Concrete Construction

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Experience shows that concrete meeting the quality requirements of most current specifications for highway pavements and other structures can provide satisfactory service. The objective of quality assurance in its broad sense is to make certain that this will happen by design rather than chance, and at minimum cost. The term quality control has become widely used to describe the process by which this is achieved through the testing and inspection of the constituent materials and of the concrete as it is produced and when incorporated in the work. In fact, although in present practice they are often combined, there are two distinct elements to this process. The first is product control by the contractor to ensure that the concrete as produced and used meets the specification, and the second is the acceptance of the product by the owner as part of the completed work.

Product control is needed because each of the materials incorporated in the concrete and each process used contributes variations of their own to the end product. These variations occur both within a batch and from one batch to the next. Some are naturally occurring random variations that cannot be controlled. Others, and these are usually much larger, are the direct result of malfunctioning processes or human action, and these can be detected and changed. The effects of variations are often interdependent and cumulative. For example, if control is by slump and the sand content changes, this alters the water requirement, air content, etc. Furthermore, it should be borne in mind that accumulation of variance, including errors that arise from sampling and testing used to detect variance, is not arithmetic. For this reason, and because of the heterogeneous nature of concrete, the effect of variations in component materials and processes can have far-reaching and probably detrimental effects if left unchecked.

Acceptance of the product requires confirming that it complies with the specification. Ideally this should be done by examination and testing, as needed, of the concrete after all operations concerned with its manufacture have been completed and it is in place in its final form in the work. In practice, however, acceptance at an earlier time may be advantageous to both the contractor and the owner because it is difficult and costly to remove and replace defective concrete work. For this reason, acceptance inspection and testing of the component materials and of the concrete as it goes into the forms have been standard practice although owners have endeavored to retain a contractual right of later rejection. To avoid apparent duplication in inspection and testing, this naturally led to product control and acceptance judgment becoming combined for many years on most jobs in one and the same operation. The results of this and anticipated changes are discussed later.

The properties of concrete required by the specification, both when plastic and after hardening, and of the constituent materials—cement, coarse and fine aggregate, water, and any chemical additives or admixtures—are based on methods of test and limits prescribed by AASHO (18), ASTM (17), CSA (11), or other recognized standards. Quality assurance requires that the constituent materials be inspected and tested before use and that, taking into account the necessary features of the particular materials to be used, they be handled, proportioned, and mixed to produce concrete that in the plastic state will remain workable and uniform during transportation and placing, and will, after consolidation, finishing, and curing, display the required properties of strength, durability, impermeability, appearance, etc., in the completed work.

There are still serious gaps in our knowledge as to what variations in concrete and concrete materials can be tolerated before adverse effects show up. Often there is no abrupt change for the worse, and this makes the setting of limits (and rationally their enforcement) often a matter of judgment based on experience rather than fact. The significance of the available methods of test has been reported (3), and it should be kept in mind that uncertainty also exists that it is always a relevant property that is specified and, hence, controlled. Often properties are specified simply because a convenient or conventional method of measuring them exists. Much effort may then be put into their control on the job. This is often beneficial; e.g., low slump probabilities imply a low water-cement ratio. However, it is likely that injudicious control may, at the same time, be adversely affecting some desirable property. For these and other reasons, the perfect concrete specification in respect to quality has not yet been written. In spite of this, experience over many years has indicated that field control of (a) strength (as determined by cylinders or cores broken in compression or beams broken in compression or beams broken in flexure), (b) workability and indirectly water content (as determined by the slump, Kelly ball, or other test), (c) air content (as determined by the pressure or a volumetric method), (d) gradation and cleanliness of the aggregates and adjustment of the mix proportions to compensate for moisture in the aggregate, (e) batch weights for compliancy with design mix proportions (by visual inspection or printout), and (f) quality of constituent materials (by both sampling before and during use for laboratory testing), together with inspection of the production, use, consolidation, finishing, and curing processes can provide satisfactory quality assurance on most jobs.

With the exception of the air test and refinements such as automatic plants with control of slump, moisture content, and printout of batch weights, all the other control elements listed have existed essentially in their present form for 50 years. The main change has been in the manner in which they are used and the interpretation and application of the results.

