QUALITY CONTROL/QUALITY ASSURANCE OF HIGH-PERFORMANCE CONCRETE

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ABSTRACT

It is well documented that the sensitivity of high-performance concrete (HPC) to many quality control/quality assurance (QC/QA) procedures is greater than that of conventional concretes. Slight variations in mix proportions, and small deviations from good testing practices can have a greater effect on the strength and other properties of HPC than on those of conventional concretes. Thus, a clearly and well-understood QC/QA program is key to the successful implementation of HPC.

The main objective of this paper is to explore quality management issues of HPC using ISO 9001 elements, instead of relying only on quality control (material testing) to assure performance of in-place materials. Using quality management, the emphasis is placed on systematic control of the processes for producing the finished product. This represents a philosophical change from the acceptance of testing the product components as the sole criterion for QC/QA, which is common in public works construction today.

Keywords: High-Performance Concrete, ISO 9001, Quality Control/Quality Assurance, Quality Management.

INTRODUCTION

During the past decade, there have been major improvements in the field of concrete materials. High-performance concrete (HPC), with its increased strength and improved durability, has been successfully produced using conventional materials and production techniques. Several research studies have shown the potential structural and economic benefits from the use of HPC in bridges[1,2]. In addition, a number of successful applications of the material in actual bridge projects have been demonstrated in several jurisdictions. Despite this, the implementation of HPC has been slow in many other jurisdictions. This can be attributed, in part, to the perception that the production of HPC is associated with higher initial cost and increased quality control requirements. Several studies have indicated that the economic short-term and long-term benefits of HPC can far outweigh the additional initial cost needed to produce the material[1-3]. On the other hand, it has been shown that the sensitivity of high-performance concrete (HPC) to many quality control/quality assurance (QC/QA) procedures is greater than that of conventional concretes[4]. Slight variations in mix proportions, and small deviations from good testing practices can have a greater effect on the strength and other properties of HPC than on those of conventional concretes. Thus, a clearly and well-understood QC/QA program is key to the successful implementation of HPC.

This paper explores quality management issues of HPC using ISO 9001 elements[5], instead of relying only on quality control (material testing) to assure performance of in-place materials. Using quality management, the emphasis is placed on systematic control of the processes for producing the finished product. This represents a philosophical change from the acceptance of testing the product components as the sole criterion for QC/QA, which is common in public works construction today. The issues discussed in this paper are applicable to conventional concrete as well as HPC. However, since the intent behind HPC is to design concrete mixtures to specific performance criteria, new quality management philosophies should disproportionately benefit the applications of HPC.

WHAT IS ISO?

ISO (International Organization for Standardization) is the world's largest developer of technical standards for business, government, and society. It is a network of the national standards institutes of 148 countries with a Central Secretariat in Geneva, Switzerland, that coordinates the system and publishes the finished standards. ISO is a non-governmental organization. Nevertheless, it occupies a special position between the public and private sectors. This is because, on the one hand, many of its member institutes are part of the governmental structure of their countries, or are mandated by their government laws on matters related to standardization. On the other hand, many other members have their origins uniquely in the private sector, having been set up by national partnerships of industry associations[5]. The American National Standards Institute (ANSI) is such an organization in the United States.

The word ISO is derived from the Greek isos, meaning “equal”. Because “International Organization for Standardization” would have different abbreviations in different languages, it was decided to use a word that could be used everywhere, whatever the country, whatever the language. The word also reflects one of the hallmarks of the ISO brand: Equal footing. Each participating ISO member institution is on an equal footing to influence the direction of ISO’s work at the strategic level, as well as the technical content of its individual standards[5].

ISO STANDARDS

ISO standards contribute to making the development, manufacturing and supply of products and services more efficient, safer and cleaner. They provide the framework for compatible technology worldwide.

An ISO standard is “a documented agreement containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics to ensure that materials, products, processes and services are fit for their purpose”[5]. ISO develops only those standards for which there is a market requirement. These standards are developed by more than 2,850 ISO technical groups (technical committees, subcommittees, working groups, etc.) comprising experts on loan from the industrial, technical and business sectors which have asked for the standards, and which subsequently put them to use. These experts are often joined by others with relevant knowledge, such as representatives of government agencies, testing laboratories, consumer associations, and so on. It is estimated that some 30,000 such experts participate annually in the development of ISO standards[5].

ISO standards are voluntary. Since ISO is a non-governmental organization, it has no legal authority to enforce the implementation of the standards it develops. Although voluntary, ISO standards may become a market requirement, as has happened in the case of ISO 9000 quality management systems.

THE ISO 9000 FAMILY OF STANDARDS

ISO 9000 is among ISO’s most widely known and successful standards ever. It was introduced in 1987. ISO 9000 is actually a family of standards, which are referred to under this generic title for convenience, and it is concerned with quality management. This means what the organization can do to enhance customer satisfaction by meeting customer and applicable regulatory requirements, and to continually improve its performance in this regard. ISO 9000 is a generic management system standard that can be applied to any organization, regardless of its size and whatever its product. It concerns the way an organization goes about its work, and not directly the result of this work. In other words, ISO 9000 concerns processes, and not products – at least, not directly since the way in which the organization manages its processes is obviously going to influence its final product. ISO 9000 lays down what requirements an organization’s quality system must meet, but does not dictate how they should be met, which leaves great scope and flexibility for implementation in different business sectors and business cultures, as well as different national cultures[5].

