) **Production** or internal control procedures carried out by the party, firm, or company involved in each of the five activities, to confirm that its own personnel and operations are conforming to its own quality control standards. This is normally carried out regularly by the person responsible for the particular operation, preferably supported by occasional independent internal control.

In the United Kingdom, the new British Standard, BS 5750, Quality Systems, defines, in framework terms, the elements of internal quality control systems that cover the design, manufacture, installation, final inspection, and testing of products or components.

- c) **Compliance** or acceptance control procedures carried out by the person who receives the resultant product of the previous activity. In certain cases this can be done by an independent authorized body. Although the public authority or building control system should be making checks of all the activities (see Fig. 1), it is particularly interested at the points of transfer between activities.

Production and compliance control is an area where product certification and approval, and certification schemes can play an important role. CERTICO, the International Organization for Standardization's (ISO) committee on certification, has assessed the various product certification schemes operated by standards organizations throughout the world.⁵ The European Economic Community (EEC) draft directive on construction products,⁶ has attempted to formulate a common basis for product certification including type approval, type examination, and self-certification. In many European countries, third party certification schemes are officially recognized as part of the building control system.³

... complete assurance of quality and reliability can only be achieved when design, materials, and construction are not considered in isolation from use and maintenance. The whole process is interdependent.

- d) **Definition of tasks, functions, and responsibilities** of each party and activity. Tasks and functions should include the scope and limitations of technical and organizational aspects. However, the definition of responsibilities is linked with the legal and regulatory aspects. Since, when taken together, they determine the contract for the whole construction process, they form one of the cornerstones of quality assurance.
- e) **Guarantees for user**, including liabilities for faults, are covered by the contract and in certain cases by the building control system. For example, in France the dominant influence on building control is liability of architects, designers, and contractors to the building owner. Under the civil code (Code Napoleon) dating from 1804, the building owner is given a guarantee for ten years against all major structural defects, and two years against lesser defects. Insurance coverage is obligatory, which is why French insurance companies are so closely involved in framing the necessary technical rules.

When taken together, these components of quality assurance add up to a complete system that applies to each of the five activities and parties (see Fig. 2).

Quality assurance systems in practice

How far have quality assurance systems been developed for the five activities in the construction process?

Client or promoter. This, the first stage of the construction process, involves the basic decisions to build and the definition of the corresponding performance requirements. The many different types of clients and projects means, inevitably, that there are few standardized procedures for this activity.

A more systematic approach would enable many problems to be overcome, including:

- The lack of standards defining what has to be fulfilled at the promotion stage, both for private work, including housing and industrial building, and public and civil works.
- The lack of standards or general guidelines outlining procedures to be adopted and the conditions to be fulfilled when defining the project for the designer.
- The lack of awareness of clients of the need for a complete definition of their performance requirements and of the time required to prepare detailed designs.
- In the public field, the conflicts that can arise resulting from political pressures on the engineer to produce designs and finished constructions within unrealistic financial and time limits.

Designer. In the past, engineers have concentrated on the three intermediate stages of the construction process: design, materials, and construction. Almost all codes and standards for construction are divided among these three activities.

It is becoming apparent that complete assurance of quality and reliability can only be achieved when these three stages are not considered in isolation from the other two of promoting, and use and maintenance. The whole process is interdependent. Although quality control procedures are applied rigorously to materials and construction, they are rarely applied to design. Design quality control systems should be

whether the designed structure has the safety, serviceability, and durability required for the use for which it is intended; should confirm that the technical requirements of the relevant codes are achieved; and should insure that the required structure is clearly defined in the drawings and specification.

Common problems that would benefit from a more systematic approach include:

- a) Lack of coordination between designers of different parts of the project.
- b) Lack of consultation and discussion between designers and contractors.
- c) Inadequate consideration given to durability and the influence of the environment on design details, selection of materials, and methods of construction.
- d) Design executed by staff with insufficient skill and experience.
- e) Errors in calculations and construction details, or insufficient and incomplete drawings.
- f) Errors resulting from computer calculations, including errors from inputs, program, and wrong interpretation of input or output data.

It would be interesting to know how many design practices truly operate a strict form of internal control in their offices.

Producer. Because they lend themselves readily to assessment and testing, the control of materials is the most developed and widely used application of quality assurance techniques in the construction field. Nevertheless, there are many areas in materials quality control that need improvement, including:

- a) The need for the designer to differentiate between the qualities of materials and products requiring a specific "performance in use," in contrast to specified requirements that should be in terms of "performance against standard tests."

- b) The need for more comprehensive standards or guidelines covering production control rules or the quality systems to be operated by the producer.
- c) The need for greater confidence that companies actually do operate production control systems without having this to be confirmed by third parties.
- d) The operation of compliance criteria by the designer without proper account being taken of information available from production control tests.
- e) The need for improvements in testing methods to remove any doubts concerning the validity of test results.
- f) A clear statement to be made of the courses of action to be followed when materials or components are found not to comply with the specification.

Contractor. The construction stage is inevitably an intermittent process with many different operations and people involved, and it is here that systems of quality assurance are most difficult to apply. Since, during the execution of the project, it is the contractor who is carrying the greatest financial risk, he undertakes the responsibility of carrying out both production and compliance control. In practice, compliance control becomes the main duty of the manager of the construction site.

Difficulties that occur and that could be improved by a more systematic approach, include:

- a) The lack of professional and technical qualifications of construction workers, with many countries having no legal requirements for contractors to substantiate their technical ability.
- b) The peripatetic nature of the industry resulting in a considerable turnover of staff at all levels, making it difficult to establish true teamwork.
- c) Although general guidance on construction standards and workmanship are given in codes

of practice, details are left to the skills and abilities of the available staff. In many contracting companies, production control does not exist.