The "conventional" approach taken for many years to assure quality in concrete used in highway work is typified by that reported in Illinois (20). Using their own well-trained staff, the Illinois State Highway Department undertook the complete inspection and testing of the materials and the concrete. The contractor was considered to have done his job correctly if he drew his aggregate from approved stockpiles produced under state inspection and his cement from state-tested and sealed silos, and complied in every respect with the direct instructions given as the concrete was produced and used to reject out-of-specification concrete or make corrections to the next batch. For this purpose, frequent "representative samples" were usually taken at fixed intervals and tested for compliance with exact specified limits, and simple control charts—such as bar graphs for strength, aggregate grading curves, and slump ranges—were used as decoration on field office walls.

This system worked well in generally improving quality where previously it had been poor, probably because at least tests were made and persons knowledgeable in making good concrete were there to see that things were done right. However, many people (14) recognized that this approach had limitations that, by not properly taking into account such inherent variations in concrete as, for example, its strength, made the specification of absolute limits unrealistic and often costly. A major advance was made by introducing a statistical basis for the analysis, evaluation, and specification of concrete strength as the overall criteria for concrete acceptability. This permitted the proportioning of concrete to meet the specified requirements without reference to such safeguards as a fixed cement factor, with consequent savings in cost. Following its success on the construction of the Illinois Toll Road and its standardization by ACI Committee 214 (7), this "How Good Is Good Enough?" approach (5) gained a wide following. Most highway authorities, however, continued to undertake the whole of the inspection and testing operation and to manually prepare the necessary statistical analysis and attendant control charts showing moving averages, required averages, coefficients of variation, etc.

The increased pace of construction, the delays involved in decision-making while awaiting evaluated test results, and often the sheer impossibility of sampling, inspecting, or influencing the increasingly sophisticated and automated plants coming into use caused frustrations that have led to the questioning of both the "conventional" and "how good is good enough" approaches for the control of concrete quality on logical, economic, and legal grounds. Some of the points raised have been as follows:

1. Sampling plans are required because there can be no such thing as a single representative sample (1, 2, 3).
2. Errors due to sampling and testing and effects of the naturally occurring variations in materials were not properly recognized. Tolerances were required on most specification limits (1, 2, 3).
3. Assumption of dual responsibility by the owner for both product control and for acceptance was not justified, and that control of concrete quality during production and use must rest with the contractor (4, 9).
4. Under current specifications, the risks to the producer of having good material rejected and to the owner of accepting poor material were not soundly or equitably based (2, 13, 15, 16).
5. The impact of the automation of batching and mixing plants or other processes was not taken into account (10).
6. The rapid pace of concrete production and use outstripped the currently available methods of testing, inspecting, and evaluating the results (8, 10).
7. Fact rather than opinion should govern acceptability and provide justification to the auditors for payment for the work (2, 3, 15).
8. Possibilities of financial bonus or penalty payments for quality that exceeds or falls short of the specified standard should be considered (13).
9. In many other industries, process control and product acceptance were on a different and apparently more satisfactory basis. Their experience and methods should be equally applicable to concrete (4, 9).

Possible solutions to these questions are currently the source of much research, debate, and anguish. Idealized specifications employing the principle of substantial statistical compliance have been developed (3), although their full acceptance has not yet proved desirable or feasible on the basis of results to date. Investigations have been undertaken to examine the validity of sampling and testing based on random statistical concepts within overall quality assurance plans (13, 19, 21). The risks inherent in concrete production in relation to current specifications, and suggestions for more realistic ones have been examined (13, 16). Precision statements are being introduced into most test methods (1, 17). Dissatisfaction with the adequacy of conventional methods of inspection and testing has been documented, together with areas in which either improvements or new methods are required (8). Faster methods of testing [for example, accelerated strength tests (6) or determination of cement and water content (12)] are being developed into practical use. Systems approaches are being introduced (10) in which the data obtained during quality control at the time of construction are being evaluated by computer processing and also stored for subsequent retrieval for use in subsequent performance studies or for material selection and the drafting of specifications for future work.

There is every promise that these and other developments will lead eventually to better procedures for quality assurance in concrete than are currently available. However, it must be recognized that any job will benefit immeasurably from the application of control measures currently available. This must, however, be meaningful and realistic control planned on a routine basis and relentlessly carried out by trained personnel using properly conducted tests on which to base decisions as to changes needed in the various materials or processes in use or on which to judge acceptance.

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