As indicated earlier, ISO 9000 is actually a family of international quality standards and guidelines. ISO 9001:2000, which was published by ISO in 2000, specifies requirements for a quality management system for any organization. It is currently the only standard in the ISO 9000 family against which third-party certification can be carried.

QUALITY MANAGEMENT IN THE CONSTRUCTION INDUSTRY

To assure performance of in-place construction materials (e.g., HPC), contractors almost always rely on material testing[6]. Usually, the sole criterion for accepting the finished product is "good" performance in tests. This quality control concerns the operational means to fulfill the quality requirements. Quality assurance, on the other hand, aims at providing confidence in this fulfillment, both to the contractor and to owners and regulators. Quality management encompasses both quality control and quality assurance[5]. In this section, a brief review of the state-of-the-art of quality management in the public works construction industry using ISO 9001 elements is presented. The discussion is focused on the critical factors for the successful implementation in the construction industry.

Most people who are familiar with ISO 9001 Standards have probably seen the term connected with manufacturing companies and facilities. ISO quality standards were first applied to manufacturing for several reasons. Key among these reasons is the relative ease the standards could be applied to mass production, where processes and inputs occur under much more controlled conditions than in construction. For example, most manufacturing takes place under enclosed, climate-controlled conditions inside of a factory, while most construction takes place outside, where temperature, precipitation, humidity, wind and other variables must be accounted for. Most manufacturing seeks to make many identical products. Construction, on the other hand, is typically for unique, one-of-a-kind projects.

ISO 9001 Standard has gained much acceptance in the construction industry in the past decade. The standard has been used successfully on recent major projects around the world. For example, ISO 9001 requirements were used to provide a standard benchmark for assessing the contractors who bid for the 109km Channel Tunnel Rail Link project between London and the Channel Tunnel in the U.K.[7] In another major project, the Øresund Fixed Link between Denmark and Sweden, a quality system that was tailor-made to the actual job was required by the owner[8]. This system contained a number of requirements, which either supplemented or added to the requirements of ISO 9001 Standard.

The literature is filled with other case studies and surveys of the use of ISO 9000 elements in the construction industry around the world[9-17]. Various degrees of success have been encountered. In some jurisdictions, ISO 9000 requirements are mandatory. For example, the Housing Authority in Hong Kong has mandated the implementation of ISO 9000[18]. Surveys there and elsewhere have shown that the most critical factor for the successful implementation of ISO 9000 is the senior management's genuine commitment to quality[19,20]. Chin and Choi[19] indicated that management should adopt an open attitude to change so that the integration of quality management can bring improvement to quality.

While ISO 9001:2000 is the current standard, there is no requirement that agencies or companies adopt the current standard. For purposes of this paper, the format of ISO 9001:1994 Standard provides a format that can more easily be understood. It has the additional advantage, that because it has been in use for a longer period of time, more people will be familiar with its organization. Additionally, some federal agencies have used a format very similar to the 1994 Standard, and have not transitioned to the new standard yet. The Federal Transit Administration requirements for quality management plans fall into this category. For example the controlling document for federally funded transit projects, which uses sixteen of the twenty ISO 9001:1994 elements, is FTA-Quality Assurance and Quality Control Guidelines, FTA-MA-06-0189-92-1.

INTRODUCTION TO THE ISO QUALITY STANDARD

In the preceding paragraph reference was made to twenty ISO 9001 quality elements. Twenty elements provides for a robust approach to quality management. The number of elements provides for redundancy (alternate paths to accomplish quality goals). As structural engineers, the authors find this robustness and redundancy comforting. The twenty elements are:

1.0 Management Responsibility
2.0 Quality System
3.0 Contract Review
4.0 Design Control
5.0 Document and Data Control
6.0 Purchasing
7.0 Control of Customer Supplied Product
8.0 Product Identification and Traceability
9.0 Process Control
10.0 Inspection and Testing
11.0 Control of Inspection, Measuring and Test Equipment
12.0 Inspection and Test Status
13.0 Control of Nonconforming Product
14.0 Corrective and Preventative Action
15.0 Handling, Storage, Packaging, Preservation and Delivery
16.0 Control of Quality Records
17.0 Internal Quality Audits
18.0 Training
19.0 Servicing
20.0 Statistical Techniques

ISO 9001:2000 Standard provides tables to document the correspondence between the location of each element in the 1994 Standard and the 2000 Standard. The tables provide for forward and backward tracking of changes.

Each of the elements typically has several subheadings. For most of the elements, the discussion of the subheadings is beyond the scope of this paper. Whereas most specifications for HPC include requirements for inspection and testing (element 10.0), and some specifications include requirements for process control (for example, the requirements for fogging slabs and bridge decks based on temperature, humidity and wind velocity prior to curing), it is clear that ISO requirements are far more extensive.