- d) Many construction activities are ill-defined, which negates the establishment of trades and clearly defined lines of promotion. The introduction of the job activity approach would help here. In this, the skill and experience in each activity is clearly defined, which provides a clear standard against which personnel can be judged.
- e) Good and mediocre work are often certified and paid for at the same price, which forces down both the level of quality and future tender prices.

Owner or user. In the use of a building or structure, two parties are involved: the owner and the user. As the one who owns the building in the legal sense, the owner is often also the user.

Although the construction codes both in United Kingdom, CP110,⁷ and United States, ACI 318,⁸ are legal documents covering the construction of a building, neither make reference to the responsibilities of the owner regarding the use and maintenance of structures. The preparation of codes for use and maintenance is essential if the quality assurance circle is to be completed. Such codes should make reference to:

- a) The carrying out of periodical inspections to ascertain the need for maintenance and repair, and to check that no changes in the use of the structure have been introduced. The CEB Model Code⁹ suggests that, for the information of users, plates should be fixed to the structure indicating a maximum authorized loading and that, during the life of the structure, the user should be required to check that these loads are not exceeded.
- b) The intervals between inspections, for moderately aggressive environments and user

suggested by the CEB Model Code, are:

- Dwellings—10 yr
- Industrial structures—5 to 10 yr
- Road bridges—1 to 4 yr
- Rail bridges—1 to 2 yr

- c) The user's responsibility for observing the owner's rules and conditions of use.

Definition of life

In economic terms, the quality-to-cost ratio of a building should be expressed in terms of initial cost *plus* maintenance costs, not just the initial. A major deficiency in building codes is their unwillingness to give any indication of the expected life of the building or structure. In fact, as Fagerlund has shown,¹⁰ prediction of service life is now possible with regard to steel corrosion, frost, and acid attack. As yet this information has not been incorporated in concrete codes. Normally, structural concrete should be expected to remain fully serviceable for at least 30 to 50 yr. In practice, the working life of a concrete structure may be limited either by visible signs of deterioration of the surface or, more seriously, by loss of service or function or of structural integrity.

In his introductory note to a recent symposium on durability,¹¹ CEB President Ferry Borges asked the question, when considering investing in more durable structures, how to split the total life cycle costs into initial costs and costs concerned with maintenance and repair? He showed how cost effect comparisons can be made on the basis of discounted values over various periods of time and that for a discount of 6 percent, maintenance costs after fifty years can be practically disregarded. The problem of such analyses, of course, is that not only do we lack the information to predict durability but also to define positively the practical life of a building which is so dependent on fu-

. . . the engineer must become more aware of the need to specify in measurable parameters and of his responsibility to check that his requirements are, in fact, satisfied.

ture attitudes and economic uncertainties.

Specifications for concrete

Definitions of concrete uses. One of the main problems with concrete is its great versatility. This is reflected, not only in its many different uses for all types of buildings and civil engineering works, but also in the considerable variety of materials and methods of construction which are used. This results in an enormous number of standards, codes, and specifications for concrete, each implying that there is something rather special in this particular use which requires a unique solution. Give me a concrete specification and I will give you 100 engineers who will rewrite it to take account of their own particular foibles and prejudices.

To try to overcome the unnecessary and meaningless multiplicity of specifications, current efforts in the United Kingdom are aimed at establishing a catalogue of uses of concrete covered by all the national architectural, building, and civil engineering specifications. Then against each of these uses will be given recommended grades of concrete which will satisfy the particular purpose and environmental condition. The question then remains: How should these suitable mixes be specified?

The current revision of CP 110, soon to be published, will show the way. It recognizes, for the first time, a limit state for durability in addition to those for ultimate strength and serviceability. The combined importance of adequate cover to reinforcement and con-

crete of suitable quality is recognized by interrelating these requirements in one table for various conditions of exposure. (see Table 1)

Concrete mixes, properties, and performance. The other main lesson to be drawn from recent problems is that the engineer must become more aware of the need to specify what he needs in terms of measurable parameters and of his responsibility for checking that his requirements are, in fact, satisfied. This assurance of quality in construction can be achieved if he adopts an overall system involving performance-based specifications and quality systems.

With concrete, the performance characteristics required are workability for placing, and strength and durability in use. Workability and strength are easily defined and tested, but with durability we are concerned with performance over a number of years. Durability requirements are often expressed in terms of limits on cement content or water-cement ratio, but, as yet, there are still no simple rapid tests for these. That is why there has been a joint proposal in the United Kingdom by the British Ready-Mixed Concrete Association (BRMCA), the Cement & Concrete Association (C&CA), and the Cement Makers' Federation for national grades for durability. Strength grades are defined which, with the materials available in the United Kingdom, give assurance that the concrete supplied will satisfy the requirements for cement and water-cement ratio.¹²

The philosophy here is, "If you can't measure it, don't specify it." It is vital that the required properties are expressed in terms which *can* be measured by simple, routine methods. Even if "performance in use" cannot be defined, the engineer's requirements should be defined by "performance against standard tests." The basic tests which are used for concrete both in North America and the United Kingdom are the

slump for workability, and the cylinder or cube test for strength. The proposed developments in the United Kingdom are that all concrete should be able to be expressed in terms of these parameters. Of course there will be additional requirements such as special types of cement for chemical attack or the use of air entrainment to combat freeze/thaw effects.

An examination of all the concrete mixes used in the United Kingdom at the moment has confirmed that most requirements can be satisfied by a total of five strength grades as given in Table 1. When taken together with the basic three consistencies required, i.e., dry [slump 0 to 1 in. (0 to 25 mm)], medium [slump 2 to 4 in. (50 to 100 mm)], and wet [slump 5 to 8 in. (125 to 200 mm)], this gives a total of fifteen concrete mixes, which should satisfy most requirements throughout the United Kingdom.