Understanding the definitions of terms as used in ISO standards is crucial to understanding how the standards impact quality management. The terms used in quality management are precise, and often different from the common understanding of words, just as structural engineers and materials engineers have their own understanding of technical terms. The best compilation of these definitions is found in ISO 8402 Standard. To provide a flavor of the terms used and define some of the most important terms needed for a good understanding of the topic, this paper uses the following terms.

USEFULL DEFINITIONS

Quality: Conformance to requirements. (Not to be confused with the term Grade, which means degree of excellence, or to be confused with the term performance.)

High Performance Concrete (HPC): Concrete meeting specific combinations of performance and uniformity, which are developed for a particular application and environment. (Note that ease of placement is as likely a requirement of HPC as low permeability or high strength. Compare similarities in the way the terms quality and high performance are used. Quality does not mean excellent, and high performance does not mean high strength.)

Quality Control: The acts of examining, witnessing, inspecting and testing of in-process or completed work. (The authors' experience is that the construction industry relies on inspection and testing of in-process work, using tools such as testing slump and air entrainment of concrete. Note that even the testing of concrete cylinders for compressive strength does not test the completed work, but tests a proxy for the work.)

Quality Assurance: A program of planned policies, procedures, responsibilities and systematic actions, including surveillance and audits of the quality control program. (Note that quality assurance is process oriented, as opposed to task oriented. Many individuals use the term quality assurance and quality control interchangeably, often implying that quality assurance is quality control performed by more senior inspectors.)

Quality Audit: A documented activity performed in accordance with written procedures and checklists to verify, by examination and evaluation of objective evidence, that the applicable elements of the quality management plan have been developed, documented and implemented in accordance with specified requirements. (An audit should not be confused with inspection or surveillance activities. An audit is not an exhaustive examination of records and evidence, but typically has a scope that can be accomplished in one or two days. Multiple, periodic audits are generally utilized to ensure a quality management plan is functioning as desired.)

Corrective Action: Measures taken to rectify conditions adverse to quality, and where necessary, to avoid repetition. (In this use, corrective action is focused on the processes required for producing a product or service. Corrective action is not the same as re-work or replacement.)

Nonconformance: A deficiency in characteristic, documentation or procedure that renders the quality of an item indeterminate or unacceptable. Indeterminate, in this application, means that information is not available to make a determination. Examples include missing test records as well as low 28-day concrete compressive strength. Consider the point of reference that work is accepted only when there is an objective basis to accept the work. Contrast this approach to rejecting work only when there is evidence to reject work. The first approach places a much higher burden on accepting work. In the second approach, work can be accepted by default, i.e. when no contrary evidence is available.

Testing: An element of verification to determine the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental or operating conditions.

Product: The result of activities and/or processes, which can be tangible or intangible, or a combination. (Note that this definition includes services and procedures, as well as constructed elements and materials.)

Verification: Confirmation by examination of objective evidence that work conforms to specified requirements.

Validation: Confirmation by examination of objective evidence that requirements for a specific intended use are fulfilled. (Contrast with verification. Verification focuses on specifications. Validation focuses on fitness for use.)

As with newer probability-based performance specifications, such as load and resistance factor design (LRFD) codes, the quality management systems provide for increasing the probability of successfully meeting the customers' requirements (quality). They are no guarantees of achieving perfection. For example, a structural engineer using the AASHTO Load and Resistance Factor Design Specifications for Highway Bridges cannot guarantee the bridge will not fail. Similarly, a quality assurance manager cannot guarantee that a project using an ISO certified or compliant quality management plan will result in all elements of a project meeting all of the owner's expectations. Probabilities, however, are on the side of the engineer using a current LRFD design code, and on the side of a contractor using ISO compliant quality management plan.

HISTRORICAL DEVELOMENT OF QUALITY STANDARDS

Some background on how ISO standards, and in the United States, how the American National Standards Institute (ANSI) quality standards came into use is instructive. Coursework, for the National Accreditation Program for Training of Quality Management Systems Auditors, provides a background for the development of military procurement specifications into ANSI/ISO Quality Management requirements.

After World War II, the U.S. government had more suppliers of military equipment than were required during peacetime. To support a systematic determination of which suppliers to retain and which to terminate, studies were done to find correlations to supplier performance with respect to cost, schedule and quality. The findings of the studies, which are paraphrased here, are that organizations with quality management plans outperformed organizations without quality plans in all aspects. It is interesting to note that in these first attempts to quantify relative performance of the military suppliers, no judgments were made regarding the content or the excellence of the various quality plans. Simply having a plan or not having a plan resulted in a measurable difference between organizations.

In the half-century that has passed since this realization, requirements for quality plans have evolved and become more standardized through the efforts of organizations such as ISO and ANSI. The voluntary and the required implementation of quality management plans has spread to additional industries over time and is now impacting the construction industry. Some government agencies and jurisdictions have been more proactive in adopting quality management requirements; the FTA was cited earlier. And some countries have provided leadership in adopting ISO requirements[9-17]. Sometimes the impetus is provided by government agencies, and sometimes by industry.

ISO QUALITY ELEMENTS

Brief descriptions of each of the twenty elements of a quality management plan are necessary for a better understanding of quality management. The point of examining the twenty elements of an ISO quality plan is to demonstrate that there are many tools, in addition to inspection and testing, that can be used to improve the quality of a project.

1.0 Management Responsibility – Management's commitment to quality is the most important condition for successful implementation of a quality management, as has been emphasized in the literature[19,20]. Without the commitment a plan is not likely to be effective. Requirements of this element include, a Quality Policy, a Quality Organization and management review of the quality program on a periodic basis. The Quality

Organization identifies personnel and assigns responsibility for quality control and quality assurance functions and defines reporting relationships.

2.0 Quality System – To ensure conformance to requirements, it is necessary to formally document (write down) the requirements and procedures designed to guide the performance of quality management. These procedures typically include General and Administrative Procedures, Project Management Procedures and Quality Control Procedures. This Section of the Quality Management Plan can account for the majority of the pages of a plan. It is typical that one or more procedures in the Quality System addresses each of the other elements. Each procedure often includes sections that define Purpose, Scope, Responsibilities and Procedure. They may also include Exceptions, References, Forms and Exhibits. The procedures will describe how to document each activity, as well as how to perform each activity. Topics for a Construction Quality Management System for HPC work could include procedures for, Constructibility Review of Plans and Specifications, Pre-activity Meetings, Quality Program for Suppliers and Subcontractors, Control of Construction Documents, Tracking of Design Changes, Control of Quality Records, Inspection Reports, Control and Calibration of Test Equipment, Pre-Pour Inspection, Concrete Testing, Post-Pour Inspection. The procedures included in the Quality Systems should not be confused with work procedures or operating procedures, which are covered in Element 9, Process Control.

3.0 Contract Review – Requires that the organization understands the project requirements and ensures that it is capable of delivering and coordinating the required services, including documentation and record keeping. In ensuring it understands the requirements, it is necessary that the requirements are documented in written form. Oral requirements must be documented in writing. The organization must have the experience, resources (human, financial, equipment and management) and relationships to complete the project. The reviews occur at three different phases: solicitation (request for proposal/bid), prior to signing the contract and for contract amendments and change orders.

4.0 Design Control – For Bid/Build construction projects this element is not generally applicable. However, there are situations where a construction contractor is responsible for design. These cases include formwork and falsework design, as well as temporary work necessary to construct the permanent work. The design effort can also include preparation of shop drawings and other designs necessary to proceed from construction documents to realization of the project. Elements of design control include planning, organizational and technical interfaces, inputs, outputs, reviews, verification, validation and design changes. Designs may be verified, but cannot usually be validated until after construction is complete.

5.0 Document and Data Control – Requires that a system be developed and implemented that ensures that documents necessary for quality of the delivered product be properly controlled. The types of documents covered under this requirement include contract, plans, specifications, Quality Manual, quality procedures, work instructions, inspection and test results, quality audit reports and management reviews. Controls that must be exercised include review, approval, distribution, revision control, identification and removal of obsolete records, and record retention requirements.

6.0 Purchasing – This element defines requirements for evaluation of purchased products and services. A sub-element is the evaluation of subcontractors and suppliers. Included in the evaluation are measures of experience (past results), quality program, and availability of resources and facilities. Purchasing data should be recorded and kept. Provisions can be made of verification and validation of supplied materials and services.

7.0 Control of Customer Supplied Product – This element is not typically used in concrete construction. An example that could occur in commercial construction is when an owner procures equipment separately from the construction contract and the contractor is responsible for installing the equipment. Where applicable, the contractor must establish and maintain documented procedures for the control of verification, storage and maintenance of customer supplied materials.

8.0 Product Identification and Traceability – For bulk commodities, such as concrete, identification and traceability is not as precise as for high value manufactured items. Attaching a serial number, or other unique permanent marking to individual items is how this element is usually realized. A system for recording the parts that comprise the item, when and where it was built, when and how it was shipped and where it was delivered are all elements of traceability. For concrete, documentation of the constituent parts blended to make the concrete, material test records of those parts, time of batching, time and conditions of delivery and placement, on-site testing associated with the truck load and approximate location within the final project are all records that are important to identification and traceability. The importance of this information is clear if a corrective action is found to be necessary, such as a later determination that a particular lot of cement did not perform as expected in other projects. But it also should be noted that the very effort of measuring and documenting work influences the behavior of the suppliers and therefore the quality of the product. This relationship is well understood inside of quality management organizations, but is generally unrecognized outside of the practice.