Materials. With the performance approach, any limits on types of materials used and mix proportions should be kept to the absolute minimum. The user of any material, however, needs to be assured of its quality and uniformity, especially with by-products such as pulverized fuel ash and slag. That is why the revised CP 110 permits the use of these materials, provided they comply with the new standards. The performance-based specification requires information on all materials. As a result of recent discussions, the European Ready Mixed Concrete Organization (ERMCO) has agreed with Cembureau, the European cement association, that there should be an exchange of information on a private basis between individual cement suppliers and ready mixed concrete producers. This information, additional to that contained in the European or national standards, relates to those characteristics of cement which can have a significant influence on the properties of fresh and hardened concrete.

It is obvious that, if he is to be able to supply concrete of uniform quality in compliance with a performance specification, the concrete producer must have information on the quality and uniformity of all raw materials, cement, aggregates, additions, and admixtures. The available raw materials and concrete requirements in, say, Stockholm or Helsinki, are very different from those in Rome or Madrid. For this reason, the draft European Standards for Cement (CEN/TC 51) and Concrete (CEN/TC 104) are frameworks within which each country can decide the quality levels most suited to its own requirements.

Production and compliance control systems

As previously indicated, the second and third most important components of quality assurance are that the manufacturer operate production or internal control procedures, and that the contractor, designer, or public authority adopt compliance or acceptance control procedures.

Production control. Within the framework of the basic quality control system, each industry sector must establish its own standards of good practice for the production and control of products. This has been done by the ready-mixed concrete industry in Europe. ERMCO, in 1977, produced its Code of Good Practice¹³ for the production and control of ready-

mixed concrete. This, again, is a framework standard and, in many countries throughout Europe, the ready-mixed concrete industry operates quality control schemes that comply with, and are amplifications of, the ERMCO Code.

Quality manual. In order that checks can be made easily that a company's plant is operating a suitable quality control system, each company should keep a quality manual. This manual covers all aspects of inspection, production, maintenance, and control, together with an indication of those people who are responsible for the various operations. Many of the certification schemes for ready-mixed concrete in Europe require company staff to keep up quality manuals that are provided by the authorizing body.

Third party assessment. In all countries, the implementation of building legislation involves detailed inspection of the design, materials, and workmanship against specific standards. To facilitate this work, various product certification and approval schemes have been built up. The important role of material or product certification is that it provides assurance to the user and avoids unnecessary and often useless compliance testing.

A large number of schemes certifying standards of production and quality control have been set up by industry groups in order to establish recognized standards of

TABLE 1 — Concrete cover required* for various exposure conditions on various grades of concrete (CP 110 Rev. February 1984).

Concrete					
max w/c ratio	0.65	0.60	0.55	0.50	0.45
min cement (kg/m ³)	275	300	325	350	400
lowest concrete grade	C30	C35	C40	C45	C50
Exposure	Nominal cover (mm)				
mild	25	20	20	20	20
moderate	—	35	30	25	20
severe	—	—	40	30	25
very severe	—	—	50 [†]	40 [†]	30
extreme	—	—	—	60	50

*Normal weight aggregates, 20 mm (0.8 in.) maximum size.

[†]Air entrainment
kg/m³ x 1.69 = lb/yd³
mm x 0.04 = in.

reliability and performance of their products. In several countries, the various industry quality control organizations are officially authorized as part of the building control system. The most widely accepted schemes are those operated by a third party certification body that is completely independent of the manufacturer, user, seller, or buyer. Obviously, the value of any third party certification scheme depends on the status of the authorizing body in that particular country.³

Compliance control. Even though the products being supplied for a building may have general approval or certification, there is still the question of whether individual items comply with the specified requirements. Compliance testing involves the sampling and testing of products to a plan that defines the number of tests representative of a batch, the rate of sampling, and compliance criteria for assessing results against acceptable quality levels expressed in statistical terms. Concrete cylinder and cube results lend themselves to this form of assessment and in recent years changes in codes of practice for concrete have raised this subject almost to the level of an art form.

When compliance testing is examined against the definition for quality assurance, several deficiencies are revealed, including:

- the large number of test samples needed to make confident decisions on the acceptance or rejection of the batch represented by the tests, and
- the complications of true "performance in use" specifications and the necessary degree of sophistication of the methods of assessment and testing, which are available in only a few laboratories.

In practice, batch or consignment testing is a most imprecise and ineffective means of achieving assurance that the products represented by the batch comply with the specification.

Accurate repeatable testing in accordance with prescribed standards is a fundamental requirement for all types of production and compliance control.

The objective of compliance control is to insure, with the least margin of error, that the agreed quality has been achieved. On the other hand, the aim of production control is to produce the agreed quality at minimum cost. Nevertheless, both systems have the common goal of achieving quality and together make up the total quality control system, as Fig. 3 shows. The degree to which they overlap differs from country to country and in the extreme, either production or compliance control may exist alone. Clearly a control system which satisfies both production and compliance purposes is the most effective and economical.

Workmanship control. As has been said, the quality of any structure, product, or component depends on the appropriate contribution from the designer, products manufacturer, and contractor, each of which, ideally should comply with separate, but equally stringent, quality control systems. Any product or component can only perform satisfactorily if it is properly installed in the building. This poses the question of workmanship on site which, as yet, appears to have received little attention.

While there are several schemes in being for concrete products, as yet few systems define quality requirements for workmanship. It is understood that several years ago, a U.S. national board of accreditation in concrete construction introduced such a certification scheme covering standards of site workmanship under controlled conditions by suitably trained per-

sonnel. It would be interesting to learn of the success of this venture. Clearly the operation of production control systems by contractors is one of the key points in providing overall quality assurance.