9.0 Process Control – Requires the contractor to identify and plan the production, installation and servicing processes which directly affect quality and ensure that these processes are carried out under controlled conditions. All those familiar with conditions under which construction is accomplished will realize the importance of this element. Briefly, work is accomplished through processes. For concrete work, the multiple processes necessary include formwork, batching, delivery, placing, finishing and curing. Processes have inputs and outputs. The difficulty of controlling inputs such as weather (including temperature, humidity, wind speed, sun light, etc.) is easily understood. A slightly more subtle, but still generally understood input is labor. It is generally accepted that the labor available in most locations has experience with, and know how to place and finish conventional concrete. It is recognized that finishing HPC with mineral admixtures such as silica fume requires different experience than finishing conventional concrete. The response to these difficulties is generally to provide prescriptive specifications that require the contractor to make provisions for fogging bridge decks, under certain weather conditions, prior to curing. ISO standard makes provisions for certifying and/or qualifying operators and processes when the results of the process cannot be verified by inspection and testing.

10.0 Inspection and Testing – Finally at the tenth element of ISO 9001, we are getting to activities that are routinely connected with quality control in the construction industry. The terms inspection and testing are used the same way in ISO standard as they are understood in the construction industry. Inspection and testing include materials that are received as well as processes performed directly by the contractor. With concrete, on-site testing is done before the concrete is incorporated into the work. This testing is in addition to testing that the supplier would perform at its plant. Likewise, the concrete supplier performs tests on the materials they receive (cement, course aggregate, fine aggregate, water, admixtures, etc.) that are in addition to the tests that the suppliers of the constituent parts make. Inspection of the on-site processes is common, but testing of concrete during or after placement is rare, as is the verification or validation of completed work. From a systematic point of view, the testing of outputs, rather than just inputs, is a logical extension of a quality management system. Durability of concrete is better evaluated by measures such as permeability, and size and distribution of entrained air in the cured concrete. Also important for durability is the number and size of cracks in the concrete. This element also describes requirements for inspection and test records.

11.0 Control of Inspection, Measuring and Test Equipment – This element contains requirements for the calibration and control of test equipment, and the certification of testing laboratories. The documentation requirements are also included.

12.0 Inspection and Test Status – Requires that methods of identifying and tracking the status of work elements, through acceptance, are in place. The goal is to identify and explicitly accept work, not to reject work. Quality management does not work on a basis of exception reporting. It is necessary to have a basis of acceptance for all work accepted. As such we define work in a number of ways, including accepted, indeterminate, nonconforming and rejected. It is necessary to understand that indeterminate work can exist for reasons that include testing not being completed, or because the calibration of test equipment was found to be out of date. For example, concrete work cannot typically be accepted until the results of cylinder testing exceed the 28-day strength requirement. Work, which is nonconforming or indeterminate, can often be brought into conformance (and therefore eligible for acceptance), through additional testing, rework and updating calibration records. Only when it is not possible for work to be brought into conformance is rejection of the work indicated. Even nonconforming work can be accepted by the owner, if adjustments to price or preventative actions are taken that ensure the work will meet the intended function.

13.0 Control of Nonconforming Product – Similar to the requirements for identification and traceability, this element provides for identification, documentation, evaluation, segregation (when practical), and disposition of nonconforming product. The notification of effected parties, which include the owner and subcontractors that may incorporate the work into their processes, is included in these requirements. Often this requirement could be fulfilled through the use of a Nonconformance Report (NCR). This report identifies the element of work and the specific requirement that was not met. An engineering evaluation is often performed to determine if the work can be used as is. An example where such a determination could be appropriate is if concrete failed to attain the 28-day strength required by the specification, and an evaluation of the design determined that the required strength was lower than the tested strength. The authority for evaluating nonconforming work is generally placed with the Engineer of Record. Quality control staff should not have the responsibility for evaluating work that is not in conformance with the plans and specifications.

14.0 Corrective and Preventative Action – This element incorporates two different functions: the corrective action and the preventative action. The corrective action included in this element should not be confused with rework required by an isolated nonconformance. Corrective actions are intended to identify root cause of an actual or potential nonconformance. The need for corrective action should be thought of as resulting from systemic causes. There are three types of causes, product, process and quality system. An example of a root cause of a nonconformance could be that an employee missed training in a certain process. The corrective action would address training issues. Rework for the element(s) that were nonconforming would be different. Preventative actions are proactive, and they generally include ideas and suggestions from all employees. Both these actions are part of the quality management philosophy of continual improvement. Any actions taken should be related to the severity of the problems caused by the nonconformance.

15.0 Handling, Storage, Packaging, Preservation and Delivery – This element is relatively self-explanatory. On construction projects a contractor is usually responsible for receiving products and incorporating them into the permanent work. Often the supplier will store, package and handle materials and they are directly and immediately incorporated into the work. This is typically the case with concrete, which is delivered to the site by the supplier and immediately incorporated into the final work. If, for example, the contractor batched concrete on-site, the contractor would be responsible for handling and preserving the constituent parts of the concrete. Notably, handling and preservation requirements for cement are different than for aggregates, and the contractor would need to plan and document procedures for each of the different materials, with their unique requirements. Preservation and delivery requirements can include methods of protection required between the completion of the work (including the contractor's inspection) and acceptance of the work by the owner. Construction projects often include a long period of time between the completion of individual items of work and final acceptance by the owner.