Testing laboratories. Accurate repeatable testing in accordance with prescribed standards is a fundamental requirement for all types of production and compliance control. Where quality schemes require independent supervision, inspection, and control, the manufacturer's internal controls and testing equipment will be subjected to external control checks by the authorized control organization.

Several countries have national testing establishments. The Federal Materials Testing Establishment (BAM) not only issues German Agrément certificates, but is also responsible for authorizing all other testing laboratories concerned with approval, certification, and control testing.

It is only recently that the need for such an accreditation scheme for test houses was recognized in the United Kingdom. Following discussions with all sides of industry, the Department of Industry introduced its National Testing Laboratory Accreditation Scheme (NATLAS). To avoid duplication of effort, NATLAS recognized schemes operated by the Ministry of Defense, the British Standards Institute, Lloyd's Register of Shipping, and the British Ready-Mixed Concrete Association's Register of Test Houses for concrete cube testing. BRMCA engineers act as NATLAS assessors and the scheme has been extended to a wide range of construction products.

Assurance of concrete quality in structures

Having discussed the principles of quality assurance, methods of specification, types of concrete, and control systems, it is now useful to examine how the building owner can be assured that the

concrete in his finished structure will perform satisfactorily in use.

The functional requirements to obtain the required performance can be defined as:

- Adequate strength of concrete in the finished structure, both on completion of the building and throughout the life of the building.
- Adequate durability of the concrete in the finished structure, in terms of:
 - a) the ability to stand up to the external environment (temperature variations, wetting and drying, abrasion, and chemical attack), and still maintain a good appearance.
 - b) the internal structure of the concrete for chemical stability (degree of hydration, alkali-aggregate reaction, and calcium aluminate conversion), and paste-pore structure (permeability, and porosity), and
 - c) the ability to resist corrosion of the reinforcing steel.

These functional requirements can be defined in terms of a wide range of performance criteria, standards, and methods of testing. The following are proposed as the most convenient and appropriate tests for measuring the actual properties and potential performance of concrete in the structure.

In situ strength of concrete. European codes of practice for structural concrete give design recommendations based on the characteristic strength of the material and a partial safety factor γ_m . For concrete strength, γ_m is taken as 1.5 to account for differences between the strength in the structure and the strength derived from standard specimens.

Clearly, structural designs could be more rigorous if the in situ strength was known. It is proposed, therefore, that, measurements should be taken of the actual concrete strength using cores and pulse-velocity tests and com-

parisons made with the design strength. This subject and the difference between "lab-crete" and "real-crete" has been developed elsewhere.¹⁴

Maturation of in situ concrete.

The hydration of cement (or combinations of cement and other materials) is a relatively slow process. With normal curing methods, the complete hydration (i.e., full maturity) of in situ concrete takes many years and may, in fact, never be achieved. Since in situ concrete contains unhydrated cement particles, engineers tend to assume that concrete will always gain strength and become more stable. Therefore, it could be advisable to make measurements of the amount of unhydrated cement in the structure throughout its life.

The need to conserve energy, however, will mean that greater use will be made in the future of mixtures of cement clinker and such partially cementitious materials as blast furnace slag and pulverized fuel ash. With such combinations, there is often little or no strength gain after one to two months and there may not be the same reservoir of unhydrated material and therefore little need for continued testing.

Corrosion of reinforcing steel.

Provided suitable cement and aggregate materials are chosen related to its use, a finished concrete structure will normally meet

the functional requirements for durability if:

- it has a dense cement paste structure with low permeability;
 - it contains entrained air to resist frost;
 - it is made with strong, dense, clean, inert aggregates; and
 - the materials contain a minimum of impurities such as chlorides, alkalis, and sulphates.
- In recent years, there has been a growing number of occurrences of steel corrosion due to new types of construction and uses including:
- bridge decks from deicing salts,
 - structures in the Middle East where ground salts contaminate aggregates and water,
 - buildings where calcium chloride has been used in the concrete, and
 - marine structures above the high tide zone.

The mechanisms and rate processes governing the initiation period and subsequent rate of steel corrosion have been the subject of numerous studies in recent years.^{10,11,15} The following discussion summarizes a recent paper by Browne.¹⁵

There are two distinct phases in the mechanism of attack, as shown in Fig. 4: an initiation period (t_0), which is the time for penetration of deleterious substances into the concrete to cause activation of the

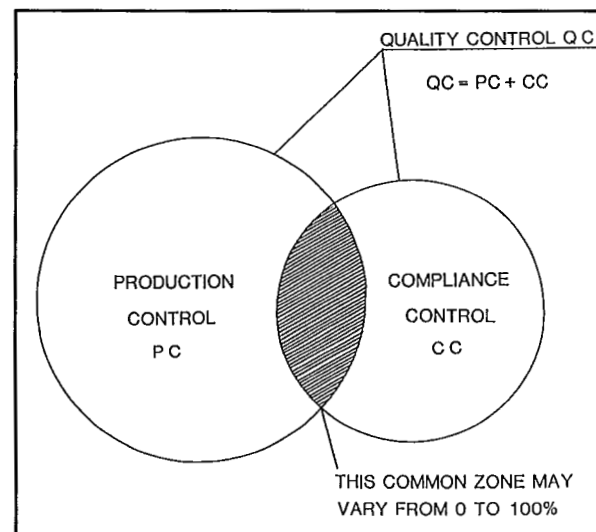


Fig. 3—Both production control and compliance control have the common goal of achieving quality and together they make up the quality control system.

deterioration mechanism; and a propagation period (t_1) before loss of serviceability, or other requirements, prevents the structure's continued use.