16.0 Control of Quality Records – Records that demonstrate conformance with requirements are called Quality Records. Procedures for identification, collection, indexing, accessing, filing, storage, maintenance, and disposition of quality records are required. The quality records of subcontractors and suppliers are included in this element. The retention time for different quality records may be different. The owner may or may not take possession of quality records, depending on the contract requirements. An example from design is drawing check prints. These are defined as quality records, (they demonstrate conformance with checking procedures.) Owners rarely take possession of check prints. Different designers and agencies have different retention policies for check prints.

17.0 Internal Quality Audits – Internal Quality Audits are performed by an employee of the organization being audited. The auditor will normally be independent of the function being audited and have no operational responsibilities in the activity being audited. The audits are performed on a periodic basis, with the frequency influenced by the importance of the activity. The audit results are reported to the group that was audited, as well as senior management. Corrective actions and follow-up audits may be necessary. ISO Standard 10011 provides the auditing principles that govern audits. For audits to be effective, it must be understood that the purpose of the audit is to improve performance. Adversarial relationships between the auditor and the subject of the audit are counter-productive.

18.0 Training – Requires the contractor to have procedures for identifying training needs and providing training for all personnel affecting quality. It is necessary, but not sufficient for employees to be capable, experienced, educated and, sometime, certified. Training on the work procedures and quality procedures is also necessary. As with all other elements, documentation (training records) should be maintained. The need for training applies equally to professions, managers and trades. When new activities, such as the placing and finishing of HPC, are planned, training is an important element for the successful completion of the work.

19.0 Servicing – This element concerns activities after completion (sale) of the project. Servicing is not a common requirement on construction projects. Servicing is a separate issue from warranties. Incorporation of servicing responsibilities into construction contracts, especially design-build contracts (to make them design-build-operate-maintain projects), could provide effective and efficient incentives to improve quality and/or reduce costs.

20.0 Statistical Techniques Statistical Techniques – Statistical techniques cannot be handled on an informal basis. Most construction specifications and owners provide prescriptive requirements that nullify statistical techniques. Further discussion of statistical techniques is beyond the scope of this paper.

Many researchers and observers of the trends in quality management, including critics, have commented that much of the effort of quality management results in additional paperwork and has little impact on the actual quality of the product or service. Based on the authors' observations, this criticism has merit. However, the ineffectiveness of many quality programs likely has less to do with the programs than it does with misunderstanding of the challenges of effectively implementing a quality management plan, and with the incentives that are acting within a particular market segment.

INCENTIVES

Understanding the incentives and disincentives of providing the required level of quality is important in specifying quality requirements. One of the significant changes between the 1994 Standard and the 2000 Standard is that the 2000 Standard specifically addresses Customer Focus, and the importance of management determining and fulfilling customer requirements, with the goal of enhancing customer satisfaction. In the private sector, customers constantly determine tradeoffs between cost, grade (level of excellence), location of transaction, level of service and other factors that make up purchase decisions. Organizations determine the customer requirements of the sector of the market they hope to serve and using the elements of the quality management plan make their products as attractive to the market as possible, taking into account all of the factors that the customers consider in their decisions. To be most efficient in satisfying customer requirements, companies must be as consistent as possible.

In the private sector, companies that are not successful at determining the quality requirements of its customers will generally lose customers until they correct the deficiencies in their processes, or get out of the business.

It is important to understand that the customer defines quality. Public works projects present unique challenges for defining the customer and quality. We can ask who is the customer for a public works project. Is it the agency that will own and operate the facility? Is it the politician who promised the jobs and the facilities to his various constituencies? Is it the public who will use and benefit from the facility? Is it the taxpayers who paid for the facility? Most of the individuals, groups and agencies involved in public works construction are acting as agents for the customer, rather than being direct customers. Analysis of the customer needs in this situation is quite different than for a company selling to direct customers. The indirect relationships also create incentives that are different and perhaps more complex than direct customer relationships. Researchers and writers in public policy and economics have explored incentives and behaviors by differing groups related to incentives and disincentives that a particular group may be subject to[21].

As an example of such difficulties in the public works sector, many times written requirements do not reflect actual needs, prevailing industry practices or achievable results. A recent example is a warranty statement made by a public agency that allowed no thru-deck cracking on a bridge deck and no cracking in a concrete pavement, as if these are achievable, industry standard results. This condition of unrealistic specification requirements may be a result of applying a quality control mentality in place of a quality management philosophy. As an illustration, an owner that has experienced cracking in concrete pavements that impacted ride quality or durability may react by changing a prescriptive specification to require a lower concrete slump for the concrete placed in pavements. Due to the number of factors that impact the slump of concrete, this specification may not improve the performance of concrete pavements, and it could prove to be detrimental to overall pavement quality.