Four conditions must be met for reinforcement corrosion to occur:

- Chloride or CO_2 penetration through the cover zone to the reinforcement destroys the natural passivity provided by alkali protection of free lime in hydrated cement.
- Low concrete resistivity allows electrolytic cells to be established at the steel surface.
- Oxygen must penetrate through the cover to fuel the corrosion process. The corrosion products so formed occupy two to four times the volume of metal replaced, causing damage to the concrete cover.
- The quality of the concrete cover controls the diffusion rates of CO_2 , oxygen, and chloride ions.

It is the inter-relationship between these variables that dic-

... the engineer should decide which are the critical parts of a structure and concentrate his measurements of quality in these areas.

tates the time to activation of the steel (t_0) and the time from activation to damage (t_1).

Fig. 5 shows a typical chloride distribution measured on a structure by taking drillings at discrete depths into the cover. Generally, a level of 0.4 percent Cl^- by weight of cement is required at the reinforcement before activation can begin. Hence, the best-fit curve through the results can be compared to the critical level. This curve also provides the diffusion coefficient, D , and an estimate of the chloride level at the surface (C_0).

Having obtained estimates of D and C for a range of actual struc-

tures, a family of curves has been drawn (See Fig. 6). This chart allows us to input chloride drillings data and estimate the time to activation (t_0) for a structure or structural component. This time is determined using estimates of C_0 , D , and the depth of cover. Using the same chart, it is also possible to select a depth of cover required to meet a design life, given an assumed surface chloride level and diffusion coefficient for the concrete.

Specification for adequate durability. Since the propagation time (t_1) is too sensitive to random factors, it is proposed that only the time to activate the steel (t_0) should be considered when designing concrete for a specific life.

Chloride protection must be provided by the design since the rate of penetration of chloride is greater than that of CO_2 . Thus, if a structure is to be subjected to a marine atmosphere, salt water wash down, or contact with deicing salts, the following conditions must be met:

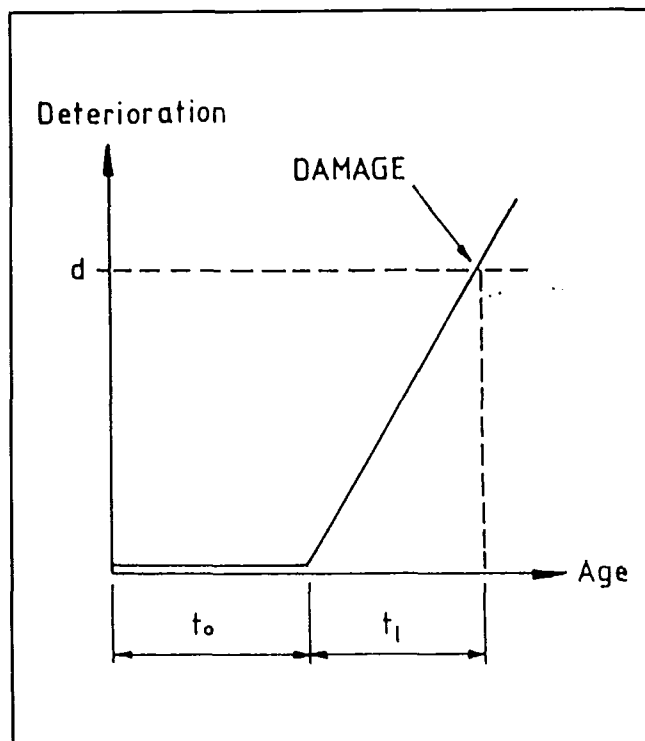


Fig. 4—The stages of chloride-induced corrosion of reinforced concrete: t_0 is the time taken by the chloride or CO_2 to reach and initiate deterioration; t_1 is the time before significant damage to the concrete cover occurs.

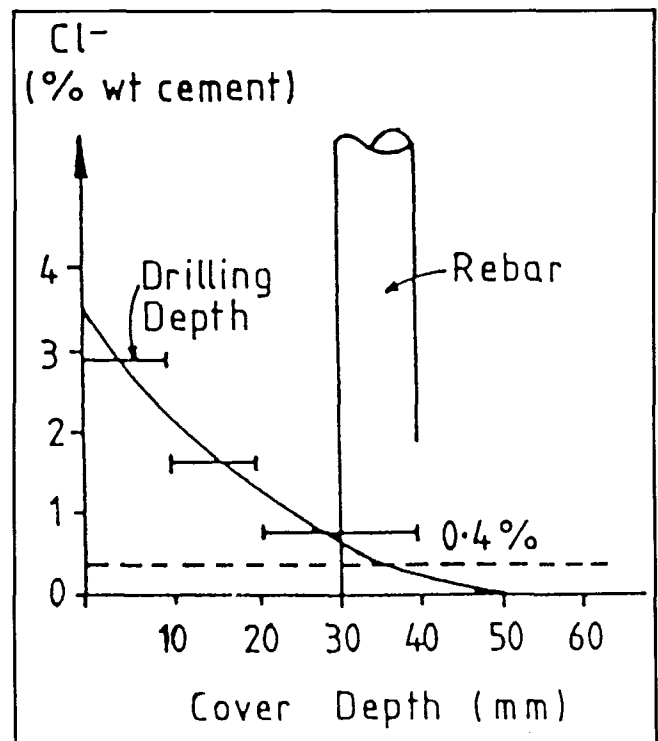


Fig. 5—Measured variation in the chloride level with depth from the surface of a concrete structure exposed to a marine atmosphere or deicing salts. ($\text{mm} \times 0.04 = \text{in.}$)