There are several additional reasons why public works construction presents special challenges for implementing a quality management plan. Among the challenges are the low-bid method of procurement, the relatively few projects and relatively large project size of public works projects, the extreme long life of projects, the reliance on prescriptive requirements as opposed to performance requirements, and the division of quality management responsibilities between the owner and the contractor. The number and size of construction projects make each project a high stakes undertaking for both the contractor and the owner. The optimum behavior for participants in transactions that have a very low number of occurrences is different than for transactions that have many occurrences or an indeterminate number of occurrences[22]. The long life of project makes determining the durability of project elements at the time of construction very difficult. Incentives and/or penalties directly connected to quality and durability issues have such long terms that the actual financial risks cannot be efficiently priced. The use of prescriptive requirements eliminates all incentive and any possibility to solve the problem differently or provide an improvement. The distribution of control, and therefore responsibility, also works against quality management philosophies that demonstrate improved results through more narrowly assigned responsibility.

Low bid requirements, typical in public works procurement, can create perverse incentives for the implementation of quality management plans and attaining the required degree of excellence. Many authors identify the critical success factors for public works projects as cost, schedule and quality[23]. Trade-offs exist between these factors, and increasing one factor has an adverse impact on the other two factors. For example, if an owner wants the lowest possible cost, it must expect lower quality and/or a longer schedule. By definition, low bid work puts the emphasis on lowest cost, and the owner and designer rely on detailed requirements for minimum acceptable quality standards, and schedule requirements that include the maximum number of working days and/or calendar days.

Procurement methods, such as the “Best Value” method seek to minimize the quality conflicts inherent in the low-bid method of procurement. Other methods of procurement are possible, and are used in private transactions.

NEW PRODUCTS AND SERVICES (HPC)

For obvious reasons, change and variability are enemies of quality. Readers should not confuse the term “change” with the term “corrective action”. Quality requires consistency. The term quality should not be confused with excellence or performance. HPC is a new material, which may require new techniques for mixing, transporting, placement, finishing and curing. For the contractor, the laborers and inspectors, these new requirements create the need for additional training and possibly new equipment. Frequently on construction projects, when an inspector or Engineer of Record tries to correct what they consider a deficiency in construction, they are told, "this is how we always do it," "this is how we did it on the last project," or some variation of this theme. Changing materials and industry practices carries risk. In an industry such as construction where most labor is only employed by the contractor for the short term, and more likely has a stronger identity with the local branch of their trade union, providing appropriate training and experience, and modifying work practices is more difficult than in manufacturing or service industries.

As mentioned above, divided responsibility for quality is a departure from a quality management philosophy that assigns responsibility for quality management to a single organization[24]. When the U.S. automobile industry was becoming uncompetitive with the Japanese automobile industry on price, quality and reliability, the successful response was to decrease the number of suppliers and increase the suppliers' responsibility for quality and design. It may seem counterintuitive, but reducing the number of suppliers and increasing their responsibilities made the suppliers more competitive and responsive to the manufacturers than the previous system that relied much more on open competitive bidding with price being a primary factor. The U.S. automakers transformed a low-bid system into best-value partnership. Ownership of the results is considered to be key to improving performance.

One other observation that can be made on the current quality control guided practices in the construction industry is that it has a heavy reliance on inputs. Taking HPC as an example, construction specifications provide for quality control testing at the batch plant, and testing of the mix as it is unloaded from the ready mix trucks. Normally a battery of tests is performed, including slump, temperature, air-entrainment and cylinders are cast for later testing. All this testing measures inputs. The slump testing is a very indirect measure of any of the variables that affect the cured concrete. These tests are taken before the concrete is incorporated into the work. After the inputs are tested, inspection is used for the remainder of the processes. No tests are usually taken of the in-place concrete. No attempt is made to validate the performance of the finished concrete pour.

The topic of recommending tests that would validate the finished product is beyond the scope of this paper. There may not be any standard tests that will accomplish this objective. However, some suggestions and caveats can be provided.

Extracting small-diameter, partial-depth cores would facilitate petrographic examination of the top three inches of the concrete. Chloride permeability testing could be done using these cores. Strength testing could also be done. The petrographic examination can confirm the water/cementitious materials ratio and the proportions of other constituent materials. The characteristics of the air entrainment can also be directly determined from this type of analysis. A petrographic examination provides direct measurements of several characteristics that are considered key to the long-term performance of concrete, as opposed to traditional material testing that only provides indirect measurements. A caveat regarding chloride permeability testing is required. The testing done on cores would essentially be looking at microscopic behavior. The influence of cracks on the permeability of the deck in its entirety would not be accounted for. Additional inspection of the completed deck, after substantial shrinkage and temperature drop have occurred, may be desirable to document the size, spacing and other characteristics of cracks. Cracks are essentially inevitable, since concrete is a relatively non-ductile material that is subject to volume changes that are restrained.

SUGGESTIONS

New products and procedures always present challenges for quality management. By definition, change is the opposite of consistency (the hallmark of quality.) Experience is missing. Those who are familiar with the properties of the learning curve understand that the more times an activity is performed, the better and more consistent the results will be. Both training and experience are necessary elements. Training alone cannot compensate for experience. In most markets, multiple contractors will have to go through the learning curve independently. This extends the time required to improve performance on new or modified activities industry-wide.