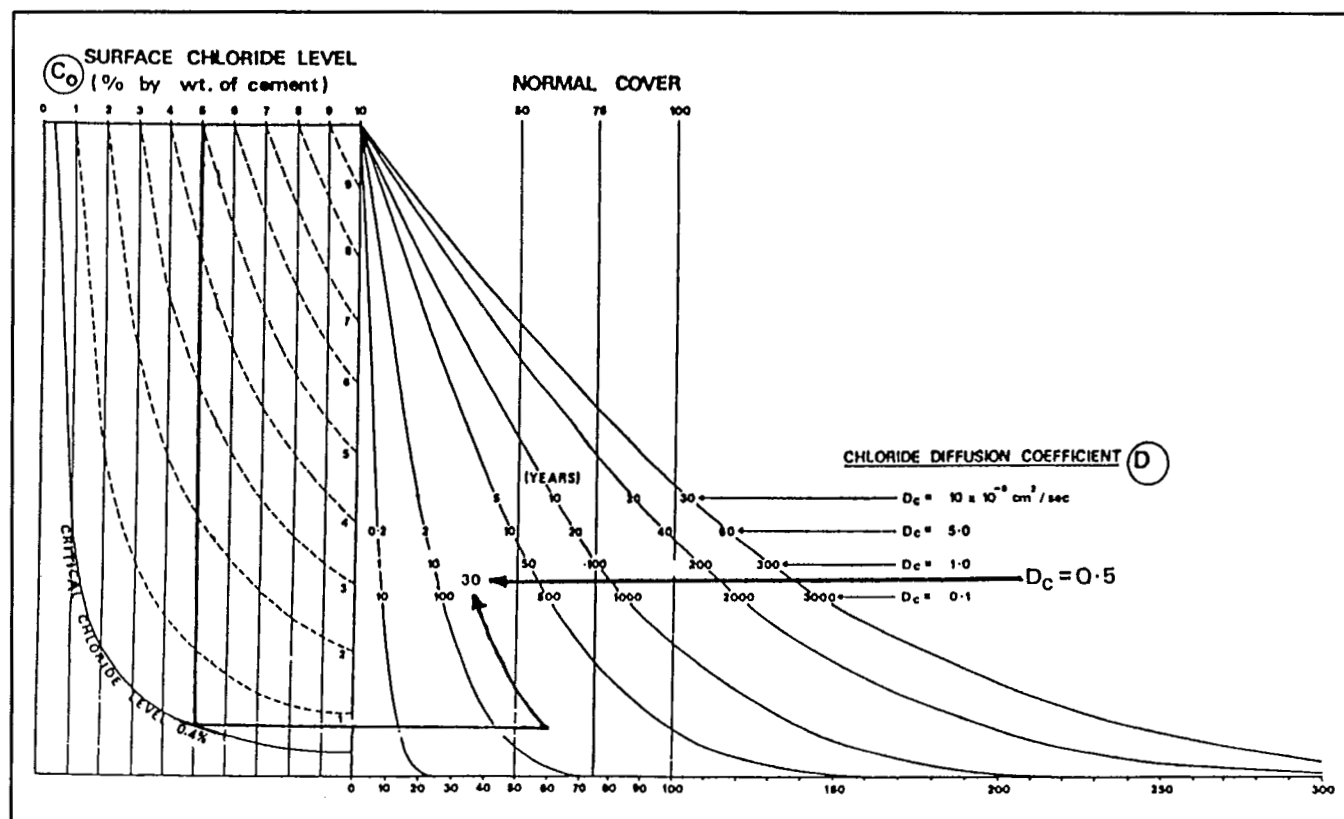


Fig. 6—A graphical method for determining concrete quality and cover requirements to produce a desired life under chloride exposure conditions

- 1) low chloride diffusivity (water-cement ratio of 0.4 and high cementitious content),
- 2) extended wet curing, and
- 3) cover of at least 60 mm (2.4 in.).

If these conditions are not readily achievable, then serious consideration should be given to the following alternatives:

- 1) coating the concrete with a low chloride penetration coating,
- 2) using coated reinforcing bars (e.g., epoxy coated),
- 3) using corrosion inhibiting admixtures (e.g., calcium nitrite), or
- 4) cathodically protecting the reinforcement.

In hot climates, it is even more imperative to consider combinations of these alternatives if a long life is required, say 50 years. Also in-service monitoring of chloride penetration is essential to identify whether the protection is adequate, so that extra protection can be applied, if necessary, before damage occurs.

CO₂ Protection can be provided by cover requirements and concrete quality that is lower than that required for chloride protection, but not such that penetration occurs within the required life. Although the interaction of the factors influencing penetration have not been quantified sufficiently, Browne believes¹⁵ that to achieve a 50 year life, requires:

- 1) low CO₂ diffusivity concrete (water-cement ratio of 0.5 or less with a moderate cement content),
- 2) wet curing of the surface, and
- 3) cover of at least 25 mm (1 in.).

Again, in-service monitoring of CO₂ penetration is easy to undertake and will identify whether additional protection is required before damage occurs.

In the recently revised draft of CP110, the durability recommendations (See Table 1) generally comply with the above requirements. Of some concern, however, is the uncertainty of CO₂ attack

for the "mild" exposure situations. For example, in the interior of centrally heated "buildings," CO₂ penetration may be high and thus could prove to be a major problem in the future, particularly where a cover of only 15 mm (0.6 in.) is specified.

Corrective action. When tests on in situ concrete raise doubts concerning the actual and potential quality of concrete, what action should be taken?

For the range of concrete elements in question, the engineer must first establish acceptable limits for in situ strength, and the various performance criteria for durability. He must determine the type and number of tests required and define clear acceptance rules, which may involve different safety factors for different elements. Whenever possible, he should decide which are the critical parts of a structure and concentrate his test measurements of actual and potential quality in these areas.

The action will depend very much on the particular situation, but the following factors should be kept in mind:

- The design rules for reinforced concrete are extremely conservative with relatively high safety factors compared with other materials. There have been few, if any, structural failures of in situ concrete.
- Concrete that is built into a structure is very costly to remove and difficult to replace. Alternative actions to the complete removal of concrete should always be considered.
- Any reparation costs should be compared with future repair and maintenance costs.
- It is more the interfaces between materials and components that are the probable causes of failures than it is the basic materials or components themselves.

Information retrieval

It has been proposed that, by examining the in situ concrete throughout the construction, the engineer can satisfy to the building owner, that his "just finished" structure is satisfactory. Results of in situ tests give a measure of the "state of health" of the building "at birth" which can then be checked during its "life" by further regular routine tests. The performance criteria for in situ concrete described previously indicate the extent of the changes in current practice that this philosophy would bring about. The problems of developing simple, rapid tests and reliable limits of performance for in situ concrete should not be underestimated and much work still needs to be done.

... one page data sheets should be prepared for all known concrete problems and stored in microcomputers for ready access. This should be the main task of ACI and the Concrete Society in the next decade.

But there is so much information already available on the limits of performance of concrete under different environments. This is buried in the towering and ever-growing files of international research reports on concrete, dating back to the beginning of the century. If all these reports were piled on end, and they reached higher than the Hancock Building, I would not be at all surprised! As I have suggested elsewhere, newcomers to concrete research should not be encouraged to tackle imaginary problems on "lab-crete" but to go out to the biggest laboratory of all, the construction site, and there examine the real problems on "real-crete."¹⁴

At the same time, if I had my way, any further research work on concrete would be stopped tomorrow. Every research worker and concrete specialist would be required to choose, from a comprehensive catalogue of subjects, one topic on which he would be required to prepare a one page data sheet preferably composed mainly of illustrations, which would:

- a) Define the problem.
- b) Provide the solution.
- c) Give guidance on action to be taken when things go wrong.

With almost every product, especially in the consumer field, an

operating manual is provided in which there is usually a troubleshooting checklist. The time is long overdue for a similar approach with concrete. With the recent explosion in home and personal microprocessors of ever-increasing capacity and ever-decreasing size and cost, it should be possible to store all the data sheet information for all known concrete problems for ready access whether in the office, on site, or on the production floor.

This should be the main task of the American Concrete Institute and the Concrete Society in the next decade.

Concluding remarks

Concrete has been used as a structural material since Roman times but it is only within the last century that the complexities of this deceptively simple, prosaic material have come to be appreciated. If concrete is to maintain its position as the basic material for building and civil engineering, its reputation as a solid, reliable material must be restored.

Despite the fact that concrete does not lend itself to modern technological improvements, we do have the knowledge to produce a foolproof concrete, one which is easily handled, is self-compacting and self-curing, and capable of producing the required properties to resist any environment to which it is subjected.

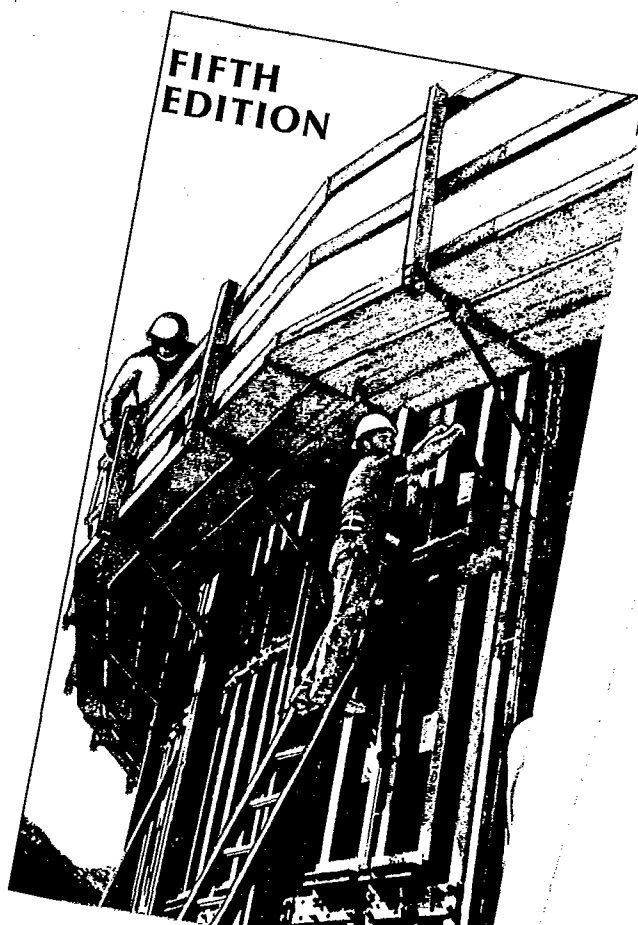
But when will this be achieved? Bryant Mather¹⁶ has already asked "When will the concrete industry enter the 20th century?" Let us all hope that it *will* happen before the 21st!

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Point of View

Future Trends in Concrete QC

By Joseph F. Artuso

Whenver the construction budget must be cut, quality control (QC) is usually the first thing to get the ax. It is always easier to reduce a service rather than construction. The inevitable result is a reduction in construction quality.

A few years ago a Department of Transportation had the answer to quality concrete construction: they required a one year guarantee for all concrete structures. They consequently reduced inspections and tests by state inspectors. There was a transfer of all testing to the contractor, and state inspectors merely witnessed some testing. Alas, better quality of concrete structures did not happen (it usually takes longer than one year before defects appear). As a result of continued failure, major revisions have been taken and primary QC is now assumed by the engineers.