A second problem with changing materials is that, despite the best efforts of specification writers, written description of outcomes are much less clear than actual demonstrations of outcomes. If a picture is worth a thousand words, how many pictures is a physical object and actual experience worth? More objective measures can be used to demonstrate minimum and desirable standards.

This could be accomplished in several ways. Taking a bridge deck using HPC as an example. The owner could act as general contractor, either supervising a crew on a time and materials basis, or using its own forces to construct bridge decks under several conditions. In the latter case, interested contractors could observe so that the techniques and challenges would be understood by future prospective bidders, and the results of the cured concrete could be objectively observed and used as a basis for acceptance.

Another way to address potential quality problems that are common with low-bid procurement is to provide for a qualification-based selection or best-value selection for the critical element of work, such as the HPC bridge deck. A sole source contract for bridge deck construction is one possible result of this option. This option has several disadvantages: it may limit competition and it may reduce the contractor's ability to manage subcontractors, if a subcontractor is added to the contractor's project team without selection by the contractor. The situation would be similar to a contractor's coordination with utility companies.

A simpler way would be to provide performance specifications for concrete permeability and other factors directly related to the performance and durability of the bridge deck and have graduated incentive/disincentive payments related to tests of the completed bridge deck. For example, if the permeability of a conventional concrete bridge deck is 4000 coulombs and the expected life of the deck is 35 years, then (if testing proves this) a deck with a permeability of less than 1500 coulombs would likely have a design life of greater than 75 years and would equal or exceed the design life of the bridge. Full payment would be provided for decks with performance tests for permeability meeting or exceeding the target life. Lesser payments would be made for projected deck lives less than the target design life. It would be critical to measure the actual deck materials and compensate for macro conditions such as the number and size of cracks. Tests on small-scale samples made during placement of the deck (as concrete cylinders are) should not be considered representative unless research establishes reliable correlations between samples and full-scale installations.

This approach directly identifies an area where research on actual results of the construction and maintenance of infrastructure is currently inadequate. There are few examples in the literature such as the analysis of the National Bridge Inventory data performed by Dunker and Rabbat[25].

The growing body of data available in bridge management systems, such as PONTIS, appears to present future opportunities for examining the durability of bridge components at an unprecedented level of detail. Elements of PONTIS, such as the deterioration models, could be modified to address different approaches to bridge construction related to HPC. It is clear that, in order to be considered a successful application, HPC bridge decks should demonstrate improved durability relative to conventional concrete decks. The rate of aging should be much slower for HPC decks. The trends could be identified using PONTIS data.

Payments based on the value of deferred maintenance or deferred replacement of bridge decks provides some intriguing possibilities, but the results of the durability (quality) of the bridge deck will not be known until so far into the future that the time frame is probably too long to influence behavior. In addition, the bridge or the bridge deck may be replaced or made obsolete for reasons other than durability. This would increase the uncertainty of incentive payments even more.

A fifth approach to improving quality of HPC bridge decks is to require certification of firms and key individuals performing specific tasks. Element 9, Process Control, provides for certification for processes where the results cannot be fully verified through inspection and testing until after the product is in use. HPC bridge decks easily fit this definition.

The last alternative presented in this paper is for the owner to perform those activities, such as placing and curing high performance bridge deck concrete, that are inherently difficult to achieve the desired quality on. The owner would certainly be in a much better position to control the quality on its own construction then it would be to try to control the quality of a contractor through inspection and testing.

CONCLUDING REMARKS

The construction industry in the United States has just begun transitioning to ISO 9001 type quality management plans. The philosophies behind the plans and the tools that the plans provide for managing quality seem to be little understood by owners and contractors in the construction industry. The transition to effective quality management plans will likely take many years. Conditions unique to the construction industry, and especially to public works projects will slow the implementation of ISO compliant quality plans and reduce the effectiveness of the plans that are implemented.

The traditional approach to achieving quality on public works construction projects has been through ever more rigorous prescriptive specifications, reinforced by inspection and testing. This approach focuses on inputs to the exclusion of outputs. An analogy for designers is to include more decimal places (i.e., precision) in their calculations, but not checking the calculations for accuracy or for applicability of the analysis method chosen. Specifications focusing on "how" to achieve results and not what results are required do not allow for effective process control or innovation. Engineers and researchers, with their analytical bias, seem determined to provide ever more detailed prescriptions for projects, without incorporating feedback or determining root causes for nonconforming outputs.

There are many difficulties in describing necessary requirements through specifications. More important, achieving desired results through command and control techniques is less efficient than controlling outcomes though providing appropriate incentives and disincentives[26]. Designing effective incentives, so that all parties can work in their own self-interest and have a common goal provides a more effective framework for quality management. Limitations in knowledge transfer and decision making using public institutions provide difficult challenges to implementing effective incentives.

Many readers of this paper will be looking for detailed guidelines for the application of the ISO quality management to HPC. The point of the ISO standard is that it does not provide detailed, prescriptive procedures to attain quality. The standard is written to allow flexibility. It allows each firm to tailor its approach to achieving a desired outcome. If the desired outcomes can be clearly identified, it is possible to achieve those outcomes through a variety of techniques and procedures.

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