There is a common misconception by some owners that QC must be performed by the contractor in order to hold the contractor responsible for any deficiencies found later. It is clearly stated in the Code

and upheld by the courts that the contractor is not relieved of responsibility when defects are uncovered later. Also, concrete is manufactured during construction and must be tested at this point to verify quality. There have been many cases where concrete deteriorated later in years when the contractor was long gone. For example:

- Cooling towers deteriorated because sulfate resistant cement was not used; it is extremely difficult to prove that the proper type of cement was not used.
- Roads and sidewalk deteriorate; it is extremely difficult to prove poor curing and high w/c.
- Slabs crack and settlement occurs; it is extremely difficult to prove poor curing, high w/c, and proper subgrade compaction.
- Concrete cracks; it is difficult to prove incorrect rebar placement.
- Low in-place concrete strengths exist; it is difficult to know how much of the factor of safety has been compromised.

We are now getting back to the original requirements of ACI 318, that concrete construction shall be inspected throughout the various work stages by a competent engineer or architect or by a competent representative responsible to that engineer or architect, and that records be maintained of:

- Quality and proportions of concrete materials.
- Construction and removal of forms, reshoring.
- Placement of reinforcement.
- Mixing, placing and curing of concrete.

- Sequence of erection and connections of precast members.
- Tensioning of prestressing tendons.
- Any significant construction loading on completed floors, members or walls.
- General progress of work.

Also when the ambient temperature falls below 40 F (4.4 C) or rises above 95 F (35 C) a complete record shall be kept of concrete temperature and of protection given to concrete during placement.

These are very specific requirements that take the form of legal requirements when cities or states invoke the ACI Building Code. Non-compliance can not only be unlawful but leave the engineer and owner in a weak position in the event of any litigation.

History of QC

Concrete QC has had a very shaky history. The requirements of inspection by the engineer have been in the Code for many years, but the process deteriorated to merely having a few cylinders made, which in many cases was not even representative of the quality placed. On many projects, the concrete cylinders were made on a stiff mix and then the balance of the concrete would be placed with high slumps.

For various reasons the state agencies and the Corp of Engineers attempted to transfer the responsibility of QC to contractors. They enacted procedures whereby contractors were required to provide inspectors and perform testing. The

POINT OF VIEW This article was selected for reader interest by the editors; however, the opinions expressed by the author are not necessarily those of the American Concrete Institute. The editors invite comments from our readers about the personal views given in this article.

It has become a common practice, particularly in some states, that lawyers are assembled as construction starts to prepare for litigation of construction claims. A good QC system will minimize these problems.

required tests and inspections were detailed and comprehensive in scope. The agencies then merely overruled the contractor's QC. This system has finally been acknowledged as ineffective and the agencies are abandoning this method. It demonstrates the fact that if you don't do the tests and inspections you probably will not get the quality you paid for.

The Nuclear Regulatory Commission tried to assure quality in other ways. Their original intent was to explicitly follow the Code. They later succumbed to a procedure that allowed contractors to perform all of the QC with an audit of the QC by engineers. This resulted in a considerable amount of duplication and excessive overhead and costs. With the most recent construction of nuclear power projects, however, owners were encouraged to perform the QC for greater effectiveness and economy.

There are detailed recommendations in ACI 311 "Guide for Concrete Inspection." Other standards have been developed such as ANSI/ASME NQA "Quality Assurance Requirements for Installation, Inspection, and Testing of Structural Concrete," which contains the types of tests and frequency required to assure concrete quality.

In most major commercial and industrial projects, a viable QC program will include:

Preliminary testing of concrete material and mix design development and approval. The supplier should submit current test results to verify conformance with the speci-

fications. The mix design should be established in accordance with ACI 318 by trial mixes, proven mix designs, or w/c limits. The proven mix designs should be verified by proper statistical evaluation of recent test results.

Establishment of comprehensive inspection and test programs and designation of responsibilities. The selection of the testing agency should be made by the owner/engineer. The laboratory shall meet the requirements of ASTM C-1077 "Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria For Laboratory Evaluation." The laboratory shall submit proof of Certification by AASHTO or National Voluntary Laboratory Accreditation Program.

Detailed inspections should be performed to verify:

- Correct location of forms and reinforcing steel.
- Proper batch plant operations.
- Correct mixing, placing, and curing of concrete
- Use of the proper mix.
- w/c control by free water determinations and water additions.
- Field testing of concrete for air entrainment, slump, temperature, and compressive strength.
- Correct precast connections and prestressing operations.
- General loading of finished construction (for conformance with specifications).

Nonconformance conditions shall be reported to the engineers, and reports shall be submitted as required by the City Code and own-

er's direction.

There have been considerable improvements in concrete QC in recent years. This has resulted from a greater awareness within the construction industry, and may have been expedited by the large shadow of litigation that has formed due to recent proliferation of construction lawsuits. It has become a common practice, particularly in some states, that lawyers are assembled as construction starts to prepare for litigation of construction claims. A good QC system will minimize these problems. Following are some of the new practices that have promoted better quality control.

Certified technicians

ACI Committee E 902, Certification, has developed several programs with requirements for testing and certification of concrete construction personnel. ACI chapters and other concrete industry groups sponsor programs to certify individuals who meet specific education, work experience, training, and examination requirements. ACI Certification as a Concrete Field Testing Technician—Grade I is required for compliance with ASTM C-94, "Structural Specifications for Ready Mixed Concrete," and ACI 301, "Specifications for Structural Concrete for Buildings."

Certified inspectors

Many states and agencies have required certified inspectors for concrete construction.

The state of Florida requires a Threshold Inspector for concrete